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Full Papers 2026

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LRN's main objective is to facilitate the generation, promotion and dissemination of relevant research to professionals working across all sectors within the supply chain. The LRN 2024 Conference was based upon accepted abstracts and was an opportunity to meet and share research, and discuss sustainable and resilient supply chains in disruptive times.

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Welcome

It is my pleasure to welcome you to CILT(UK)'s Annual **LRN Conference 2026**. This years theme is all about **'Sustainable Global Trade and Integrated Logistics Systems for Resilient and Future Ready Supply Chains.'** Together with our inspiring speakers, we will explore pioneering research and thought leadership that address today's most pressing challenges - from environmental impact and sustainability to technological innovation and the future of skills.

As academics and professionals working in some of the most dynamic and vital fields of our economy, your contributions are driving progress. From supply chains and shipping lanes to last-mile deliveries and advanced logistics technologies. From buses and trains to airlines and digital mobility platforms. Your research and innovation underpin the systems that ensure goods and people move efficiently, shelves remain stocked, businesses stay resilient, communities remain connected, and societies thrive through accessible and reliable transport.

The strength of our profession lies not only in the systems and technologies we build, but in the ideas, knowledge, and discoveries that continue to advance them.

Thank you for joining us, and I hope you enjoy the event.

Helen Hardy FCILT
Chief Executive Officer (Interim) CILT(UK)

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A MILP OPTIMISATION MODEL FOR SUSTAINABLE TECHNOLOGY ALLOCATION IN MULTI-PART, MULTI-PERIOD HYBRID MANUFACTURING SUPPLY CHAINS

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1. Introduction

Maintenance, repair and operations (MRO) in asset-intensive industries hinge on the availability of critical metal spare parts — pump impellers, gears, flanges, turbine components — whose unplanned unavailability halts production at very high cost. Demand for such parts is intermittent and low-volume, driven by the stochastic failure of a large installed base (Syntetos et al., 2005; Van der Auweraer and Boute, 2019; Pinçe et al., 2021), while conventional resupply through original-equipment-manufacturer (OEM) procurement carries lead times of many months (Westerweel et al., 2021). Additive manufacturing (AM), notably laser powder bed fusion (PBF) and wire-arc additive manufacturing (WAAM), offers on-demand, near-net-shape production with radically shorter lead times, and is increasingly promoted as a route to a more sustainable spare-parts supply chain (Sgarbossa et al., 2021; Kunovjanek et al., 2022).

The environmental case for AM, however, is not clear-cut. Life-cycle studies repeatedly conclude that AM is greener only for particular parts and conditions (Kokare et al., 2023; Kunovjanek et al., 2022): WAAM's near-net deposition can cut material waste and carbon sharply (Mattos et al., 2023), whereas PBF is highly electricity-intensive (Priarone et al., 2019), and mature conventional processes can be very efficient for the right geometry. The result is a decision that is inherently part-specific and system-level: for a portfolio of parts, which should be made additively, which conventionally, and does coordinating the mix outperform committing to a single technology? Most published models optimise cost or availability (Knofius et al., 2019; Westerweel et al., 2018), or compare AM and CM one part at a time (Sgarbossa et al., 2021); the feasibility-aware, portfolio-level allocation of parts across AM and CM to minimise total emissions is under-explored.

This paper addresses that gap. It is guided by an explicit research question: for a portfolio of metal spare parts with heterogeneous manufacturability, which process should produce each part to minimise total supply-chain emissions, and does a coordinated additive–conventional (Hybrid) allocation outperform a pure additive or a pure conventional strategy? To answer it, we formulate an emissions-minimising MILP that allocates a metal spare-parts portfolio across four processes, respecting which parts each process can actually make (compatibility), finite machine capacity, and mode-specific lead times. Extending the bi-objective cost–carbon direction of Sheikh et al. (2025) towards a feasibility-aware portfolio allocation, we compare three configurations — AM-only, CM-only and Hybrid. Using a four-part oil & gas / mining case, we show a coordinated Hybrid allocation is environmentally optimal at an interior additive share, quantify the part-attribute thresholds that determine the greenest route, and demonstrate — through sensitivity and scenario analyses and comparison with independent life-cycle studies — that the finding is robust. The study makes three contributions: (i) a feasibility-aware MILP that allocates a metal spare-parts portfolio across additive and conventional routes under manufacturability, capacity and lead-time limits; (ii) an explicit AM-only vs CM-only vs Hybrid comparison establishing that hybrid coordination is environmentally optimal at an interior additive share; and (iii) part-attribute thresholds that convert ambiguous life-cycle evidence into decision rules.

2. Literature review

A substantial literature examines AM in spare-parts supply chains. Sgarbossa et al. (2021) compare AM and conventional supply for Poisson-distributed failure demand; Knofius et al. (2019, 2021) study AM as a consolidation and dual-sourcing option; Westerweel et al. (2018, 2021) analyse life-cycle cost and on-site printing at remote locations; and Song & Zhang (2020) model on-demand printing against conventional stocking. Systematic reviews (Kunovjanek et al., 2022; Mecheter et al., 2022) confirm the recognised benefits — shorter lead times, lower inventory, decentralised production — and the prevalence of failure-driven, Poisson-type demand.

On sustainability, the evidence is process- and part-specific. Mattos et al. (2023) find WAAM produces a flange with roughly 95% lower carbon and 76% less solid waste than forging; Kokare et al. (2023) report WAAM's environmental impact about 2.5× lower than CNC machining and 3.4× lower than selective laser melting; Priarone et al. (2019) provide a WAAM environmental–economic modelling framework. Conversely, PBF is energy-intensive, with specific energy an order or two above conventional processing, and casting/forging factors depend heavily on route and energy mix. Reviews therefore describe AM's environmental benefit as context-dependent — a 'yes and no' that turns on material waste, part mass and the electricity mix.

Optimisation for sustainable AM supply chains is emerging. The closest work, Sheikh et al. (2025), presents a bi-objective (cost and carbon) MILP for an AM-enabled spare-parts supply chain. That model optimises an AM-enabled chain but does not allocate a physical parts portfolio across additive and conventional routes under manufacturability limits, nor compare pure and hybrid configurations. To our knowledge, no prior study formulates a feasibility-aware, portfolio-level, emission-minimising allocation across AM and CM with an explicit AM-only vs CM-only vs Hybrid comparison and part-attribute sustainability thresholds — the contribution of this paper.

3. Problem description

We consider a spare-parts hub (an in-house or service-bureau facility) supplying a large oil & gas / mining installed base over a 12-month planning horizon in monthly periods. Intermittent, failure-driven demand for the parts is met from a hub that operates additive (PBF, WAAM) and conventional (casting, forging) machines of finite capacity, holds safety stock, and can procure externally from an OEM as a long-lead fallback, with each supply mode carrying a distinct lead time. Four representative metal spare parts are studied (Figure 1), chosen to span materials, geometries and manufacturing routes: a centrifugal pump impeller (super duplex stainless steel), a gearbox pinion gear (case-hardened alloy steel), a weld-neck pipe flange (carbon steel) and a turbine nozzle guide vane (Inconel 718 nickel superalloy).

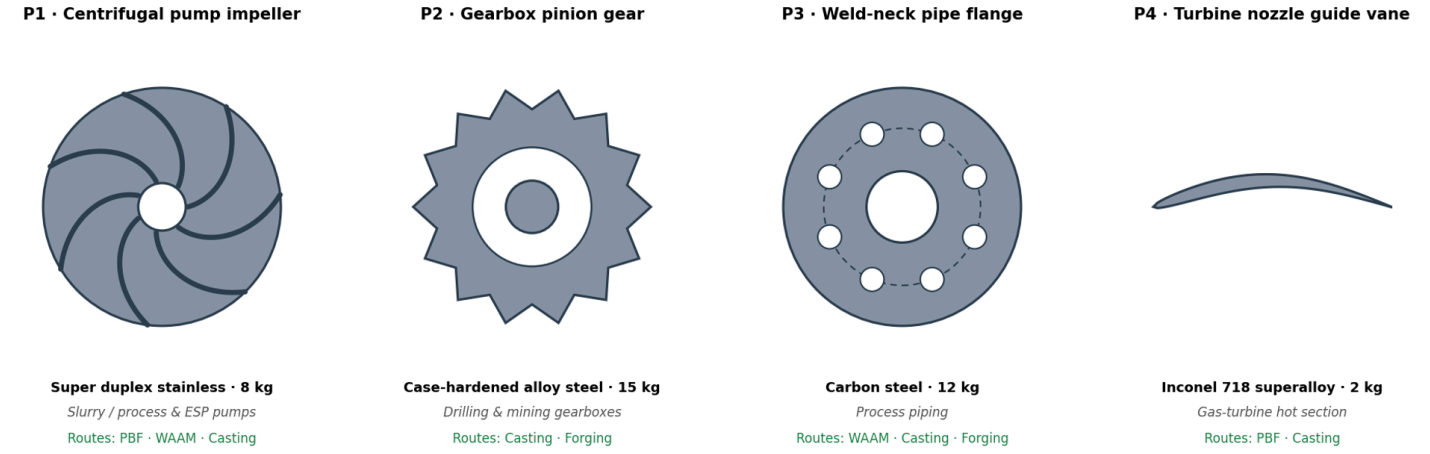

Figure 1: The four metal spare parts, their materials, masses and feasible manufacturing routes.

Four processes are available: PBF and WAAM (additive, AM); casting and forging (conventional, CM). Crucially, not every part can be made by every process — part–process compatibility reflects engineering feasibility. The gearbox pinion is conventional-only (casting or forging); the nozzle suits PBF or investment casting; while the impeller and flange support both additive and conventional routes. Demand is intermittent, modelled as a Poisson process with a monthly rate derived from installed base and annual failure rate. Each month, the hub decides how many of each part to produce on each feasible process, how much to hold, and how much to procure externally (a costly, long-lead fallback), so as to minimise total supply-chain CO_2 emissions while meeting demand within finite machine capacity and lead times.

4. Mathematical Model

This section presents the mixed-integer linear programming (MILP) model that determines the monthly production, inventory and sourcing decisions minimising total CO_2 emissions across the spare-parts portfolio, subject to compatibility, capacity,

lead-time and demand requirements. The notation is defined first, followed by the objective function and the constraints.

4.1 Notation

Sets and indices

$i \in I$: spare parts.

$p \in P$: manufacturing processes; additive $P_{AM} = \{PBF, WAAM\}$, conventional $P_{CM} = \{Casting, Forging\}$, $P = P_{AM} \cup P_{CM}$.

$t \in T$: monthly planning periods, $T = \{1, \ldots, 12\}$.

Parameters

$d_{i,t}$: demand for part i in period t (units).

$ep_{i,p}$: cradle-to-gate production emissions of part i on process p (kg CO2/unit).

eo_i : outsourcing (procurement and transport) emissions of part i (kg CO2/unit).

eh_i : inventory holding emissions of part i (kg CO2/unit/period).

$cp_{i,p}$: unit production cost of part i on process p. $cs_{i,p}$: setup cost. h_i : holding cost. co_i : outsourcing cost.

$\tau_{i,p}$: machine-time consumed per unit of part i on process p (hours/unit).

N_p : number of machines of process p. H_p : operating hours per machine per period.

$Cap_p = N_p H_p$: available capacity of process p per period (machine-hours).

$comp_{i,p}$: 1 if part i can be produced on process p, 0 otherwise.

Lp_p : production lead time of process p (periods). Lo_i : outsourcing lead time of part i (periods).

M : a sufficiently large constant.

Decision variables

$X_{i,p,t} \geq 0$: units of part i produced on process p in period t.

$Q_{i,t} \geq 0$: units of part i outsourced in period t.

$I_{i,t} \geq 0$: inventory of part i at the end of period t.

$Y_{i,p,t} \in \{0,1\}$: 1 if a setup for part i occurs on process p in period t.

4.2 Objective Function

The objective minimises total supply-chain CO2 emissions from production, outsourcing and inventory holding over the planning horizon:

$$\min \; E = \sum_{i,p,t} ep_{i,p} X_{i,p,t} + \sum_{i,t} eo_i Q_{i,t} + \sum_{i,t} eh_i I_{i,t} \qquad (1)$$

Total cost — production, setup, holding and outsourcing — is computed from the same decision variables and reported as the cost–emissions trade-off; it does not enter the objective.

4.3 Constraints

Inventory balance

$$I_{i,t} = I_{i,t-1} + \sum_p X_{i,p,t-Lp_p} + Q_{i,t-Lo_i} - d_{i,t}, \quad \forall i \in I,\ t \in T \qquad (2)$$

Inventory equals the previous stock plus production that started Lpp periods earlier and outsourced orders placed Loi periods earlier, less demand — capturing the three-tier, mode-specific lead times (additive = 1 period; conventional in-house = 2–3; outsourcing = 4–6). Opening safety stock is rebuilt by the end of the horizon.

Machine capacity

$$\sum_i \tau_{i,p} X_{i,p,t} \leq Cap_p = N_p H_p, \quad \forall p \in P,\ t \in T \qquad (3)$$

Each process is limited to the capacity of its Np machines operating Hp hours per period.

Setup forcing

$$X_{i,p,t} \leq M\, Y_{i,p,t}, \quad \forall i \in I,\ p \in P,\ t \in T \qquad (4)$$

A setup Yi,p,t is incurred whenever part i is produced on process p in a period.

Part–process compatibility

$$X_{i,p,t} = 0 \quad \text{if } comp_{i,p} = 0, \quad \forall i \in I,\ p \in P,\ t \in T \qquad (5)$$

Production is permitted only on engineering-feasible part–process routes.

Variable domains

$$X_{i,p,t},\ Q_{i,t},\ I_{i,t} \geq 0; \quad Y_{i,p,t} \in \{0,1\}, \quad \forall i \in I,\ p \in P,\ t \in T \qquad (6)$$

The three configurations follow by restricting the process set P to PAM (AM-only), PCM (CM-only) or their union (Hybrid). Emission factors epi,p are derived from published life-cycle studies multiplied by part mass, while costs, masses and capacities are engineering assumptions subjected to the uncertainty analysis of Section 6. The model was implemented in Python/PuLP and solved with the CBC solver.

5. Numerical Experiments and Results

The model was implemented in Python using the PuLP modelling library and solved with the open-source CBC (COIN-OR Branch-and-Cut) solver; any standard MILP solver, such as CPLEX or Gurobi, is equally applicable. For the four-part, four-process, twelve-period instance the model comprises 384 decision variables (120 binary) and 220 constraints, and solves to proven global optimality in under one second. The following numerical experiments compare the three configurations and probe the robustness of the outcome.

Solving each configuration to minimise emissions (Figure 2), the Hybrid allocation is the greenest at 337 t CO2 — about 18% below conventional-only (413 t) in the case studied. Conventional-only is cheapest but the most carbon-intensive; AM-only is cleaner than CM-only but, unable to make the gear and facing long procurement lead times, is forced into costly outsourcing and the highest cost. This ordering aligns with independent life-cycle evidence that WAAM is substantially lower-carbon than powder bed fusion — around 3.4x in Kokare et al. (2023) — and than forging (Mattos et al., 2023), while PBF is the most electricity-intensive route (Priarone et al., 2019).

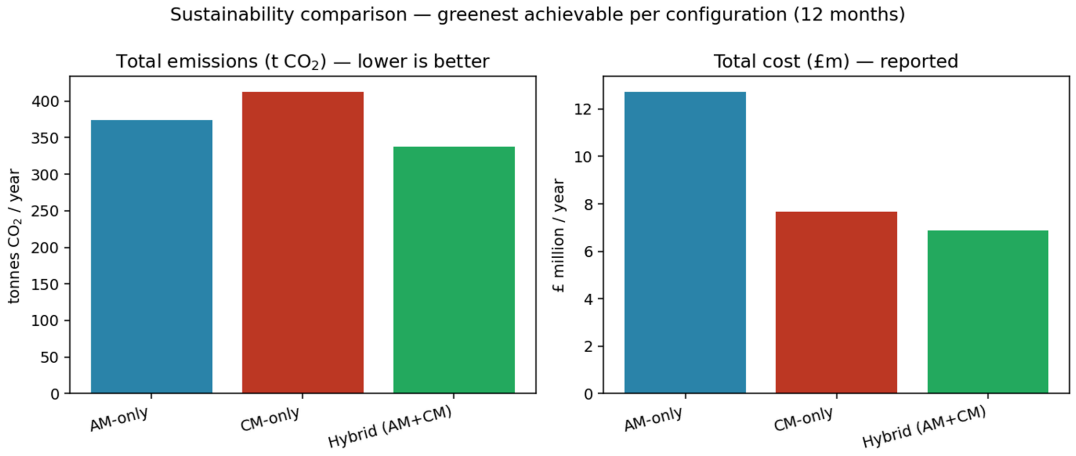

Figure 2: Emissions (primary) and cost (reported) of the greenest achievable plan by configuration.

The mechanism is visible at part level (Figure 3): each part's greenest feasible route is determined by its nature — material, mass and geometry. WAAM is greenest for the impeller and flange (near-net, low waste), whereas the energy-intensity of PBF and the higher waste of forging make casting greenest for the nozzle and forging greenest for the gear. Because the greenest routes span both additive and conventional processes, the emissions-optimal portfolio is intrinsically a hybrid. That two of the four parts are greenest conventionally echoes the literature's central finding that AM's environmental benefit is context-dependent rather than universal (Kunovjanek et al., 2022; Sgarbossa et al., 2021).

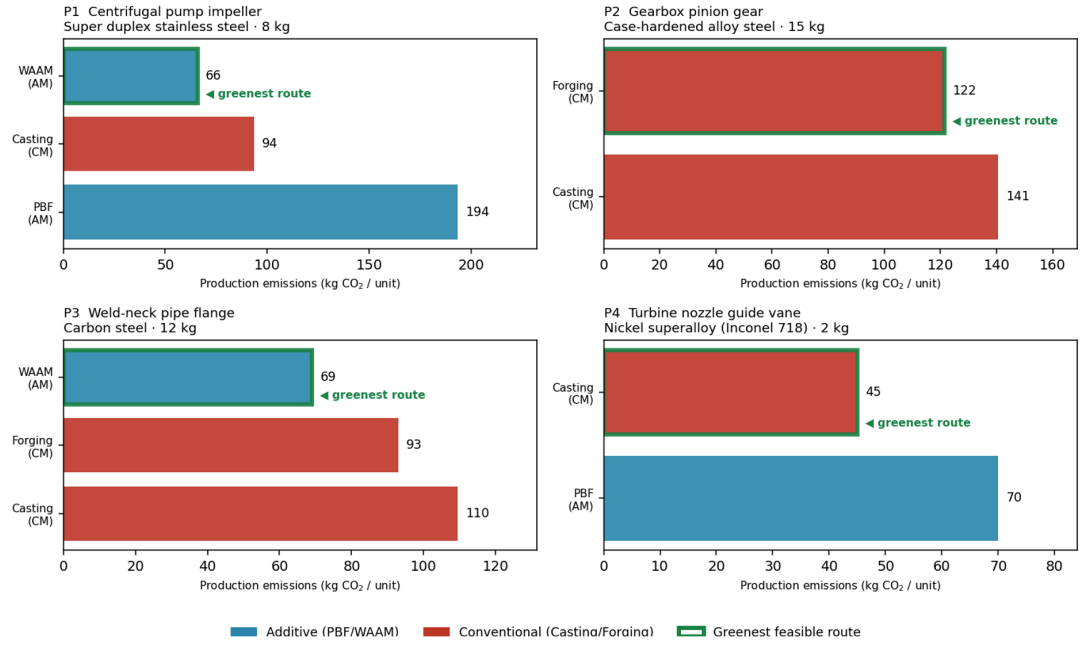

Figure 3: Production emissions by feasible route for each part; the greenest route is highlighted.

Sweeping the enforced additive share (Figure 4) confirms this: total emissions fall as work shifts to AM, reach a minimum at an interior share (roughly 50% in this instance), then rise as production is forced onto energy-intensive or infeasible additive routes. The greenest strategy is therefore to coordinate the portfolio, not to commit to a single technology. Part-attribute analysis further shows the additive advantage is robust: AM remains the greener route until the electricity carbon intensity rises to about 2.3× today's value, and across the plausible range of conventional material-waste. Cost is the trade-off: relative to the cheapest conventional plan, the emissions-optimal Hybrid carries an implied abatement cost of the order of £26,000 per tonne CO2 in this instance — high against current carbon prices, underlining that AM adoption for sustainability is driven by capability and material efficiency rather than carbon pricing alone.

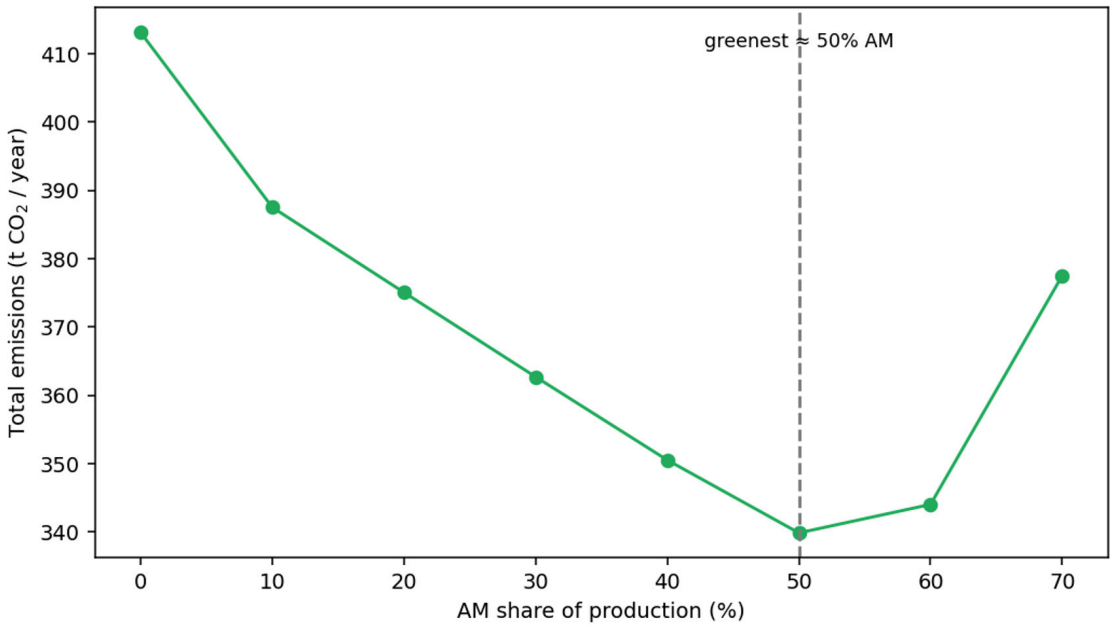

Figure 4: Total emissions versus additive share — the greenest allocation is an interior hybrid mix.

6. Discussion

The numerical results above are consistent with the independent life-cycle literature cited alongside them, giving the illustrative model credible face validity: the ordering of process carbon intensities (WAAM lowest, PBF highest), the context-dependence of AM's benefit (two of four parts greenest conventionally) and the large additive lead-time advantage all reproduce published findings.

Robustness is established three ways. A one-at-a-time tornado over six influential inputs — the two emission factors plus the assumed machine capacity, processing time, outsourcing emissions and demand — moves the emissions-optimal additive share within roughly 10–85% but never to a pure strategy. A Monte-Carlo analysis varying all six simultaneously finds the greenest plan is a genuine additive–conventional hybrid in 100% of runs. Six named scenarios (green grid, coal-heavy grid, cleaner conventional industry, capacity-constrained, high demand, baseline) all remain hybrid, with the additive share ranging from 10% (coal grid) to 64% (green grid). The central conclusion therefore does not depend on any single assumed value.

The novelty of the study lies in moving from part-level life-cycle comparison to a feasibility-aware, portfolio-level allocation of parts across additive and conventional technologies, with an explicit AM-only vs CM-only vs Hybrid comparison and part-attribute thresholds — an angle not addressed by the closest bi-objective cost–carbon formulation (Sheikh et al., 2025). For practitioners, the model yields clear decision rules: route each part to its greenest feasible technology, expand additive capacity where the local electricity grid is clean, and treat pure-technology strategies as dominated. Its main limitations are that part-level costs, masses and the casting emission factor are illustrative assumptions — bracketed by the sensitivity analysis — that demand is represented by a single Poisson realisation, and that a single hub is modelled. The qualitative conclusion also depends on WAAM being lower-carbon than casting for some parts — the input to which the tornado assigns the greatest single influence — and the allocation is shaped as much by finite additive capacity and part–process compatibility (notably the conventional-only gear) as by part material and geometry.

7. Conclusions

This paper contributes a feasibility-aware, portfolio-level MILP that allocates a metal spare-parts portfolio across additive and conventional manufacturing to minimise supply-chain emissions, respecting part–process compatibility, machine capacity and mode-specific lead times. For the oil & gas / mining case studied, a coordinated Hybrid allocation is environmentally optimal — no pure additive or pure conventional strategy is best — with the emissions-optimal additive share lying in the interior (around 50% in this instance) and emissions roughly 18% below conventional-only. The greenest route is governed by part attributes (material, mass, geometry), and the result is robust across one-at-a-time, Monte-Carlo and scenario testing and consistent with independent life-cycle evidence. Future work will extend demand to a stochastic, multi-scenario formulation, treat machine capacity as an investment decision, and broaden the objective to a full multi-criteria (cost–carbon–service) trade-off.

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DATA CHALLENGES IN RAILWAY OPERATIONAL DATASETS: A SYSTEMATIC ANALYSIS

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Abstract

This study offers an empirical, systematic analysis of data quality problems for two fundamental operational datasets for railways in the UK: Network Rail's Train Describer (TD) berth-level data and the BPLAN (Train Planning Data) Geographic Reference System (GRS). This research quantifies quality failures based on a direct examination of 32,347 SMART (Train describer berth offset data used for train reporting) berth-step records, 11,886 BPLAN location entries, and 55,868 CORPUS (Codes for Operations, Retail and Planning – Unified Solution) TIPLOC (Timing Point Location) records. 47.0% of BPLAN location records carry invalid geocoordinates (zero values, 999999 placeholders or out-of-range positions, several in the open ocean or overseas). 97.8% of SMART records do not contain the TOLINE. An innovative, transferable five-stage diagnostic and preprocessing framework is proposed, mapping each quality failure to a remediation stage with quantified recovery estimates, alongside three direct recommendations for Network Rail to enhance data quality at source. No comparable framework has previously been reported for UK open rail reference data.

Keywords: railway data quality; Train Describer; BPLAN; STANOX; TIPLOC; geocoordinate validation; journey identification; preprocessing; machine learning; freight capacity planning.

1. Introduction

Each year the UK railway network is used for approximately 1.61 billion passenger journeys and around 31.4 million freight train kilometres (Office of Rail and Road, 2024). Open data is a project of Network Rail, which has opened up access to operational data and allowed academic researchers and commercial innovators to utilise it to research and create solutions. These datasets, however, can only be useful for analysis if they are of high quality. Data quality (accuracy, completeness, consistency, timeliness and validity) is a key precondition for any meaningful analytical result (Wang and Strong, 1996).

Although the use of Network Rail open data in transport research is increasing, there is no comprehensive empirical study that systematically examines data quality and quantifies deficiencies in the core reference datasets. This paper addresses that gap through direct measurement on 32,347 SMART berth-step records, 11,886 BPLAN location records and 55,868 CORPUS TIPLOC entries. The study has two objectives: to quantify the prevalence and structure of quality failures across completeness, validity, identifiability, cross-dataset consistency and timeliness in these datasets, and to assess the extent to which a systematic preprocessing framework can recover analytically usable data. A consolidated map of the validated UK rail locations supports this analysis.

The paper is structured in six sections. Section 2 reviews related work. Section 3 sets out the datasets and methodology. Section 4 reports the results across the five quality dimensions. Section 5 develops the preprocessing framework. Sections 6 and 7 discuss the findings and conclude.

2. Literature Review

The seminal work of Wang and Strong (1996) states that four key dimensions of data quality are accuracy, completeness, consistency and timeliness. They have been widely used and expanded in later work (Batini et al., 2009). The dimensions become very relevant in the context of railway operations: a single wrong STANOX (Station Number) code can send a signal-control event to the wrong point, a lack of coordinate means that a spatial query in the entire TD area is thrown out, incorrect identifier schemes can even cause entire joint operations to fail. In machine learning applications the quality of the training data directly determines the model performance beyond the architectural sophistication (Bałdyga et al., 2024). Predictive modelling of running and dwell times also depends on the integrity of TD timing fields (Kecman and Goverde, 2015). Recent evidence confirms that such quality deficiencies are widespread in open transport data. A survey of 632 General Transit Feed Specification (GTFS) feeds found that approximately 21% contained at least one validation error against

the published specification (Devunuri and Lehe, 2024), demonstrating that completeness and validity failures are common in publicly released transport datasets. This evidence, however, is drawn almost exclusively from public-transit schedule feeds and from the wider open-government-data domain. The literature contains no comparable study that systematically quantifies data quality in the open reference datasets that underpin UK rail operations.

The TD system is provided by Network Rail's open data programme and records real-time signalling messages as trains move through berths (discrete track sections controlled by the signalling system) in 191 TD area controllers. SMART Step Messages include timing offsets, route designations and platform identifiers for berth-to-berth movements (Open Rail Data Wiki, 2019). The BPLAN database (BPLAN, Train Planning Data, is Network Rail's master geographical model for train-schedule planning) includes all the canonical geographic reference information, such as the British National Grid (BNG) easting and northing coordinates for each TIPLOC, and STANOX, NLC (National Location Code) and CRS (Computer Reservation System; the three-letter '3ALPHA' station code) codes (Open Rail Data Wiki, 2023). This is expanded in CORPUS with an extensive mapping from TIPLOC to NLC (STANOX).

The importance of data quality has been observed in several areas in transport, such as GPS trace cleaning in urban mobility (Zheng, 2015), inconsistent stop identifiers in public transit GTFS feeds (Antrim and Barbeau, 2013), delay analysis on regional passenger lines (Palmqvist et al., 2017), and stale or erroneous reference data in rail timetabling systems (Palmqvist et al., 2018). The particular set of structural weaknesses that occur as a result of the interaction between TD signalling data and BPLAN geographic references, however, is unique to the UK rail environment and has not been empirically quantified. The present study fills that gap.

3. Methodology

3.1 Data sources

This study uses three main datasets from the Open Data portal of the Network Rail. A summary of the information is given in Table 1. In BPLAN, LOC denotes the Location record type, holding each network point's TIPLOC, coordinates and associated codes.

Table 1: Summary of datasets examined in this study

Dataset	Records	Key Fields	Source
SMART (TD Berth Steps)	32,347	FROMBERTH, TOBERTH, STANOX, TD, PLATFORM, ROUTE	NR Open Data
BPLAN LOC (Location) Data	11,886	TIPLOC, Easting, Northing, NLC	NR BPLAN
CORPUS TIPLOC	55,868	TIPLOC, STANOX, NLC, 3ALPHA, UIC	NR Open Data

3.2 Quality assessment methodology

Data quality was assessed across five dimensions:

1. **Coordinate validity:**
   Sentinel values were excluded first (coordinates with an easting or northing of 0 or 999999), and the remaining coordinates were then range-checked against the British National Grid (BNG) extent ($0 < E \leq 700{,}000$; $0 < N \leq 1{,}300{,}000$); records passing the sentinel check but falling outside this extent (for example easting $> 700{,}000$) were also treated as invalid.
2. **Field completeness:**
   Null and blank proportions were computed for all fields.
3. **Journey identifiability:**
   STANOX-to-TD sharing rates and multi-area berth codes were enumerated.
4. **Cross-dataset consistency:**
   All three datasets were compared to each other using TIPLOC identifier sets.
5. **Timeliness:**
   Date stamps were analysed to check for coverage.

The geographic figure is derived from valid BNG coordinates using pyproj (EPSG:27700 to EPSG:4326) to transform to WGS84 latitude and longitude and plotting this against an outline of the UK coastline.

These five dimensions operationalise the Wang and Strong (1996) framework for the reference-data setting. Uniqueness and standalone consistency were not adopted as separate top-level dimensions: uniqueness surfaces within cross-dataset integrity (for example, duplicate TIPLOCs in Table 4), and consistency is assessed through cross-dataset alignment rather than as an independent axis, because these reference tables lack the redundant intra-record fields that make isolated consistency testing meaningful.

4. Findings

The BPLAN LOC dataset contains the easting and northing coordinates of the locations within the UK rail network, represented in the BNG reference system, for 11,886 distinct TIPLOC-identified locations, which is the geographic backbone for spatial analysis of UK rail operations.

Figure 1 shows the coordinate-validity breakdown of these 11,886 BPLAN LOC records, obtained by applying the Section 3.2 validation rules to each easting/northing pair. Barely half the records survive validation: the invalid 47.0% renders the geographic reference layer unusable without remediation, although the dominance of sentinel values (zeros and 999999) over genuinely erroneous positions means most failures are systematic and therefore recoverable.

4.1 Geographic distribution after coordinate validation

To show the consequences of removing invalid records, the spatial distribution of rail locations is shown in Figure 2 after the invalid records have been removed. The cleaned distribution of BNG is displayed, based on 6,302 of the 11,886 BPLAN entries; a density overlay on this distribution shows the true distribution of railway infrastructure across Britain. Concentrations can be seen around London and the Southeast, the Midlands, the Northwest and central Scotland. In contrast, by using the raw coordinates, the zero-value records are placed at 0°N, 0°E in the Gulf of Guinea (some 5,500 km from the nearest UK railway) and the out-of-range records are scattered across continental Europe. Validation is thus a prerequisite to any spatial analysis that is of any value.

4.2 SMART berth data: field completeness

Table 2 shows the completeness of SMART fields for all important fields. The missing TOLINE and FROMLINE values, which record the running line a train is moving from (FROMLINE) and to (TOLINE) as it steps between berths, are the most operationally significant gaps, making directional path reconstruction infeasible without imputation from TD-area context.

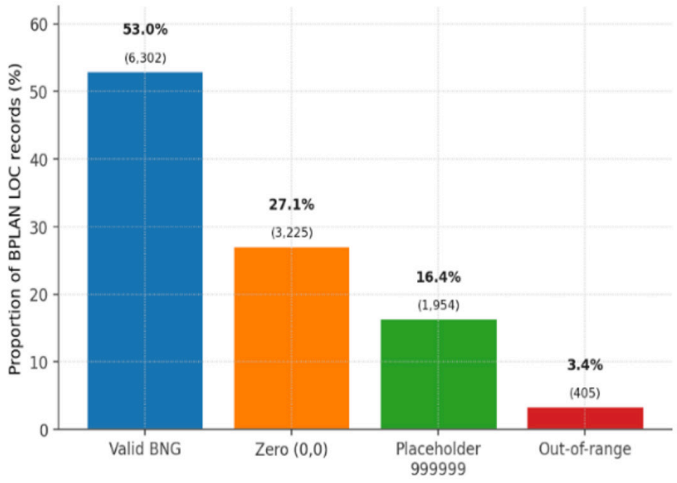


Figure 1: BPLAN coordinates validity breakdown.

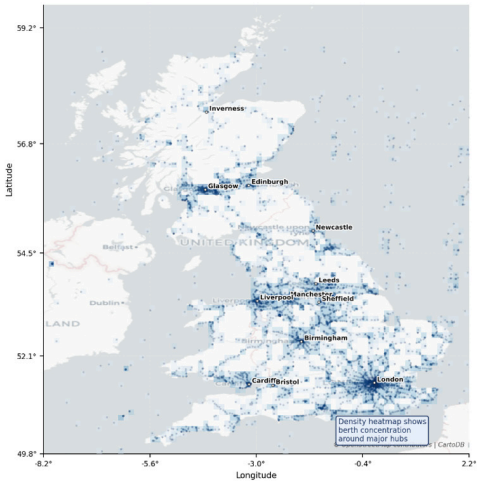


Figure 2: UK rail location distribution after coordinate validation.

Table 2: SMART berth dataset field completeness (N = 32,347 records)

Field	Present	Missing	% Missing	Impact
STANOX	32,347	0	0.0%	None
TD Area	32,347	0	0.0%	None
FROMBERTH	32,131	216	0.7%	Low
TOBERTH	31,825	522	1.6%	Low
PLATFORM	20,104	12,243	37.8%	High
ROUTE	19,682	12,665	39.2%	High
FROMLINE	15,356	16,991	52.5%	Critical
TOLINE	720	31,627	97.8%	Critical

This sparsity is consistent with how the feed is documented: Network Rail's own specification notes that SMART entries need not populate every field, and TOLINE/FROMLINE are descriptive line identifiers rather than fields required for the core berth-stepping and TRUST-timing functions (Open Rail Data Wiki, 2024). The gap is therefore a data-collection characteristic rather than a structural limitation.

4.3 Journey identification and headcode disambiguation

The number of disambiguation challenges during journeys is quantified in Table 3. The vast majority of records (96.3%) are for standard berth steps (type B) with the remainder representing Cancel, Description, Trust, Fail, Interpose and Enter events that are vital for journey continuity reconstruction.

Table 3: Journey identification ambiguity statistics

Ambiguity Metric	Count	Significance
Unique berth codes in SMART dataset	10,550	Scale of network
Berth codes appear in multiple TD areas	3,220 (30.5%)	High risk
STANOX codes shared across multiple TD areas	155	Collision risk
Maximum TD areas sharing one STANOX	4	Critical
STANOX with >10 berths (geo-join challenge)	766	Complex nodes
Maximum berths at single STANOX	84	Major terminus
Berth offset mean and standard deviation	+26.5 s ± 61.6 s	Positive timing bias (59.4%)

Note: berth offset is in seconds (s); the 30.5% multi-area rate is rounded from the exact 3,220 / 10,550 = 30.52%; "positive timing bias (59.4%)" denotes the proportion of records with BERTHOFFSET > 0 (19,211 of 32,347).

4.4 Cross-dataset referential integrity

Table 4 and Figure 3 show referential integrity failures, quantified across the SMART, BPLAN and CORPUS reference chain. Coverage for identifiers is very good for BPLAN but drops significantly within the CORPUS and most records are missing STANOX and CRS together (43,402 records, 77.7%, lack both). The empty-STANOX rate in CORPUS (Table 4) is the most critical completeness gap identified, as it prevents direct station-level linkage for the majority of TIPLOC entries. By contrast, the high empty-CRS rate is largely expected, since most TIPLOCs represent non-passenger infrastructure rather than named stations.

The impact ratings in Table 4 therefore reflect analytical consequence rather than raw missingness. Although the empty-CRS rate (92.7%) exceeds the empty-STANOX rate (79.4%), CRS codes are defined only for the roughly 2,600 GB passenger stations, so an empty CRS is the expected value for most non-station TIPLOCs (High); a STANOX should exist for every operational location, so its absence blocks the SMART–CORPUS station-level join entirely (Critical).

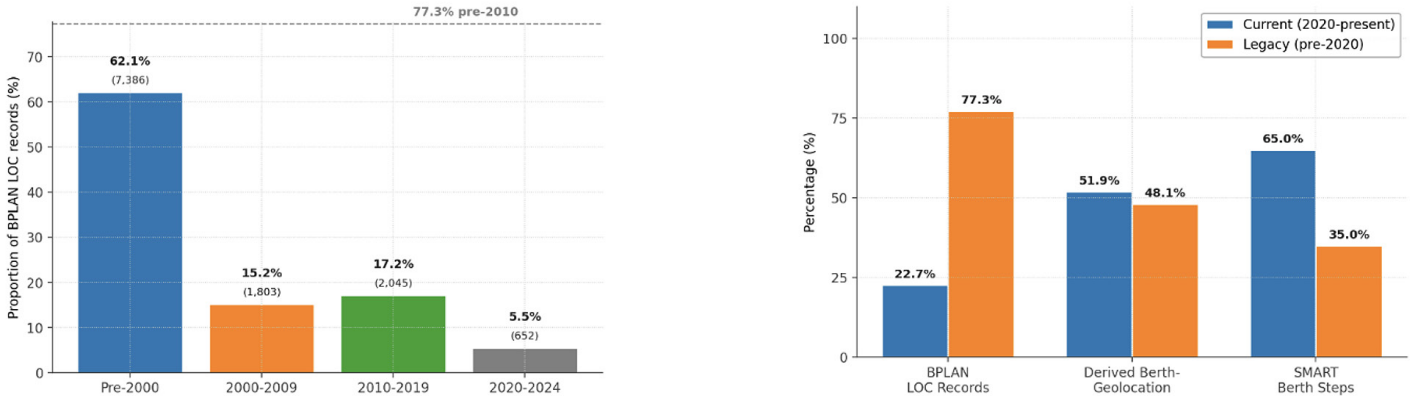
Table 4: Cross-dataset referential integrity metrics (CORPUS, BPLAN and SMART)

Integrity Metric	Count	Rate	Impact
CORPUS records: empty STANOX	44,369 / 55,868	79.4%	Critical
CORPUS records: empty CRS (3ALPHA)	51,773 / 55,868	92.7%	High
CORPUS TIPLOCs not in BPLAN	554	4.5% of CORPUS TIPLOCs	Medium
BPLAN TIPLOCs not in CORPUS	162	1.4% of BPLAN TIPLOCs	Low
Duplicate TIPLOCs in CORPUS	20	0.2% of CORPUS TIPLOCs	Low
One-to-many STANOX-to-TIPLOC (CORPUS)	331	—	High

4.5 Temporal data coverage

The temporal coverage of the reference datasets is summarised in Figure 3. Figure 3(a) shows the distribution of BPLAN LOC record dates: over three-quarters (77.3%) predate 2010, and barely one record in twenty dates from the 2020s. Figure 3(b) compares how up to date each dataset is: the SMART operational feed is roughly three times as current as the static BPLAN reference on which it depends, with the derived berth-geolocation data in between. This pre-2010 concentration is concerning considering the changes in infrastructure in the 2010s, such as HS1, the Elizabeth Line programme and large rebuilds at both Birmingham New Street and Reading and London Bridge.

Each of these schemes physically relocated or added platforms, berths and TIPLOC-referenced points (HS1 opened in 2007, the Reading remodelling completed in 2015, Birmingham New Street in 2015, London Bridge in 2018 and the Elizabeth Line in 2022) (National Audit Office, 2019; Network Rail, 2015). A coordinate or reference record predating the relevant works therefore describes infrastructure that no longer exists in that configuration. The pre-2010 age of these records thus constitutes a direct and evidenced threat to record validity rather than a hypothetical one.



(a) **(b)**

Figure 3: Temporal coverage of infrastructure datasets: (a) BPLAN record-date distribution, showing that 77.3% of records are pre-2010; (b) cross-dataset timeliness comparison across BPLAN LOC records, derived berth-geolocation data and SMART berth steps.

5. Preprocessing Framework

Therefore, this study proposes a five-stage preprocessing framework to tackle quality issues systematically. Across the five stages, expected quality rises from 53.0% to ~75% (coordinates), 2.2% to ~78% (TOLINE, estimated), 69.5% to 80.1% (journey, measured), 95.5% to 96.6% (alignment, measured), and 22.7% to 100% (timeliness tiering).

Stage 1: Coordinate validation and imputation

Three levels of validity are performed:

A. Sentinel detection of zero value or placeholders

B. Range check of the values within the BNG bounds (E = 0 – 700,000, N = 0 – 1,300,000)

C. Fuzzy name matching with OS Open Names, STANOX-cluster centroid assignment or manual assignment for high-traffic critical locations.

The desired result is to increase the percentage of available coordinates from 53.0% to approximately 75% (the midpoint of an estimated 72–78% range).

Stage 2: SMART field imputation

FROMLINE and TOLINE values are estimated based on TD area context and published TD documentation. Comparable, high-confidence proxies are possible via platform assignment of neighbouring berths. The field TOLINE should be considered as a field derived from the TD sequence context.

Stage 3: Journey disambiguation

A four-character headcode (e.g. 1A23) cannot uniquely specify a journey: the same headcode recurs across trips and, at any instant, several trains may share it on different routes. Stage 3 resolves this with four steps. Headcodes are first scoped to a 30-minute window per TD area, so services sharing a code but separated in time are not conflated, and matching is partitioned by TD area, so trains sharing a code across the 191 controllers cannot be confused.

The SMART stream is then reconciled with Darwin (real-time feed) and TRUST (train-running record) on their persistent Schedule/Service UID, matching each event to the nearest Darwin activation in time and space. Finally, the 155 STANOX codes spanning more than one TD area (typically junctions and boundary block transitions) are resolved by an area-sensitive lookup returning the location for the event's own TD area rather than a single canonical position. Together these raise unique-journey assignment from 69.5% to a measured 80.1% (8,455 of 10,550 berth codes); the residual 19.9% requires real-time feed data to resolve fully.

Stage 4: Cross-dataset harmonisation

Name matching and coordinate proximity are used to reconcile the 554 CORPUS–BPLAN TIPLOC gaps identified in Table 4. The 20 duplicate TIPLOCs in CORPUS (Table 4) are resolved by retaining the most recently updated record. The 331 one-to-many STANOX mappings are handled by making station TIPLOCs the designated join targets for each mapping.

Stage 5: Temporal classification

Records fall into three tiers, aligned with the Figure 3 date bands: current (2020 or later), legacy (2010–2019) and historical (before 2010). Confidence decay functions are used on matches of geographic history tier. Any station known to have had an infrastructure change since the record date must be re-validated with a current source.

6. Discussion

6.1 Significance

The invalid coordinate rate represents a structural problem with almost half of the geographic reference layer that cannot be used in an analytical form. The TOLINE missingness rate means the field must be systemically encoded, which it has not been. Both impose hard ceilings on the performance of any data-driven approach that does not first address them. Spatial analysis, which is critical to the path availability modelling and terminal utilisation assessment on which freight operations research is based, relies heavily on an underlying spatial layer that was found to be very deficient in raw form in this study, especially for delivery of the UK Rail Freight Growth Target (Department for Transport, 2023; Network Rail, 2022).

6.2 Recommendations for Network Rail

- Provide requirements for source coordinate validation. New BPLAN records should be published with validated BNG coordinates first, and old, zero-value or placeholder records are to be considered first for the assignment of BNG coordinates.
- Include new service identifiers on TD data exports. A journey-level UID with Darwin activation messages would remove most of the source-side headcode disambiguation problems.
- Create a 24-month data review cycle. A review of BPLAN records in a systematic way prior to 2010 would help to make it accurate and consistent with the new operational reality after the infrastructure changes.

6.3 Limitations

Two limitations bound the generalisability of these findings. First, the analysis rests on a single 2025 temporal snapshot, and the reported quality rates may drift as Network Rail revises the datasets. Second, although these three datasets are core to UK rail reference, they are not exhaustive of the open-data estate, so the prevalence rates reported here should not be extrapolated to other feeds without further sampling. The proposed preprocessing framework needs to be tested in a real research pipeline. The descriptive findings themselves, however, rest on deterministic counts over openly published datasets using the explicit rules of Section 3.2 and are therefore fully reproducible. Their plausibility is further supported by the structured nature of the failures (sentinel values at documented placeholder locations rather than random error) and by the cleaned distribution in Figure 2, which reproduces the known geography of the GB network. The analysis does not include real-time TD data, which may differ in quality from the historical SMART export. Figure 2 approximates the UK coastline, hand-coded for production and should be analysed using authoritative Ordnance Survey boundary data.

7. Conclusion

This study provides the first systematic quantitative description of data quality across Network Rail's Train Describer data, the BPLAN reference and the CORPUS TIPLOC dataset. Quality failure is shown to be the norm rather than the exception, spanning coordinate validity, directional completeness, journey identifiability and cross-reference integrity (Sections 4.1–4.5). These are quality issues with structures that, if left uncorrected, undermine any analytical or machine learning pipeline that uses these data sources. As railway analytics increasingly adopts machine learning for delay prediction, capacity planning and freight-path optimisation, data quality rather than model architecture forms the binding constraint on performance. The proposed five-stage framework presented here provides a documented and reusable foundation for constructing the trustworthy reference layer that such models require, and a transferable template for the quality auditing of open transport data.

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FROM INNOVATION SUPPORT TO SUSTAINABLE OUTCOMES: EXPLORING UK ENTERPRISE ENGAGEMENT

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Introduction

(Gov.UK, 2021). This announcement is important because most businesses in the UK have under 250 employees and are hereby regarded as SMEs. Small to medium-sized enterprises (SMEs) account for around 60% of employment and 50% of UK private sector turnover, making up 99.9% of the business population (BEIS, 2022). In response to the ongoing debate in the UK, policy has adopted innovation strategies and interventions such as funding, diagnostics, advisory support, leadership training and match-funding, aimed at accelerating sustainability adoption, particularly in regions such as the West Midlands (Made Smarter, 2026). Before Brexit, the European Regional Development Fund (ERDF) funded schemes supported various small-scale programmes in the West Midlands, England, to reduce emissions by providing information, advice, and financial incentives for SMEs (Khosravi et al., 2023). Although the ERDF support schemes stopped in the UK after Brexit, other streams of funding and support, such as the Innovative UK and other government bodies, sprang up post-Brexit. However, despite the availability of these schemes, several barriers have hindered some businesses' full engagement with them.

Small and medium-sized enterprises (SMEs) are widely recognised as pivotal to regional competitiveness and productivity growth. In 2019, the West Midlands region had a population of around 6 million people and 480,000 businesses in the private sector (both registered and unregistered). The population of the companies in the West Midlands region grew to 892,595 in 2015, which amounts to 8.0% of all 11,092,692 companies in the UK. Micro-firms and SMEs are the backbone of the West Midlands' economy, together comprising 99.9% of the total enterprises in the West Midlands, creating 58% of employment and 44% of turnover over the last ten years (Yoruk and Gilman, 2021). In 2021, the British Business Bank estimated that UK SMEs accounted for 43-53% of UK business emissions. (Blundel, 2021). Therefore, SMEs account for a significant proportion of greenhouse gas emissions, and there is a need for urgent action by SMEs on the journey to achieve net zero. Despite this research and policy intensity and interventions in achieving these SDG goals, a critical research gap remains, which is that there is limited robust evidence on why some organisations are not embracing the scheme or partially engaging with the scheme. Hence, the aim of this research is to examine the barriers that hinder SMEs from adopting available sustainable intervention schemes and to explore ways to encourage them to engage fully, as a means to achieving the SDG 9, SDG 12, and SDG 13 goals.

The outlined ***objectives*** to satisfy this aim are to:

- Ascertain how the interventions have supported SMEs in becoming sustainable
- Examine the barriers deterring West Midlands SMEs from engaging or partially engaging with sustainability schemes
- Suggest insights that could encourage SMEs to engage fully with sustainability schemes.

Therefore, the research questions are, 'Despite the available schemes,

- What are the barriers deterring SMEs from engaging with the sustainable schemes?
- Why do some SMEs partially engage?
- What factors should be considered to encourage full engagement of these SMEs?

Literature and Research Problem

SMEs have a tremendous opportunity to help the UK meet its net-zero 2050 target, such as shifting to renewable energy sources, improving energy efficiency, and implementing circular economy principles (Olarewaju et al, 2023). Despite the opportunity for reducing emissions, take-up of mitigation measures by SMEs remains low. SMEs face specific barriers in relation to Net Zero targets. These include a lack of knowledge and understanding about climate change and how it relates to their own business activities (e.g., capacity to identify and quantify emissions). NatWest Group research has revealed that 87% of UK SMEs are unaware of their business's total carbon emissions (NatWest Group, 2022). A considerable body of work has been done to identify and evaluate barriers and drivers for the uptake of decarbonisation measures and the majority of which identifies main barriers, such as financial constraints as the principal barrier (Andrews and Johnson, 2016), lack of specialist knowledge and technical skills (Fresner et al., 2017), resource constraints and, short-term tenancies (Fawcett and Hampton, 2020). According to the (Khosravi, et al., 2023) research, which sought to provide insights into the barriers SMEs face when decarbonising business operations through an online survey and interview. Although the research confirms that financial constraints have been identified as the principal barrier to decarbonisation from SMEs' perspectives, more than half of SMEs confirmed that they lack the knowledge and skills, which was the main reason for not measuring their carbon emission and starting their journey towards decarbonisation.

Therefore, this research focuses on the SMEs that did not engage or are partially engaged with the available sustainability government schemes. The SMEs that engage fully are regarded as those that enrol with the scheme (i.e., give consent when approached) receive the innovation and sustainable suggestions provided, and lastly, implement the suggestions provided by the scheme. Prior to and after the 2021 announcement, a few of the Sustainability Support Schemes for SMEs in the West Midlands are the Agri-tech Growth and Resources for Innovation, Sustaining Shropshire, and Energy and Bioproducts Research Institute (Businessclimatehub,2024). This research will explore the barriers to engaging with available schemes that prevent some SMEs from decarbonising across the West Midlands, UK, including Birmingham, Coventry, the Marches region, and Shropshire, and provide recommendations on how to overcome these barriers. The answers to the above questions would be helpful for practitioners and policymakers to better understand the sustainability challenges faced by SMEs and, in turn, put in place adequate, precise, and tailored plans to support them further.

Methods

A qualitative research approach was employed to achieve the purpose of this research and to gain insight into the participants' experiences and the meanings associated with their perceptions as managers of the schemes regarding the reasons deterring full engagement of SMEs in the midland UK (Bougie and Sekaran 2019; Saunders et al. 2019). To this end, in-depth interviews were conducted with managers and supervisors of one or more of the schemes and their understanding of what influences SMEs' engagement in the sustainable schemes to embrace Agritech and achieve Net Zero target. The 15 in-depth interviews were conducted with interviewees via video Teams calls and face-to-face. The questions were divided into two main parts; the first is to explore how the scheme has supported SMEs within the West Midlands region, while the second part delves into why SMEs have not yet or fully engaged in being sustainable and their perspective on what could be done to encourage more commitment towards sustainability. An exploratory approach was used to gain a more comprehensive understanding of the managerial role; the scheme support process and the services delivered to SMEs by the scheme.

The study adopted telephone interviews rather than focus groups due to the possibility of some privacy concerns that might be involved in some discussions. The telephone interviews allowed participants to feel more at ease when answering questions than in a focus group. Before the commencement of interviews, all ethical considerations, the purpose of the study, and confidentiality of the interview were explained in detail to participants. The interviews were conducted in September 2025, and the average duration of each interview was thirty (30) minutes. The 15 interviewees are Business Engagement Managers and/or Knowledge Exchange Researchers for Sustainability Support Schemes for SMEs in the West Midlands to assess how their interventions have supported SMEs in becoming sustainable. The interviewees are Business Engagement Managers and Knowledge exchange researchers who have worked on at least two of the Sustainability Support Schemes for SMEs in the West Midlands within the last five years and have at least six years of experience in the role, working closely with between (200 -500) SMEs on each support Scheme project in the West Midlands.

In this study, the researchers used a non-probability sampling technique rather than random selection (Gentles et al. 2015). A purposive sampling method, otherwise known as purposeful sampling, was adopted to select participants who were

willing to provide significant responses to the research questions to achieve this study's specific objectives. The sample size for this study was seven (15). The advantage of purposeful sampling is that it makes it possible for researchers to glean a great deal of knowledge from the data. NVivo 12 software was employed in this study to conduct the thematic analysis. The use of thematic analysis allows the qualitative data to be organised into themes and subthemes. Prior to the commencement of the thematic analysis, the data collected were transcribed into text using a Microsoft Word document. Subsequently, the data were imported into the NVivo software in preparation for the analysis. The use of the NVivo software for the thematic analysis allowed for the ease of searching for patterns to identify themes (Ayandibu et al. 2019).

Results and Discussion

The interviews were conducted to elicit specific responses. The first few questions resonated around establishing whether the scheme provides sustainability support and exploring how it has supported SMEs within the West Midlands region. Then the interview proceeds to the core aspect of this work that helps to satisfy the research question. This second part examines why some of the SMEs are not fully engaged in sustainability, and respondents' perspective of what could be done to encourage more commitment to sustainability. From the core aspect of the interview, two main themes and nine (5) sub-themes emerged from the thematic analysis. The main themes that emerged from the thematic analysis included Partial engagement with the Scheme and no engagement with the scheme. The themes and sub-themes that emerged from the analysed qualitative data are illustrated in Figure 1.

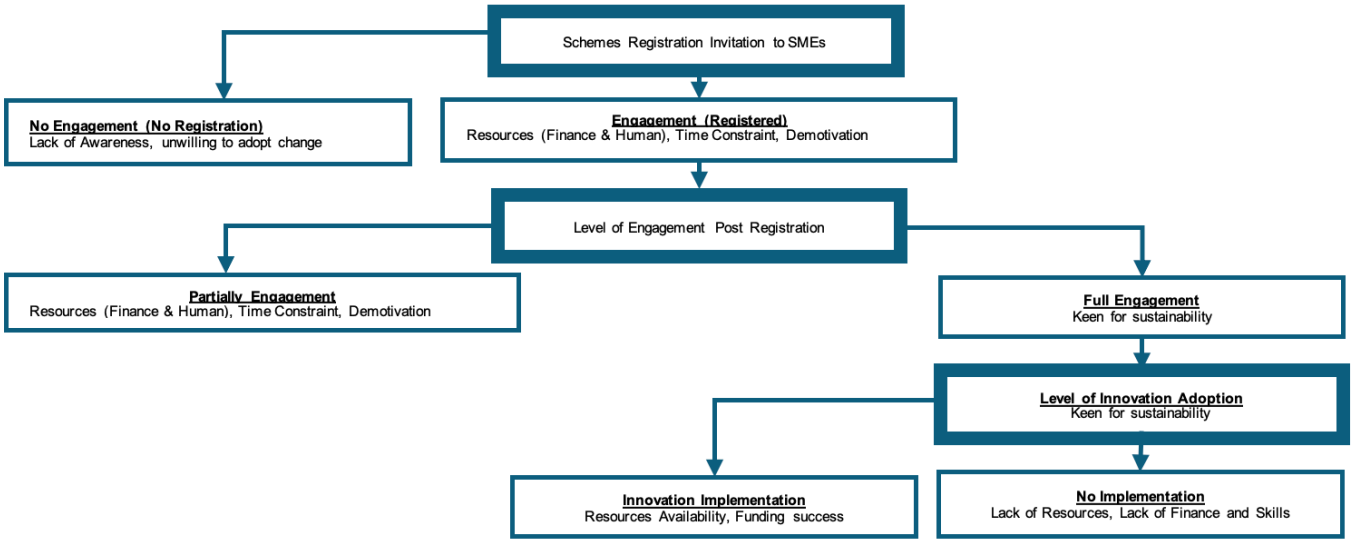

Figure I: Barriers to SME engagement in the West Midlands

Available Support for SMEs in the West Midlands For SMEs, the expectations and commitment to achieving NetZero span across identifying the near-term target, which could involve rapidly eliminating emissions through adopting carbon reduction opportunities; reducing scopes 1, 2, and 3; committing to halving emissions by 2030; and achieving near-zero GHG emissions by 2050 (Consequence, 2024).When asked, *'Do you scheme support SMEs on their sustainability journey?'* All the interviewees mentioned that they assist SMEs in decarbonisation, sustainability, or moving towards NetZero. The support ranged from carbon audits and carbon calculations to pointers on available funding and, most significantly, suggestions for appropriate innovations or technologies to support the efficiency and sustainability of the Supply Chain. Here are responses from some of the participants.

'Yes, we help with carbon calculations and circular economy innovations for different types of industries. (Participant 1)

Provide agri-food processes and technology to support SMEs in the West Midlands and the Marches region, especially the rural..support the food process, new products, lifecycle, and shelf labelling, but not the legal aspect (Participant 4)

'We support the organisation by suggesting the appropriate method to be sustainable to food and drink businesses, and also find ways to encourage collaboration among businesses to promote sustainability'… suggestions are not the same for each business …suggestions are tailored to suit each organisation's needs (Participant 5)

'Logistics is of major concern, especially with emissions we help these organisations with guidance on how to have sustainable logistics and transport options to SMEs.' (Participant 6)

We support by suggesting the best-suited technology to …enhance sustainability for the businesses from various industries that are struggling to make a choice it's sometimes difficult for them, especially with the increased software promotions' (Participant 9)

'My team and I have supported businesses across the West Midlands and outside the country ….. awareness creation about sustainability… different organisations are on different levels of adoptio needs are different too …we provide support to enhance the whole supply chain…' (Participant 15)

SME Level of Engagement Based on reports generated by some of the schemes over the years. It is evident that some SMEs fully engaged with and implemented the suggestions provided by the scheme. However, the percentage of case studies generated is far less than the number of SMEs in the regions. This suggests that there has been less engagement than expected from the SMEs. Hence, the questions were asked to explore the level of engagement: Did all SMEs that your scheme approaches engage with the available intervention supports? All participants mentioned that the responses from companies in the West Midlands on approaching them to join (register) the scheme were a mix of yes (Engagement) and no (No Engagement).

No, to Registration *For those that did not register for the scheme, why?*
Most want to start, but when they hear of the paperwork registration process to start off, they do not return (Participant 2)

…….it is basically because of time ((Participant 5)

Most say no … they are not ready for the change (Participant 6)

'I have called some SMEs up to tell them about the scheme, most of them replied that they are happy to hear about the opportunity, but it is not for them'.(Participant 8)

'When some organisations hear about it through our phone calls to them, some are in a hurry to drop the phone…although some listen as they engage with us'.(Participant 9)

They cannot be bothered to change the way they do things. My team worked mostly with food and drinks supply chain ….For example, the recipe techniques they used or the method have been passed down from one generation to the next. (Participant 7)

I think some just think change may need investing money ,…. Actually, some asked me about the financial aspect when I called them (Participant 2)

'….some complained about past experiences …..with concerns ….and not wanting to participate in another scheme (Participant 6).

From these responses, when some SMEs hear about the scheme for the first time, some are in a rush to move away from the conversation because of their busy schedules, while some seem to fear to embrace change, and for some, this could be because of lack of resources (funds and employees) thereby they try and avoid innovation or changes. Also, some organisations are not ready to change their structure, change the way they do things or create the time for such. Others say no most of the time because of a lack of awareness of the benefits of having a sustainable business. The responses suggest that most companies avoided engagement due to a lack of interest, mostly based on previous experience. Other limitations stem from a lack of resources, limited time, and fear of change.

Engagement by Registration - For those who agreed to register when approached with the idea of the Sustainability Scheme. Why do you think they agreed to join?

…the reasons could be personal sometimes…. for experience, I would say some of them have started a sustainability process and got stuck or are unsure of what they are doing (Participant 1)

Most of the organisations were just curious, especially when they hear words like sustainability, technology and innovation (Participant 2)

They haven't heard about the scheme and want to know about it (Participant 14)

… a good number of these organisations register because it is free (Participant 15)

Level of engagement after Registration - For those who completed the registration to start on the scheme, did they all complete the intervention process provided by your scheme?

…Major concern is about continuity and full engagement. Lot dropped out midway through (Participant 15).

For those that registered, did they complete the whole intervention that the schemes has to offer (registration till they get the report that the scheme provide)?

Partial engagement -The 15 participants said that some of the organisations that registered left midway through the sustainability intervention and process without getting the full support available through the schemes. Thereby revealing full and **partial engagement** with the scheme. For the purposes of this study, partial engagement refers to registering but not completing all the steps the scheme offers, while full engagement is registering and completing the entire process of the scheme, which starts with registration and ends with the scheme providing a detailed innovation recommendation report to the organisation. The exploration continued by further interviews to examine reasons why organisations register and engage partially or fully. Hence, why do you think they drop off midway?

Time - *'Time to commit is of major concern…. we offer Master classes with a great turnout, but not all who register come for it, especially on the second day' (Participant 12)*

'The speed of the academic nature is not fast-paced enough for SMEs. We focus on the fine details. SMEs have limited resources (people and money), so they struggle day to day. Their goal is to make money (long-term to see productive outcomes. The micro-small businesses really struggle. They know the interventions are good, but they cannot spare time to engage. (Participant 1)

'Some get interested initially but aren't aware of how things are done at the university because they aren't used to the university bureaucracy. So, they may not engage again because they are disappointed'.(Participant 2)

Their goal is to make money(long-term) to see a productivity outcome. There is a need to find that balance in the type of support that will be provided to them (Participant 5)

'Most want the support but cannot fully engage because of the number of workers, but larger ones stand a better chance of engagement '(Participant 7).

'Some SMEs are in rural areas with unstable internet, making it difficult to fully embrace the opportunities the scheme offers, and will not participate in available schemes'(Participant 9).

Lack of Basic technology skills - 'Some individuals lack the basic skills of using MS Word and phones efficiently and cannot effectively adopt these latest technologies'(Participant 10).The responses show that the delay and time lapse between consultation, paperwork, and intervention sometimes cause organisations to withdraw from the available scheme support. Based on these responses, schemes overseen by universities need to tell SMEs more about what to expect to prepare their minds and give them a heads-up on how things work with the scheme. The question resonates on why have some SMEs that registered with the scheme but dropped off midway, or got the recommendation and directives from the scheme but did not implement them in their businesses. The participants' responses above pointed out barriers such as demotivation, Time and Technology challenges, and scheme targets that promote Quantity over Quality. Trianni and Cagno (2012), also identified barriers such as resource constraints, lack of specialist knowledge and technical skills (Fresner et al., 2017), short-term tenancies (Fawcett and Hampton, 2020), and financial constraints as the principal barriers (Andrews and Johnson, 2016).

Full Engagement - *Why do organisations join and complete the process that the scheme has to offer? All participants mentioned that those organisations are much committed to sustainability and are keen to be a part of the NetZero goals.*

For those organisations that joined and completed the process the scheme has to offer. It has been observed that case studies produced by schemes have been few for those that adopted the strategy. This spurred the question, why did those who adopt it not implement it, or do you think they implemented it?

'The cost of implementing the suggested technologies is a major barrier to SME adoption. Some of the technologies proposed are not practical. In the short term, it isn't achievable for SMEs, and in the long term (by the time the organisation is ready, the tech might have changed)'. (Participant 1)

'Some finish the intervention process with us, but it's not certain that they implement the suggestions we give. For example, an organisation we worked with and trained on Enterprise Resource Planning software but upon follow-up they haven't gotten time to implement and some struggle with the money aspect'. (Participant 3)

'It's about not speaking SME language; ….it's communicating in the way they understand.in presenting the interventions or technology'. (Participant 7)

Time is critical to the SMEs operations because of the limited numbers of employees. For example, the Master Classes that the scheme runs for SMEs to help them achieve NetZero. Some SMEs unavailable for the two days'.(Participant 2)

Time-critical to the operational requisites on a day. (Participant 5)

They could not spare any of their day-to-day tasks. For master classes, most of them are unavailable for 2 days, as the classes run.(Participant 6)

Some communication with the SME is not in the SME's language, such that they struggle to understand the proposition and benefit.(Participant 8)

Follow-up: Some become interested but are unaware of the lengthy process (including paperwork and referrals from one end to the other) involved in the university bureaucracy. So, some SMEs may not engage fully or at another time when offered a similar opportunity because they are disappointed.(Participant 9)

It can be deduced from the participants quoted above that even when some SME gets the pointers, they need form the scheme they still face some challenges implementing some of the technologies due to time and financial constraints. Also, some of the technologies suggested are sometimes not applicable specifically to SMEs rather for larger companies, hence not meeting the immediate needs of the SMEs. The professional terminology also deters some SMEs from connecting well with the report and guidance provided through the SME as mentioned by Participant 7 -there is a need to speak SME language.

Financial and Time Constraints, and Technology Challenges - One of the top barriers identified by SMEs as preventing decarbonisation is a lack of funds (SME Climate Hub, 2023). Previous research from SME Finance Monitor report says, 41% of SMEs stated that it was difficult for them to access finance (BVA, 2021).

Conclusion

Based on the Suggestions based on experience gathered and informed from the various interviews. Here are a few suggestions. Quality should be prioritised over quantity. For example, participant 6 mentioned 'Our funding scheme speculated 100 outputs over two years, and we have to give each SME only 12 hours of support—the support is short'. The number of SMES supported versus the hours speculated to provide the support should be revisited to ensure that adequate support is provided and to encourage integration throughout the duration of the scheme. 'There is a likelihood of having more impact if the focus is more on the impact made on the SMEs. Don't focus on the number; then we can have more impact. It should depend on what each business needs and be tailored accordingly. Although some of the Schemes produce case studies from the support provided over a period of time. This percentage of the case study produced is mostly less than of the SMEs support that has been provided.This will highlight successes and reveal gaps that could help to better inform the succeeding scheme/intervention.The businesses in the rural highlight the need for infrastructure and skills upgrade sessions.

Areas for Further Research - Compared with large companies, SMEs rarely have a research and development department. It is expedient to further study how SME research and development could be improved. Based also on the findings of this work, some areas have been identified for further studies that have the potential of strengthening understanding of how SMEs in the rural and agribusinesses can be more effectively supported through sustainability and Agri-tech interventions. (Johnson et al., 2022) pointed out that tailored high intensity support could foster technology adoption and encourage organisational change rather than short, generic engagement. Hence, Future research should examine the trade-off between the depth of support and the number of SMEs reached by sustainability and agri-tech interventions. There are limited case studies in post-schemes targeting evaluation practice with the SME intervention programmes. There is a need for Post-Intervention Evaluation and Learning Mechanisms or monitoring to enhance policy and practice (European Commission, 2023).

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THE ROLE OF SUPPLY CHAIN TRANSPARENCY, FIRMS' ESG COMMITMENT AND CIRCULAR ECONOMY PRACTICES IN DESIGNING AN INNOVATIVE SUPPLY CHAIN RESILIENCE MODEL

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Abstract

Purpose

Ever-increasing disruptions caused by geopolitics and climate change compel supply chains (SCs) to prioritise resiliency. While pursuing resilience, SCs need to demonstrate environmental, social, and governance (ESG) commitments and circular economy (CE) practices to minimise their impact on climate change, e.g., by reducing emissions and waste. Hence, firms need to develop sustainable capabilities, such as CE practices and technological resources, as key to SCs' green capabilities; however, reshaping SCs toward greater sustainability and circularity also requires firms' commitment to environmental, social, and governance (ESG) principles. To address this issue, this study explores the role of transparency (SCT) and ESG commitment on sustainable SC practices to achieve SC resilience (SCRES).

Research Approach

The authors conceptualise a theoretical research model consisting of 6 hypotheses. The model was validated using partial least squares structural equation modelling (PLS-SEM) with survey data from 261 industrial enterprises. The survey was collected from Türkiye's top 1,000 industrial enterprises.

Findings and Originality

The results show that ESG commitment and CE practices positively contribute to SCRES. Our results also demonstrate the positive impact of SCT on both ESG commitment and CE practices. The study contributes to the operations and sustainable supply chain (SC) management literature by increasing our understanding of the impact of SCT and organisational ESG commitment on sustainable SC practices, and of how these capabilities enhance SCRES. The study can assist policymakers in establishing ESG guidelines and developing tax incentives for firms that integrate technology and sustainable practices, thereby fostering innovation in business models to promote sustainability and resilience.

Research Impact

This study was primarily motivated by achieving supply chain resilience in the turbulent business environment. This research will help expand understanding of the capabilities and resources required to achieve supply chain resilience. The combination of these capabilities and resources will help organisations develop innovative business models to allocate resources effectively and build robust, resilient supply chains.

Keywords: Supply Chain Transparency, Supply Chain, Resilience, Circular Economy, Sustainability, environmental and social, and governance (ESG)

1. Introduction

In the contemporary global business environment, SCs operate amid challenges related to geopolitics, natural disasters and resulting disruptions, resource shortages, and increased stakeholder demands. As the world has become more interconnected and complex, SCs now face not only physical disruptions to the supply of goods and services from suppliers, but also disruptions to supplier relationships and governance processes (Padovano and Ivanov,2025). As a result, the concept of SCRES now extends beyond the recovery of supply chain operations after a disruption. Instead, it is increasingly seen as a strategic capability within organisations that enables them to anticipate, absorb, respond, and adapt to disruption (Han et al., 2020; Ivanov & Dolgui, 2020). At the same time, resilience must be viewed alongside sustainability. In this regard, the concern is not only to supply products and services in a timely manner, but also to ensure that corporations demonstrate responsible ESG performance and achieve resource efficiency in their business processes. Hence, one of the main problems in the industrial sector is that, in practice, resilience management, ESG commitments, and the adoption of CE practices are often treated as separate management objectives (Ali et al., 2026). Circular supply chain management has highlighted that supply chain sustainability requires integrating sourcing, production, distribution, recovery, and recycling practices (Farooque et al., 2019). The practical question, therefore, is whether SCT, ESG commitment and CE practices can jointly promote SCRES.

Prior resilience research identifies capabilities such as readiness, response, recovery, flexibility, redundancy, collaboration and adaptive capacity (Han et al., 2020). ESG research also shows that environmental, social, and governance activities are connected to firm-level risk, performance, and value (Gillan et al., 2021). However, the link between sustainability and resilience remains fragmented. Limited empirical attention has been paid to how SCT enables ESG commitment and CE practices, and how these sustainability-oriented capabilities contribute to SCRES within a single model (Ali et al., 2026; Kim et al., 2026).

The aim of this study is to investigate the role of SCT, firms' ESG commitment, and CE practices in the design of an innovative supply chain resilience model.

2. Literature Review

2.1 Theoretical Background

The proposed model is grounded in the Dynamic Capability View (DCV) and the Information Processing View (IPV). This combination is appropriate because the study treats supply chain resilience as a capability-deployment outcome and an information-dependent process. DCV explains how firms reconfigure sustainability-oriented practices under disruption (Yang et al., 2026), while IPV explains why transparency is needed to process uncertainty across supply chain relationships (Balci and Ali, 2024).

2.2 Hypothesis Development

2.1.1 SCT and ESG commitment

SCT enables firms to observe, evaluate, and report on how other organisations in their supply chain are performing (Sodhi & Tang, 2019). The ability to observe SC actors is critical to ESG commitment, as ESG risks can stem from outside the focal firm. Without access to reliable information to monitor SC conduct, firms struggle to assess environmental and social performance, ethical trading practices, and governance risks across their supplier base. Transparency differs from internal visibility in that it entails credible disclosure to stakeholders of supply chain operations and compliance with expected norms (Sodhi & Tang, 2019). ESG commitment, therefore, depends not only on managerial intention, but also on the information needed to monitor, verify and govern supply chain conduct. Transparent SCs allow firms to identify environmental and social risks earlier, align procurement with sustainability standards and support more credible reporting. From an Information Processing View, transparency reduces ambiguity and improves decisions under sustainability pressure. As ESG measures increasingly need to incorporate end-to-end SC operations, transparency provides the basis for accountable ESG governance (Dai & Tang, 2021). Therefore:

H1: SCT positively impacts firms' ESG commitment.

2.1.2 SCT and CE practices

CE practices require information about materials, components, suppliers, production processes, waste streams, product returns and recovery options. Firms cannot effectively reuse, recycle, repair, remanufacture or redesign products without knowing where resources are located, how they move through the SC and where value is lost. Circular supply chain management depends on the coordination of forward and reverse flows, including sourcing, production, distribution, consumption, return and recovery activities (Farooque et al., 2019). Transparency also reduces information asymmetry between buyers, suppliers and recovery partners, which matters when circular practices depend on inter-organisational collaboration (Qiao et al., 2026). CE research argues that firms must move away from linear resource use towards systems that retain material value for longer (Amir et al., 2023). Transparent SCs are therefore more likely to support CE practices because they provide the informational basis for resource tracking, recovery planning and circular process redesign. Therefore:

H2: SCT positively impacts CE practices.

2.1.3 ESG commitment and CE Practices

ESG commitment reflects a firm's strategic dedication to integrating sustainability, ethical governance, and stakeholder accountability into decision-making processes. Recent studies suggest that ESG commitment enhances risk management, supplier governance, and long-term value creation, making organisations more adaptable to disruptions and sustainability pressures (Xu et al., 2025). CE practices complement ESG objectives by promoting resource efficiency through recycling, reuse, remanufacturing, repair, and closed-loop supply chains (Ali et al., 2026). CE initiatives reduce dependence on virgin resources, minimise waste, and create alternative material flows, thereby improving operational flexibility and resilience (Bhawna et al., 2024). Together, ESG commitment and CE practices represent dynamic capabilities that strengthen sustainable and resilient supply chain performance. Therefore:

H3: ESG commitment positively impacts CE practices.

2.1.4 ESG commitment and SCRES

ESG commitment can enhance SCRES by embedding responsible governance, stakeholder accountability and long-term risk management into supply chain decision-making (Ali et al., 2026). Firms with stronger ESG commitments are more likely to evaluate suppliers not only on cost and delivery performance but also on environmental responsibility, labour standards, and governance reliability. These criteria can reduce exposure to disruption arising from regulatory breaches, supplier misconduct, reputational damage, environmental incidents and weak compliance controls. Empirical results further indicate that supply chain ESG management can enhance SCRES by affecting information network capabilities. From a Dynamic Capability View, ESG commitment enables firms to sense sustainability-related threats, identify opportunities for more responsible improvements, and reconfigure supplier relationships amid environmental uncertainty. Hence, this approach helps enhance SCRES by making SCs more responsible, adaptive and trusted when coping with operational disruption. Hence:

H4: Firms' ESG commitment positively impacts SCRES.

2.1.5 CE practices and SCRES

CE practices can strengthen SCRES by reducing dependence on linear resource flows and creating alternative pathways for material availability (Amir et al., 2023). Traditional SCs often rely on continuous access to virgin materials, stable suppliers, and uninterrupted logistics flows. When disruptions affect these inputs, firms may experience shortages, cost volatility, and production delays. Circular practices such as reuse, recycling, repair, remanufacturing, product redesign and reverse logistics can reduce this vulnerability by extending resource life and recovering value from existing materials (Ali et al., 2026). Circular supply chain management, therefore, links sustainability with continuity by embedding recovery and reuse into the operating model (Farooque et al., 2019). Recent empirical work shows that CE practices can help firms cope with supply risks and improve resilience-related capabilities (Pellegrino et al., 2026). From a Dynamic Capability View, CE practices

represent operational reconfiguration because they reshape sourcing, production and recovery processes in response to environmental and resource uncertainty. Therefore:

H5: CE practices positively impact SCRES.

2.1.6 Mediation effect

CE practices can act as an important mechanism through which ESG commitment translates into greater supply chain resilience (Ali et al., 2026). Firms with strong ESG commitments are more likely to adopt circular initiatives such as recycling, remanufacturing, reuse, reverse logistics, and closed-loop supply chains, as these practices align with environmental stewardship and responsible resource management. By reducing dependence on virgin materials and creating alternative resource flows, CE practices enhance operational flexibility and mitigate supply risks (Pellegrino et al., 2026). From a Dynamic Capability perspective, CE practices enable firms to reconfigure resources and processes in response to disruptions (Yang et al., 2026). Therefore, ESG commitment enhances resilience indirectly by fostering circular economy practices that strengthen adaptability, resource security, and continuity in supply chain operations

H6a: CE Practices mediate between ESG Commitment and SCRES

4.7 Conceptual model summary

Figure 1 presents the proposed conceptual model. SCT is positioned as an antecedent of ESG commitment and CE practices. ESG commitment and CE practices are then modelled as direct antecedents of SCRES. This structure reflects the argument that transparency enables sustainability-oriented capabilities, which in turn strengthen resilience to disruption.

5. Methodology

5.1 Research design

This study uses a quantitative, explanatory and cross-sectional survey design. It is intended to test the theoretical hypotheses developed regarding the relationship among four latent variables: supply chain transparency, ESG commitment, CE practices, and SCRES. Because the model addresses firm-level practices and managerial perceptions, this study uses a survey, as these issues are not readily captured by secondary variables.

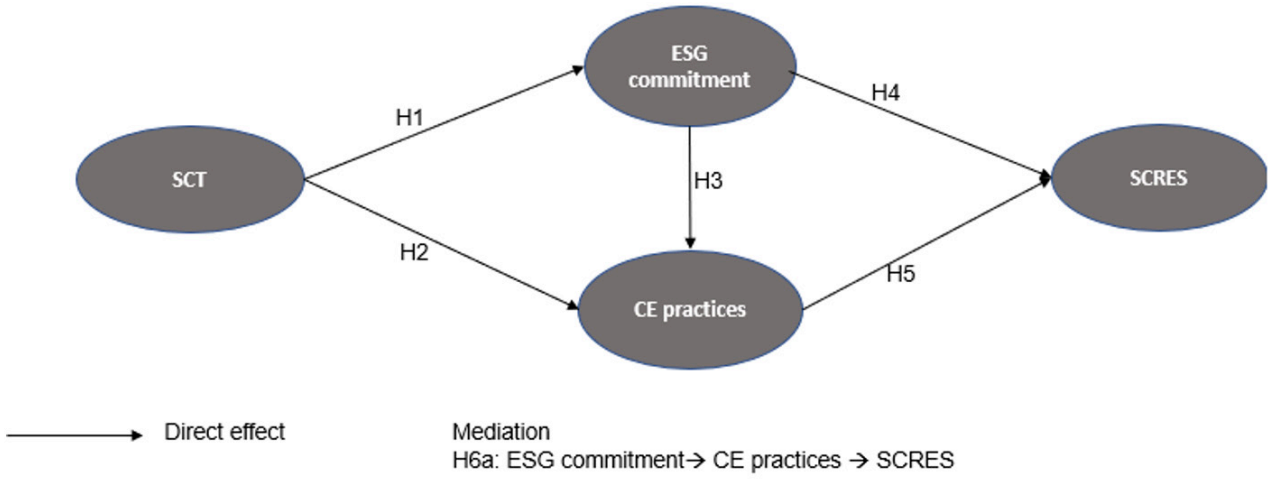

Figure 1: Conceptual Model

The empirical context is Türkiye's top 1,000 industrial enterprises. This population is appropriate because large industrial firms operate complex supplier networks, face material and logistics risks, and are exposed to ESG, circular economy and resilience pressures. Data were collected through a structured survey, and 261 usable responses were retained for analysis.

The data were analysed using partial least squares structural equation modelling (PLS-SEM). PLS-SEM is appropriate because the study is prediction-oriented and examines relationships among multiple latent constructs.

6. Findings

6.1 Measurement model results

The measurement model was assessed before testing the structural relationships. Indicator reliability was assessed using the outer loadings of the retained items. Standardised factor loadings for CE practices, SCRES, ESG Commitment, and SCT ranged from 0.777 to 0.916. The Cronbach's alpha, composite reliability, and Average Variance Extracted (AVE) of each construct satisfied the reliability requirement and were found to be above the threshold value of 0.7 and 0.5 for AVE, with statistically significant ($p < 0.001$) (Hair et al., 2019) . Discriminant validity was assessed using the Heterotrait-monotrait (HTMT) index and the Fornell-Larcker criterion. All values were below the threshold of 0.90, hence supporting the discriminant validity of the constructs (Henseler et al., 2015).

6.2 Structural model results

After assessing the measurement model, the structural model was examined to test the five hypotheses. H1 proposed that SCT positively impacts firms' ESG commitment (H1: $= 0.577$, $p = 0.003$), thereby supporting hypothesis H1. Similarly, H2 proposed that SCT positively impacts firms' CE practices (H2: $= 0.284$, $p = 0.000$), thereby supporting hypothesis H2. ESG commitment is significantly and positively associated with CE practices (H3: $= 0.414$, $p = 0.000$), thereby supporting H3. Moreover, ESG commitment is positively associated with SCRES (H4: $= 0.422$, $p = 0.000$), thereby supporting hypothesis H4. Finally, CE Practices positively influence the SCRES (H5: $= 0.367$, $p = 0.000$), thereby supporting hypothesis H5.

The explanatory power of the model, i.e. R^2 values for ESG commitment 0.333, CE practices 0.388, and SCRES 0.491.

The mediating role of CE practices was analysed to assess the relationship between ESG commitment and SCRES. The results revealed a significant indirect effect of ESG commitment on SCRES through CE Practices (H6a: $= 0.152$, $p < 0.001$). The total effects of ESG commitment on SCRES were significant ($= 0.574$, $p < 0.001$), and with the inclusion of the mediator, the effect of ESG commitment on SCRES was still significant ($= 0.422$, $p < 0.001$). This shows a complementary partial mediating role of CE Practices in the relationship between ESG commitment and SCRES. Hence, supporting H6a (ESG Commitment -> CE Practices -> SCRES).

7. Discussion

The outcomes provide theoretical evidence supporting the contention that SCRES is built through both information processing and capability development. From an Information Processing perspective, SCT reduces ambiguity by clarifying how suppliers behave, how materials flow, and how early indicators of disruption emerge. Thus, this helps explain why SCT is associated with ESG commitment and CE practices. From the Dynamic Capability perspective, ESG commitment and circular economy practices are sustainability capabilities that reconfigure governance, procurement, production and recovery processes (Farooque et al., 2019; Sodhi & Tang, 2019). This suggests that they are more adaptable than conventional supply chain functions. In sum, the results link the supply chain's informational basis to the organisational capacities for change.

For policymakers, this study suggests that industrial supply chain resilience can be improved through sustainability-related policy instruments, such as ESG disclosure regulations, circular economy tax incentives, industrial sustainability standards, and digital transparency platforms. These measures help ensure higher information quality, supplier responsibility, and resource efficiency. They are important where supply chain operations and environmental obligations or regulatory compliance need to be considered concurrently.

8. Conclusion

This study investigated how supply chain transparency, firms' ESG commitment and CE practices contribute to the design of an innovative SCRES model. Using survey data from 261 industrial enterprises in Türkiye and PLS-SEM, the study tested four relationships linking transparency, sustainability-oriented capabilities and resilience. The findings indicate that SCT supports both ESG commitment and CE practices, and that, in turn, these practices positively contribute to supply chain resilience. This suggests that resilience is strengthened when firms combine visibility, responsible governance and circular resource management in industrial settings exposed to disruption, compliance pressure and resource uncertainty.

Practically, the model provides guidance for firms seeking to design transparent, sustainable and resilient supply chains. Managers should strengthen supplier visibility, traceability, ESG governance, sustainability reporting and circular resource flows. These practices can support earlier risk detection, reduce dependence on vulnerable resource inputs and improve recovery capacity during disruption.

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INTEGRATING CIRCULAR ECONOMY PRINCIPLES INTO HIGHER EDUCATION STRATEGIES: A COMPARATIVE STUDY OF UCL AND ARU

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Introduction

The circular economy (CE) has emerged as a widely adopted and prominent sustainability framework across sectors in response to the challenges posed by resource depletion, escalating waste, and carbon-intensive production systems (Kirchherr et al., 2017; Geissdoerfer et al., 2017; Ghisellini, Cialani and Ulgiati, 2016). Recent relationship shows that universities are increasingly recognised as influential institutional actors as centres of innovation, consumers of resources and generators of waste. This has prompted calls to embed CE principles not merely in campus operations, but within governance structures, procurement policies, carbon management strategies, and long-term sustainability frameworks (Mendoza et al., 2019; Vergani, 2024). Yet comparative evidence on how CE is articulated and governed at the strategy level across institutions with different sustainability maturity profiles remains limited (Serrano-Bedia and Perez-Perez, 2022). This research addresses that gap through a comparative analysis of ARU and UCL- ranked first in the UK and fifth globally in the QS Sustainability Rankings 2026 (QS Top Universities, 2025). In the People & Planet University League 2025/26, both institutions received a 2:1 classification, although UCL ranked 26th and ARU 41st overall within the league table (People and Planet, 2025). The contrasting sustainability performance and institutional maturity of these institutions provides a useful basis for comparative analysis (People and Planet, 2025). The study responds to three research questions: How are CE principles articulated within the sustainability strategies of UCL and ARU? What governance structures support or constrain CE implementation? What transferable practices can inform ARU's Sustainability Strategy 2026-2030?

Literature Review

Sustainability in Higher Education Institutions

Sustainability has been defined as meeting present needs without compromising the ability of future generations to meet their own needs (United Nations, 1987). More recent interpretations have further expanded this concept to include a balanced integration of Environmental protection, social well-being and economic prosperity (Elkington, 1997). Higher Education Institutions have increasingly been positioned as decisive actors for sustainable development, capable of integrating sustainability across teaching, research, campus operations, and knowledge transfer (Lozano et al, 2015; Bauer et al., 2021; Leal Filho et al., 2016). Despite widespread formal commitments, implementation remains uneven. Lozano et al. (2015) states that sustainability efforts have generally been compartmentalised and not holistically integrated. The existing sustainability governance frameworks remain caught between narrow management-oriented approaches and abstract models offering little practical guidance (Niedlich et al., 2020). Fuchs et al. (2022) argue that HEI governance has tended to promote mainly formal aspects of sustainability rather than acting as a genuine agent of change, while Bauer et al. (2021) note that whole-institution approaches remain far from common. La Bara et al. (2020) illustrate how two European universities aligned with the same UN Agenda 2030 commitments adopt sharply divergent sustainability reporting structures, reflecting a sector-wide absence of unified frameworks. The literature remains predominantly case-study based, with a notable absence of whole-institution approaches (Findler et al., 2019). Veiga Avila et al. (2019 identify lack of resources and resistance to change as the most prevalent barriers to sustainable development engagement. Sustainability in UK HEIs is implemented primarily through four categories: the learning environment, research aligned to the SDGs, external collaboration, and curriculum integration (Zhou, 2025). Similarly, transformative education, interdisciplinary research, community engagement, and leadership vision have been identified as the defining characteristics of a sustainable university (Ferrer-Balas et al., 2008).

External benchmarking systems shape institutional priorities significantly. Scholars have critiqued rankings for oversimplifying complex institutional practices and privileging resource-rich institutions, yet they function as powerful reference points shaping institutional strategy (Niedlich et al., 2020; Hazelkorn, 2018).

Circular Economy: Foundations, Application, and Research Gap

Circular Economy (CE) is conceptualised as an economic system built on business models that replace the end-of-life concept with reducing, reusing, recycling, and recovering materials (Kirchherr et al., 2017). The Ellen MacArthur Foundation (2013) defines CE as an industrial system that is restorative and regenerative by design which an explicit contrast to the linear model of "take, make, and dispose". Geissdoerfer et al. (2017) structure CE around three resource strategies: narrowing loops through resource efficiency; slowing loops through repair, reuse, and lifetime extension; and closing loops through recycling and material recovery. Within higher education, HEIs are strategic actors in supporting sustainable development, and curriculum design within the HEIs as a primary mechanism for embedding CE (Mendoza et al., 2019; Renfors, 2024). Community-facing initiatives frequently remain informal and disconnected from strategic governance (Hobson and O'Byrne, 2024). Procurement governance remains inconsistently developed across the sector (Serrano-Bedia and Perez-Perez, 2022), while universities generally lack standardised CE metrics (Valls-Val et al., 2024). Nunes et al. (2018) highlight that universities contribute to CE through a hidden curriculum, and Dagiliute et al. (2018) demonstrate that students represent one of the most significant stakeholder groups in this sustainability governance.

Governance is identified as the central determinant of whether sustainability and CE initiatives produce systemic or merely symbolic outcomes. Without principled governance frameworks integrating CE into procurement, waste systems, and supply chains, circularity remains aspirational rather than operational (Velenturf and Purnell, 2021; Niedlich et al., 2020). Ceulemans et al. (2015) highlight substantial inconsistencies in sustainability reporting formats across HEIs, and existing comparative studies examining CE integration at the strategy level remain rare (Findler et al., 2019; Lozano et al., 2015). Consequently, comparative studies examining CE integration within institutional sustainability strategies and governance structures remain limited.

Methodology

Research Approach and Design

This study adopts a qualitative, comparative case study design. A qualitative approach is appropriate given the aim to interpret how sustainability and CE are articulated, prioritised, and framed within institutional documents. The focus of the research is on- exploring meaning, emphasis, and institutional intent with written material rather than measuring frequency alone (Creswell and Creswell, 2023; Merriam and Tisdell, 2016). Case study research enables in-depth examination of complex organisational phenomena within their real-world context (Yin, 2018). Document-based analysis is appropriate where the objective is to examine how organisation articulate sustainability and circular economy commitments through governance structures, and strategic narratives rather than stakeholder perceptions (Bowen, 2009).

Case Selection and Data Sources

UCL and ARU were selected because of comparability within a shared regulatory environment. Both operate under UK higher education frameworks, national net-zero commitments, and the same external benchmarking systems, while differing significantly in sustainability performance. Both institutions are represented within international sustainability benchmarking frameworks, including the QS Sustainability Rankings 2026, and the People & planet University League 2025/26 but exhibit differing levels of sustainability performance (QS Top Universities, 2025; People and Planet, 2025). This contrast provides a useful basis for comparative analysis within a shared UK higher education).

UCL's primary sources include the Sustainability Plan 2025-2035 (University College London, 2025), the Sustainability Annual Report 2023-2024 (University College London, 2024), the Wild Bloomsbury Manifesto (University College London, n.d.), and selected carbon management documents. ARU's document set includes the Sustainability Strategy 2020-2026 (Anglia Ruskin University, 2020), Sustainability Policy (Anglia Ruskin University, 2024), Responsible Procurement Policy (Anglia Ruskin University, 2022a), Sustainable Food Policy 2022-2026 (Anglia Ruskin University, 2022b), Green Society Fund Handbook (Anglia Ruskin University, 2022c), Sustainability Communications and Engagement Framework (Anglia Ruskin University, 2022d), and relevant social media content. Together these provide a multi-source basis for comparative analysis across strategy, operations, governance, and communications.

Data Analysis, Limitations, and NVivo Codebook

Qualitative thematic analysis was conducted using a hybrid deductive-inductive coding process, drawing on established CE and sustainability frameworks identified through the literature review, while remaining open to emergent codes from the data (Fereday and Muir-Cochrane, 2006). All documents were imported into NVivo qualitative data analysis software, supporting systematic coding, visualisation, and cross-case comparison while thematic interpretation remained researchers-led. Six parent codes structured the analysis, subdivided into child codes derived from the literature and data, as presented in left side of Figure 1 below, while the right panel presents the project map visualising the hierarchical relationships between codes. The study acknowledges limitations which are: coding reference counts were generated from a merged NVivo project across two separate researcher files and should be interpreted as indicative of thematic emphasis rather than precise frequency measures; and while inter-rater reliability was assessed through independent coding by a second researcher, automated Kappa calculation could not be validated due to the separate file structure, with reliability instead strengthened through iterative discussion and reconciliation of coding decisions against the codebook (Fereday and Muir-Cochrane, 2006; Landis and Koch, 1977). Reliance on publicly available documents and restriction to two case institutions, which limits statistical generalisability while enabling analytical generalisation (Yin, 2018).

Results and Discussion

The NVivo analysis generated coding reference counts for all child codes across six parent codes for both institutions, as illustrated by the matrix coding queries (Figure 2, and Figure 3).

Parent Code	Child Code	Literature Sources
Circular Economy	Circular Procurement	*Ellen MacArthur Foundation (2013); Valls-Val et al. (2024); Kirchherr et al. (2017)*
	Lifecycle Extension	*Ellen MacArthur Foundation (2013); Geissdoerfer et al. (2017); Bocken et al. (2016)*
	Recycling and Material Recovery	*Ellen MacArthur Foundation (2013); Geissdoerfer et al. (2017); Mendoza et al. (2019); Ghisellini, Cialani & Ulgiati (2016)*
	Resource Efficiency	*Kirchherr et al. (2017); Renfors (2024); Allwood et al. (2011)*
Campus Operations and Environmental Performance	Carbon Emissions and Net Zero Strategy	*Oliveira & Proenca (2025); Ferrer-Balas et al. (2008)*
	Waste Management and Resource Circularity	*Oliveira & Proenca (2025); Renfors (2024)*
	Green Infrastructure and Biodiversity	*Oliveira & Proenca (2025)*
	Environmental Governance System	
Governance and Accountability	Governance Structure and Leadership	*Fuchs et al. (2022); Niedlich et al. (2020); Bauer et al. (2021)*
	Institutional Sustainability Strategy	*Ferrer-Balas et al. (2008); Zhou (2025)*
	Reporting and Transparency	*La Bara et al. (2020); Valls-Val et al. (2024); Velenturf & Purnell (2021)*
	Environmental Governance	
Measurement, Benchmarking and Rankings	KPI and Performance Measurements	*Valls-Val et al. (2024); Ceulemans et al. (2015)*
	Awards and Recognitions	*Hazelkorn (2018)*
	Gaps and Limitations	*Findler et al. (2019); Lozano et al. (2015)*
Research and Community Engagement	Academic Curriculum and CE Education	*Renfors (2024); Ferrer-Balas et al. (2008); Mendoza et al. (2019)*
	Research and Knowledge Output	*Ferrer-Balas et al. (2008); Zhou (2025)*
	Student and Staff Engagements	*(Hobson and O'Byrne, 2024); Veiga Avila et al. (2019); Dagiliute et al. (2018)*
	Community and External Stakeholder Collaboration	*Ferrer-Balas et al. (2008); Zhou (2025)*
Strategic Integration of Sustainability	Alignment with SDGs	*United Nations (1987); Ceulemans et al. (2015); Zhou (2025)*
	Long Term Targets and Timelines	*Veiga Avila et al. (2019); Lozano et al. (2015)*
	Vision and Intent	*United Nations (1987); Leal Filho et al. (2016); Bauer et al. (2021)*
	Inter-University Networks and Policy Advocacy	*Ferrer-Balas et al. (2008); Zhou (2025)*

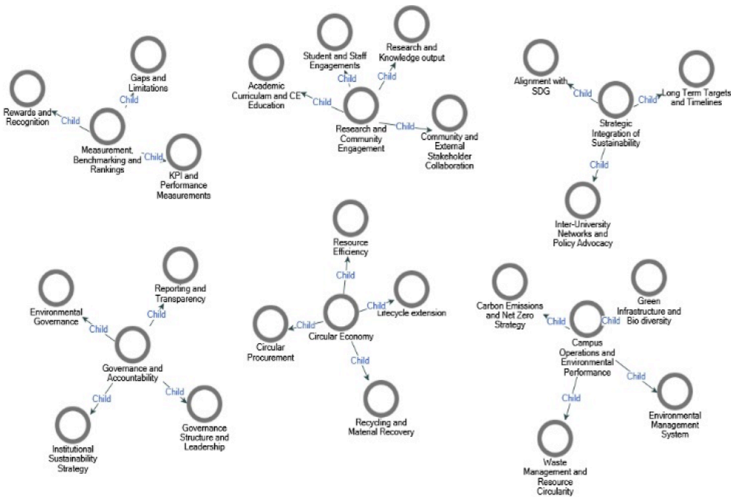

Figure 1: NVivo Codebook- Parent Codes, Child Codes, and Literature Sources (left); NVivo Project Map- Parent and Child Code Structure (right)

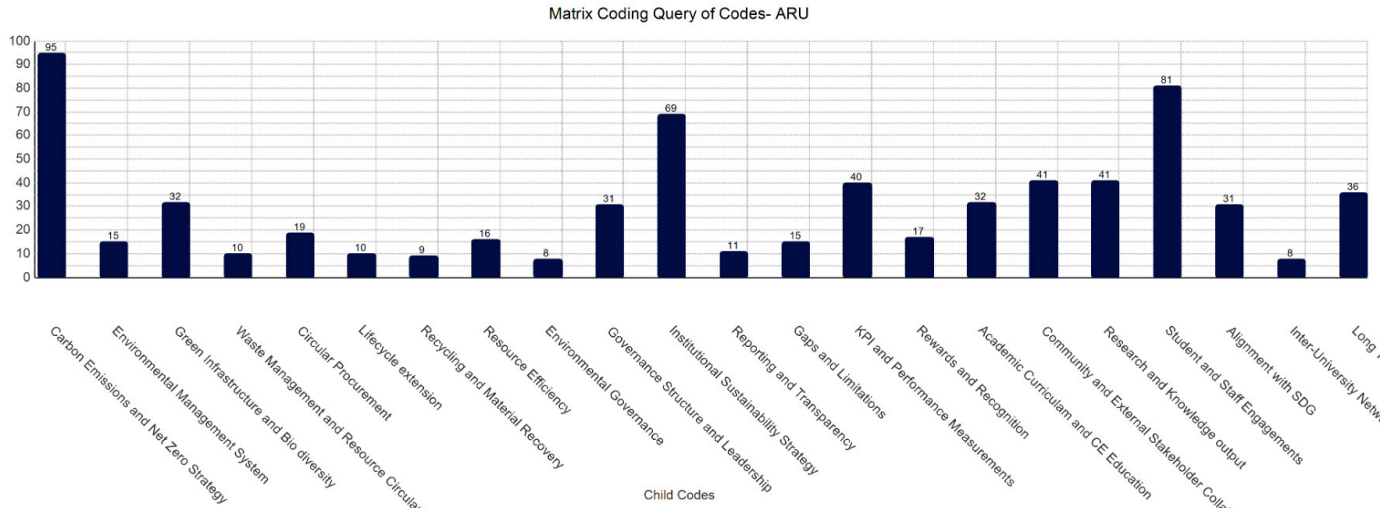

Figure 2: Matrix Coding Query- ARU

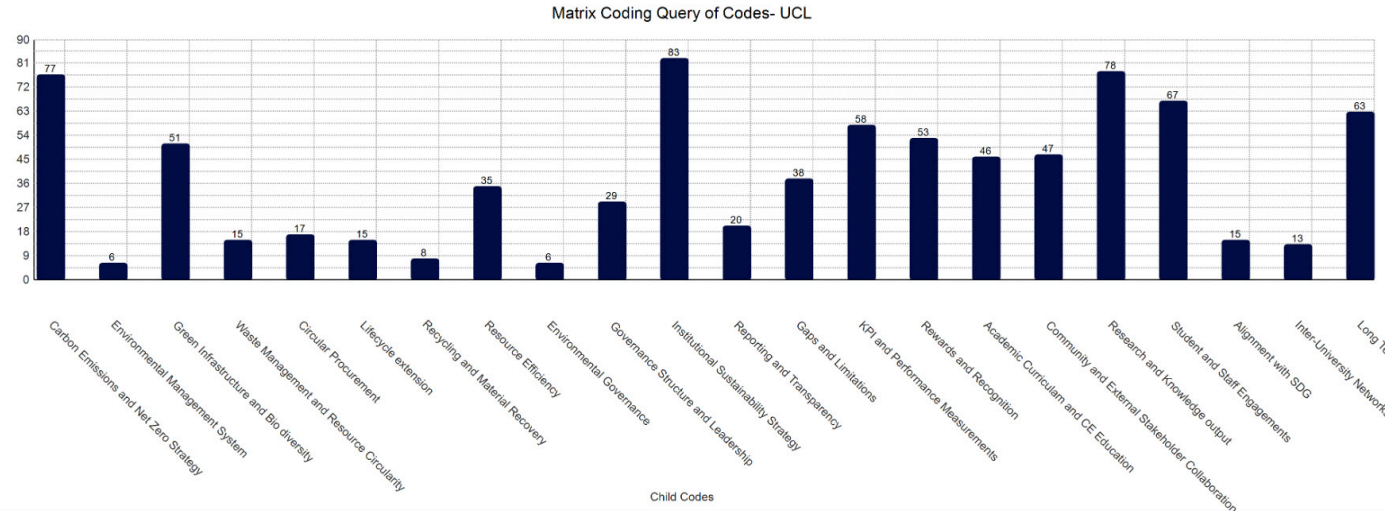

Figure 3: Matrix Coding Query-UCL

Table 2 summarises the aggregated reference counts per parent code, and comparative interpretation of the themes.

Parent Code	ARU	UCL	Comparative Interpretation
Research and Community Engagement	199	238	ARU prioritises student and community engagement more strongly, consistent with Dagiliute et al. (2018). UCL integrates engagement as one component of a broader framework encompassing research output and external collaboration, consistent with Ferrer-Balas et al.'s (2008) characterisation of a sustainable university.
Campus Operations and Environmental Performance	159	149	ARU's count is marginally higher, but domain coverage is narrower, concentrated in carbon and environmental management through the Climate Positive Plan and REFIT programme. UCL's multi-domain operational coverage is distributed across carbon emissions, green infrastructure, environmental management, and waste management which aligns with Oliveira and Proenca's (2025) finding that leading institutions embed environmental performance across systems simultaneously rather than concentrating on a single theme.
Governance and Accountability	121	138	The coding pattern suggests UCL places greater emphasis on stronger governance transparency, with strong Reporting and Transparency coding reflecting structured annual reporting, sustainability bond disclosures, and formal accountability mechanisms. ARU's governance structures are present but Reporting and Transparency is significantly underdeveloped, indicating commitments are not systematically communicated externally. This supports Niedlich et al. (2020) and Bauer et al.'s (2021) finding that whole-institution accountability remains uncommon.
Measurement, Benchmarking and Rankings	73	149	The largest divergence across all parent codes. UCL records more than double ARU's count. UCL's strong KPI Measurements and Gaps and Limitations coding reflects a mature accountability culture that explicitly documents targets and performance shortfalls. ARU's limited reflexive performance assessment constrains its external accountability positioning, confirming the absence of CE-specific metrics as the central barrier identified by Valls-Val et al. (2024) and Hazelkorn (2018).
Circular Economy	56	75	Both institutions embed CE principles but neither applies CE as a centralised institutional framework (Kirchherr et al., 2017). UCL demonstrates stronger cross-document distribution across procurement, resource efficiency, and material recovery within the Sustainability Plan 2025-2035 and The Loop programme. ARU's CE coding is concentrated in operational references across policy documents but not consolidated into an overarching CE strategy, reflecting Vergani's (2024) observation that HEIs' CE potential remains underrealised without coordinated governance.
Strategic Integration of Sustainability	78	91	UCL converts vision into measurable, time-bound commitments more explicitly, with strong Long-Term Targets and Timelines coding confirming SDG-aligned commitments embedded across the Sustainability Plan 2025-2035. ARU's Vision and Intent is present but not consistently matched by target-setting depth or SDG alignment across supporting documents, consistent with Fuchs et al.'s (2022) argument that HEI governance tends to promote formal rather than transformative sustainability action.

Table 1: Comparative Interpretation of Thematic Areas- UCL and ARU

The overall findings indicate that the principal distinction between these two organisations lies not in presence or absence of sustainability and CE commitments, but the degree of integration into governance, measurement and accountability structures. UCL showcases a more integrated approach with a more embedded reporting, performance monitoring while ARU demonstrates comparatively less formalised measurement frameworks and externally visible accountability mechanisms.

Conclusion, Recommendations and Future Research

The findings confirm that neither UCL nor ARU operates within a fully centralised circular economy framework, with circularity distributed across multiple documents and initiatives rather than consolidated into a single institution-wide CE strategy, reflecting a broader sectoral trend of incremental rather than systemic adoption (Velenturf and Purnell, 2021). UCL demonstrates stronger multi-level integration, evidenced by significantly higher coding density across Measurement, Benchmarking and Rankings (149 vs 73), Research and Community Engagement (238 vs 199), and Strategic Integration of Sustainability (91 vs 78), while ARU's genuine strengths in student engagement and operational carbon management remain strategically fragmented and insufficiently documented through formal reporting mechanisms. For ARU's Sustainability Strategy 2026-2030, five evidence-informed recommendations are proposed: develop a Centralised CE Action Framework modelled on UCL's The Loop initiative to consolidate circular principles across governance, procurement, and operations (Kirchherr et al., 2017); embed lifecycle design principles into procurement policy to extend material use and reduce emissions (Mendoza et al., 2019); establish digital reuse and exchange platforms to formalise and scale informal circular practices (Mendoza et al., 2019); strengthen external partnerships with local councils, social enterprises, and sector peers to extend circular practices beyond campus boundaries (Geissdoerfer et al., 2017); and formally integrate CE-specific KPIs into sustainability reporting structures, addressing the most significant accountability gap identified in this analysis (Valls-Val et al., 2024). Future research should extend this comparative approach to larger institutional samples and incorporate primary data through interviews with sustainability officers to examine how strategic intentions translate into operational practice.

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THE MAPPING AND MEASUREMENT OF SUPPLY CHAINS IN AFRICA: THE CASE FOR RESILIENCE

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Introduction

African supply chains operate within an unusually demanding combination of low economic density, commodity dependence, institutional fragility, infrastructure gaps and exposure to climatic and geopolitical shocks. Thirty-three of the world's 46 least-developed countries are in Africa, while many national economies depend on a narrow set of primary exports and essential imports (United Nations, n.d.; UNCTAD, 2021). In this setting, disruption is rarely confined to a single firm or transport link. Port closures, conflict, flooding, drought, fuel or food-price shocks, and failures of public infrastructure propagate through thin networks with limited alternative routes, modes, suppliers or markets. The consequences are closely connected to poverty, food security, and the capacity of states to sustain economic activity.

Supply chain resilience (SCR) has received extensive managerial and academic attention, particularly since the COVID-19 pandemic and the war in Ukraine. However, most literature focuses on firm-level capabilities in comparatively mature supply chains. Its recommendations – visibility, inventory buffers, diversified sourcing, nearshoring and agile response – remain relevant, but they do not by themselves resolve the structural constraints of African economies. Practical resilience requires evidence on what is produced and consumed, where activities are located, how commodities move, which links and nodes are indispensable, and where infrastructure, spatial planning, skills or policy interventions will create the greatest system-wide benefit.

This paper addresses that practical knowledge gap through a macrologistics perspective. Macrologistics treats the national economy as an interconnected value chain and examines the spatial movement of commodities from source to use. This research combines a continent-wide classification of economic vulnerability with disaggregated freight-flow modelling and country-level production-factor analysis. Its purpose is to show how macrologistics instrumentation can translate resilience theory into implementable priorities for infrastructure, regional value chains (RVCs), policy, and institutional coordination. The contribution is both diagnostic and procedural: it identifies characteristic African resilience challenges and proposes a data-driven strategy and policy cycle through which governments, development institutions, and industry can plan, implement, and monitor interventions.

Literature review and problem definition

Supply chain resilience in the African context

Resilience describes the ability of a system to anticipate, absorb, manage and recover from disturbance while retaining its essential functions (Holling, 1973; Brand & Jax, 2007). In supply chains, the concept extends beyond predicting individual shocks. It includes preparedness, the capacity to respond rapidly, and the ability to recover or reposition without unacceptable loss of performance (Bevilacqua, Ciarapica & Marcucci, 2017; Piprani, Jaafar, Ali, Mubarik & Shahbaz, 2022). Sources of risk may be internal to an organisation, embedded in supplier-customer networks, or external, including natural hazards, political instability and economic downturns.

Africa's transport and logistics systems amplify these risks in five recurring ways. First, inadequate capacity creates congestion at critical corridors, ports, and border posts. Second, low network density limits route redundancy. Third, weak modal diversity constrains switching when road, rail, port or waterway services fail. Fourth, climate-related events damage infrastructure and disrupt agricultural production. Fifth, increasing digital dependence creates cyber-security and information-system risks. These vulnerabilities occur alongside low manufacturing value added, high informality and commodity dependence, producing deeper and more persistent disruption than in dense, diversified economies (Ayittey, 2017; Tukamuhabwa, Stevenson & Busby, 2017; World Economic Forum, 2023).

The practical gap

The central problem is not an absence of policy aspirations or infrastructure proposals, but weak instrumentation for relating economic demand to logistics supply. Strategies are frequently prepared without a sufficiently disaggregated view of commodity origins, destinations, volumes, modes, and value-chain requirements. This can favour visible megaprojects over interventions that improve connectivity, consolidation, rural access, terminal systems or border performance. It also obscures trade-offs between efficiency, sustainability, and resilience. A data-driven macrologistics approach is required to connect economic structure, freight demand, infrastructure configuration, and implementation capability in a common planning framework (Havenga, Witthöft, de Bod & Simpson, 2020; Havenga, Witthöft & Simpson, 2022).

Building resilience under structural constraints

Common firm-level resilience strategies include multiple sourcing, additional inventory or capacity, nearshoring, and improved information sharing. In African settings, these options are constrained by small domestic markets, low purchasing power, limited manufacturing depth, and thin logistics networks. Additional stock may protect an individual firm but raises working-capital and storage costs; alternative suppliers may not exist locally; and route diversification is impossible where a corridor or border post has no practical substitute. Resilience must, therefore, include the development of the system itself: additional links and nodes, reliable multimodal services, access to trading platforms, regional supplier relationships, and the capability to process a greater share of primary production locally (Hippold, 2020; Pretorius, Drewes, Engelbrecht & Malan, 2022).

This development perspective also clarifies the relationship between resilience and sustainability. Infrastructure investment can reduce vulnerability, yet poorly selected projects may lock economies into carbon-intensive, environmentally damaging or single-commodity systems. Digital platforms can improve visibility and freight matching, while simultaneously increasing cyber-security exposure. Similarly, highly efficient dedicated export chains may perform well in normal conditions but remain vulnerable to a single port, railway, market or commodity cycle. The relevant objective is not maximum redundancy at any cost, but a balanced configuration that protects essential flows, enables substitution and supports inclusive economic development. Such decisions require an evidence base capable of showing who and what is connected, the scale and direction of demand, and the economic and social consequences of alternative configurations.

Research approach

Country classification

The research first grouped the 54 African countries into Southern Africa, the Horn of Africa, Western Africa, Central and Northern Africa, and African island nations. Island economies were excluded from the comparative classification because their spatial and logistics structures differ materially from mainland systems. The remaining 48 countries were classified according to economic density and trade openness, with additional identification of countries affected by conflict or institutional and social fragility. Economic density was calculated as gross domestic product (GDP) per square kilometre; trade openness was represented by trade in goods and services relative to GDP. Low density indicates long internal distances and a comparatively small economic return on infrastructure, while high trade openness increases exposure to external disruption. Their interaction provides a pragmatic indicator of vulnerability, although it does not replace detailed country analysis.

	High trade openness	Low trade openness
High economic density	Equatorial Guinea Morocco Tunisia	Arab Republic of Egypt Eswatini Ghana Nigeria Rwanda South Africa
Low economic density	Botswana Chad Eritrea Gabon Guinea Lesotho Libya Mali Namibia Somalia The DRC The Republic of Congo Zambia Zimbabwe	Algeria Angola Benin Burkina Faso Burundi Cameroon Central African Republic Cote d'Ivoire Ethiopia Guinea-Bissau Kenya Liberia Malawi Mauritania Mozambique Niger Senegal Sierra Leone South Sudan Sudan Tanzania The Gambia Togo Uganda

Legend: Conflict-affected countries Countries with institutional and social fragility

Figure 1: African country classification by economic density, trade openness and fragility.

The information presented in Figure 1 stems from the authors' calculations based on the World Bank Group (2023) list of fragile and conflict-affected situations, the World Bank, Organisation for Economic Co-operation and Development (OECD), and United Nations Population Division's World Development Indicators datasets (World Bank, OECD & United Nations Population Division, n.d.), the International Monetary Fund (IMF) World Economic Outlook Databases (IMF, n.d.), and the Food and Agriculture Organization of the United Nations (FAO) land area data (FAO, n.d.).

Freight-flow modelling and analytical framework

The empirical foundation of this research is disaggregated freight-flow modelling. Supply and demand for each commodity group are assembled from authoritative production, consumption and trade sources; geographically disaggregated using observed data or defensible proxies; reconciled to known port, border and rail flows; and balanced through a gravity model for residual road movements. Standardised outputs describe origin, destination, commodity, tonnes and transport mode. Freight is then grouped into logistically meaningful market segments, including export mining, domestic mining, intermediate manufacturing, finished palletised goods, and rural extraction and delivery. These segments reveal different requirements for corridor capacity, terminals, modal choice, service reliability, and policy (Havenga, 2012; Havenga & Simpson, 2018; Simpson, 2021).

Three related instruments support this analysis: South Africa's Freight Demand Model (FDM™, n.d.), the Regional Africa Freight Model (RAFM, n.d.) and the Africa Freight Demand Model (Africa FDM™, n.d.). The FDM™ provides a mature national example; the RAFM extends the method across Southern Africa; and the Africa FDM™ supplies continental agriculture, mining, and manufacturing trade views. The method accepts that data in emerging economies are incomplete. Grounded, iterative triangulation is used to combine overlapping sources and stakeholder knowledge, while observed trade and transport data provide boundary conditions (Havenga, Simpson, King, Lanz, Goedhals-Gerber & de Bod, 2012).

Freight-flow evidence is interpreted through two connected sets of production factors. Macroeconomic production factors comprise land and resources, industry, people and development, and institutions. Macrologistics (supply chain) production factors comprise spatial planning, logistics infrastructure, logistics skills, and policy. For each focal country, the analysis follows value chains from sourcing through transformation and use, with transport and logistics linking every stage. This framework makes resilience interventions specific: alternative sources, local processing, market diversification, corridor redundancy, intermodal connections, institutional reform, and skills development can be assessed against actual flows rather than treated as generic prescriptions.

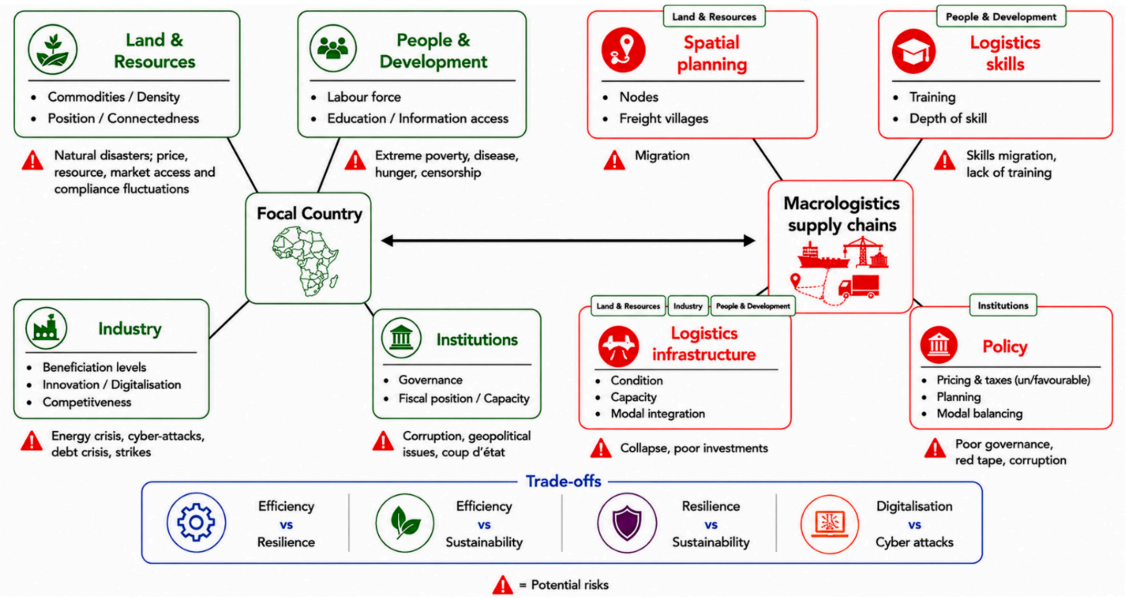

Figure 2: The link between focal-country macroeconomic – and macrologistics (supply chain) production factors, including trade-offs and potential risks.

Results and analysis

Structural vulnerability

The classification and macroeconomic analysis show a persistent divergence between Africa and the rest of the world. Population growth has frequently outpaced economic growth, leaving GDP per capita well below global levels. Manufacturing value added in Sub-Saharan Africa has remained close to 10% of GDP, compared with materially higher shares in major Asian economies. Trade has been volatile rather than following a sustained growth trajectory, reflecting dependence on primary commodities and international price cycles. A third of the mainland African countries combine low economic density with high trade dependence, a particularly exposed configuration because essential imports and export revenues rely on long, fragile logistics chains.

The 2022 State Resilience Index and the 2023 FM Global Resilience Index similarly place many African economies below high-income and leading emerging economies in institutional capacity, infrastructure quality, supply chain timeliness, visibility, and governance (Fund for Peace, 2022; FM Global, 2023). Hunger and malnutrition intensify the significance of logistics disruption: Sub-Saharan Africa records among the world's weakest hunger outcomes, while climate variability, conflict, poverty, and dependence on subsistence production undermine stable access to food (Global Hunger Index, 2022). These results support the use of economic density and trade openness as an initial screening lens, but they also demonstrate that resilience depends on institutional and social capability, not infrastructure alone.

Regional freight-flow evidence

The Africa FDM™ currently provides continent-wide agriculture and mining flows. Table 1 summarises the regional results. The results stem from the authors' calculations based on Africa FDM™ freight volume data and World Development Indicator data published by the World Bank, OECD and United Nations Population Division (n.d.). Note that the freight volumes are denoted in million tonnes (mt) and the population in millions (m).

Region	Agriculture (mt)	Grain (mt)	Fruit & veg (mt)	Mining (mt)	GDP (US$bn)	Population (m)
Southern Africa	301.8	65.9	55.8	591.4	769.5	463.2
Horn of Africa	82.9	39.7	16.7	53.0	198.4	190.4
Western Africa	377.2	83.3	58.1	528.2	751.9	417.7
Central & Northern Africa	224.1	100.7	82.8	1 018.9	851.1	236.8
Total	986.0	289.6	213.4	2 191.5	2 570.9	1 308.1

Table 1: Agriculture and mining flows by African region.

Western Africa accounts for the largest share of agricultural tonnes, while Central and Northern Africa has almost half of mining flows and disproportionately large grain and fruit-and-vegetable movements relative to its population. Southern Africa contributes 31% of agricultural and 25% of mining flows, but contains 35% of the population. The three largest economies – South Africa, Nigeria, and Egypt – together account for 49% of the regions' GDP but only 28% of their population, confirming the concentration of formal economic activity.

The disaggregated results reveal vulnerabilities hidden by regional totals. Several countries and much of the Horn of Africa are strongly dependent on grain imports. Mining export flows dominate Southern and Western Africa, making port, rail, border, and commodity-cycle performance critical. Sixteen of the 48 mainland countries are landlocked, increasing distance to maritime gateways and dependence on neighbours' infrastructure and institutions. Formal datasets also omit substantial subsistence and informal production; freight flows are, therefore, an essential but incomplete indicator of food security and livelihoods.

Cross-cutting production-factor findings

Country analyses of South Africa, Botswana, South Sudan, Ethiopia, Ghana, and Guinea point to a common set of priorities. Resource-rich economies need to balance efficient bulk exports with local beneficiation, environmental protection and wider network use. Agricultural systems require improved yields, storage, consolidation, cold chains, trading platforms, and connections between rural production areas, trunk networks, and ports. Long-distance density creates a strong potential role for rail, but modal-shift policy cannot succeed where services are unreliable or terminals are absent. Intermodal terminals and freight villages are, therefore, not merely transport facilities: they can aggregate demand, shorten first- and last-mile distances, support rural market access, and provide platforms for value-added services.

Institutional capability is the binding constraint across many cases. Fragmented mandates, weak implementation, corruption, limited project-management skills, and poor data stewardship reduce the return on infrastructure. Resilience consequently requires coordinated infrastructure, spatial and policy interventions, accompanied by human-capital development and explicit accountability. The results also support greater emphasis on RVCs. Better regional connections and border processes can diversify sources and markets, shorten supply chains, reduce dependence on distant trade partners, and create larger demand pools for processing and logistics investment.

Discussion

A data-driven macrologistics strategy and policy cycle

The findings suggest that SCR in Africa should be treated as a continuous national and regional planning function rather than a collection of isolated risk projects. Figure 3 presents the proposed cycle. Three enablers underpin it: macrologistics management focused on the real economy; collaborative planning between government, freight owners, logistics providers, and development partners; and a culture of leadership and individual accountability. The core process begins with a status-quo analysis and the mapping of the 'economy in motion'. Freight demand, logistics costs, and service gaps are translated into draft priorities, interrogated through a joint planning forum, and distilled into an integrated strategy covering infrastructure provision, spatial measures, and policy. Implementation is then monitored against actual flows and outcomes, allowing the cycle to restart as economic conditions and risks change.

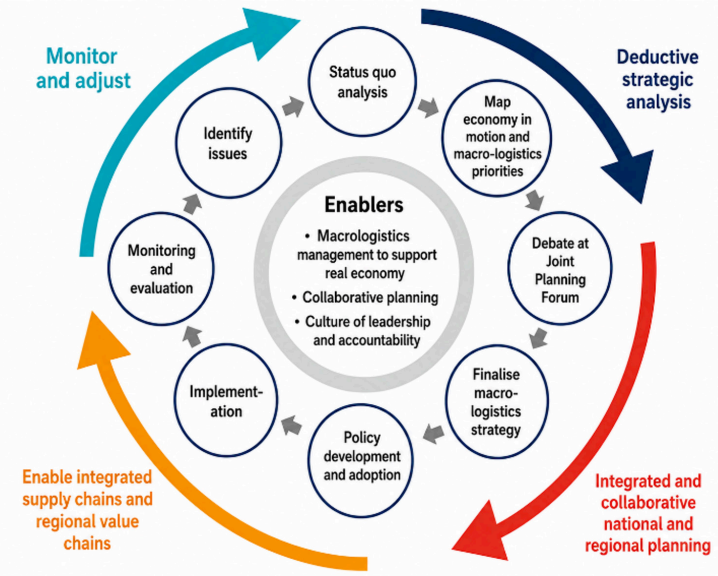

Figure 3: Data-driven macrologistics strategy development and implementation cycle.

Implications for prioritisation and implementation

The practical value of the framework lies in its ability to quantify trade-offs. Freight-flow segments can be compared by volume, value, distance, density, modal split, logistics cost, and externality exposure. This supports a portfolio rather than project-by-project view: high-volume flows may justify rail and terminal investment; high-value flows may require reliability, cold-chain or border interventions; and low-density rural flows may need targeted access and consolidation solutions. Network design should seek both efficiency and redundancy, while spatial planning should cluster compatible industries and logistics services without further marginalising peripheral communities.

Implementation should proceed through focused, sequenced interventions rather than large transformational programmes detached from local capacity. Early priorities include establishing repeatable macrologistics measurement, improving port and border reliability, protecting key infrastructure, rehabilitating high-potential rail links, developing appropriately located intermodal terminals, and strengthening data and planning skills. Aid and development finance are more likely to produce durable benefits when aligned with locally owned strategies, credible institutions, technical skills transfer, and measurable implementation milestones (Easterly, 2008; Tang & Bundhoo, 2017).

The approach has limitations. Comparable continent-wide data are currently strongest for formal agricultural and mining flows, while domestic manufacturing, informal activity, and logistics costs require further development. The economic-density and trade-openness matrix is a screening framework, not a causal model of resilience. Future research should extend the Africa FDM™, incorporate temporal and climate-risk layers, test alternative investment scenarios, and evaluate whether implemented interventions improve recovery time, accessibility, logistics cost, and food-system stability.

Conclusions

African SCR is inseparable from the structure and management of national and regional logistics systems. Firm-level buffers and agility remain useful, but they cannot compensate for sparse networks, weak institutions, commodity dependence, and limited visibility of freight demand. This paper demonstrates how country classification, disaggregated freight-flow modelling, and production-factor analysis can convert broad resilience objectives into specific priorities for different spatial areas and sectors.

The proposed macrologistics cycle provides a practical route from evidence to coordinated action. By mapping supply chains, measuring freight flows, and continuously testing infrastructure, spatial, and policy choices against economic reality, governments and their partners can direct scarce resources towards interventions that improve reliability, enable local and regional value chains, and strengthen food and economic security. The decisive requirement is not a more elaborate strategy, but disciplined instrumentation, collaboration, implementation capability, and accountability.

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RESILIENT BY DESIGN: MOVING BEYOND BEANS AND PODS WITH REGIONAL SUBSTITUTES FOR COCOA, COFFEE AND MORE

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Coffee, chocolate, and other globally traded food commodities have become integral parts of everyday consumption worldwide. However, these products cannot be cultivated under Central European climatic conditions and therefore depend on long-distance imports from tropical and subtropical production regions (Bezner Kerr, Lasco, & Hasegawa, 2019). Coffee, for example, can only be cultivated within the so-called "coffee belt" due to its specific climatic requirements (Scott, 2015). This structural dependence on global supply chains makes these commodities particularly vulnerable to environmental, economic, and geopolitical disruptions (FAO, 2026).

Climate change is increasingly threatening the production of coffee, cocoa, and other tropical crops through rising temperatures, altered rainfall patterns, droughts, and increasing pest and disease pressure (Pörtner & Roberts, 2022). As a result, agricultural commodity markets have experienced growing supply risks, price volatility, and climate-related inflation ("climateflation"), further intensified by rising global demand and geopolitical instability (Bunn et al., 2015; Kotz et al., 2024; Dávila-Fernández et al., 2025).

In response, an increasing number of companies are developing alternatives that reduce dependence on tropical supply chains by utilising regional crops, food industry by-products, and biotechnological production systems. These approaches range from traditional plant-based substitutes to emerging technologies such as microbial fermentation, cellular agriculture, and molecular flavour engineering. Besides improving supply chain resilience and potentially reducing environmental impacts, these innovations also enable new regional value chains and business opportunities (Schulp et al., 2024; Aiking & de Boer, 2020).

Despite these technological advances, alternative products must still comply with existing regulatory frameworks governing food composition and labelling. For example, products marketed as chocolate in the European Union must fulfil the compositional requirements defined in Directive 2000/36/EC, while coffee substitutes cannot legally be marketed as coffee if they do not meet the relevant product definitions (European Union, 2014; European Commission, 2026).

Against this background, this review examines the emerging landscape of companies developing alternatives to globally sourced food commodities, with a particular focus on coffee and cocoa. It identifies the main technological approaches, analyses how these innovations reshape supply chains, and proposes a classification framework for emerging business models.

Research question: How do companies developing alternatives to globally sourced food commodities such as coffee and cocoa redesign sustainable supply chains and business models?

2 Methodology

2.1 Research Design

Given the emerging nature of coffee and cocoa alternatives and the limited academic research on their supply chain implications, this study applies an exploratory qualitative research design. The research combines a systematic literature review with a multiple case study approach based on secondary data. This combination enables the integration of academic insights with empirical observations from companies developing alternative coffee and cocoa products.

2.2 Systematic Literature Review

The literature review followed the principles of the PRISMA framework to ensure a transparent and reproducible selection process. Searches were conducted in Web of Science, ScienceDirect, and Google Scholar, covering publications from 2020 to 2026. The applied search string was:

(Coffee OR Cocoa) AND (substitute OR alternative) AND ("supply chain")

Additional backward and forward citation searches were performed where relevant. The screening process included identification, duplicate removal, title and abstract screening, and full-text assessment. In total, 48 records were identified; after duplicate removal and eligibility assessment, 32 studies were included.

Studies were included if they addressed coffee and/or cocoa alternatives and their implications for supply chains, sourcing, production systems, sustainability, or value chains. Studies focusing exclusively on consumer behaviour, unrelated food substitutes, inaccessible full texts, or insufficient methodological information were excluded.

2.3 Multiple Case Study Approach

Due to the limited availability of primary data, a multiple case study design based on secondary sources (company homepages and food industry trade journals) was applied. The selected cases represent different technological pathways for producing coffee and cocoa alternatives, including plant-based substitution, upcycling, fermentation, and cellular agriculture.

Companies were purposively selected to capture variation in production technologies, raw material sourcing, geographical structures, and value creation approaches. The analysis focused on:

- production technologies;
- raw materials and sourcing strategies;
- supply chain characteristics;
- sustainability aspects;
- geographical production structures;
- product value propositions.

Data were collected from publicly available company information, including websites, sustainability reports, technical publications, press releases, patents, and publicly accessible interviews. Cross-case comparison was used to identify common patterns and differences in emerging supply chain configurations.

2.4 Interview and Data Analysis

Semi-structured interviews with industry representatives were initially planned to complement secondary data. However, despite repeated contact attempts, only one interview (Lievie, Germany) could be conducted. This limited availability reflects the early stage of the industry and the sensitivity of strategic information among companies. Therefore, the analysis relied primarily on secondary data sources.

All collected data were analysed using qualitative comparative analysis. Cases and publications were coded according to predefined categories derived from the research question, including production methods, raw material sourcing, supply chain structures, sustainability implications, and supply chain resilience. The triangulation of multiple secondary data sources supported the identification of recurring themes and emerging patterns.

Only companies actively developing or producing alternative coffee or chocolate products were included. Academic research projects without commercial activities, distributors, and products based on modified conventional coffee (e.g., decaffeinated coffee) were excluded. Generic product categories such as caffè d'orzo were considered only when a specific brand or manufacturer could be identified.

3.Results – Companies Identified

3.1 Coffee substitutes

Table 1 Overview over identified coffe substitute producers (Source: authors)

Company name (brand)	Country of origin company	Substituted raw material	Alternative raw material	Processing method	Country of origin substitute material
Food Brewer	Switzerland	Coffee, cocoa	Coffee and cocoa cells	Cell cultivation, biotechnology	/
Atomo Coffee	USA	Coffee	date pits/seeds, green tea leaves (caffeine), chicory root, grape skins, sunflower seeds, guava, aronia berry, and lemon seeds	Upcycling of food byproducts, lab, biotechnology, fermentation	USA (dates) and others
Northern Wonder	Netherlands	Coffee	Chickpeas, lupins, synthetic caffeine (-> plant blend)	Regional, plant-based alternatives, fermentation	Europe
Coffeesai Ltd. (formerly Pluri Coffee)	Israel	Coffee	Coffee cells	Cell cultivation, biotechnology	/
California Cultured	USA	Coffee, cocoa	Coffee and cocoa cells	Cell cultivation, biotechnology	/
VTT Research Centre	Finland	Coffee, cocoa	Coffee and cocoa cells	Cell cultivation, biotechnology	/
Ciao Coffee	Germany	Coffee	Barley malt, rye, herbs, and spices	Regional, plant-based alternatives	Europa
Loffee	Germany	Coffee	Sweet lupins	Regional, plant-based alternatives	Germany
Biolandhof Kelly (Lupinello)	Germany	Coffee	Sweet lupins	Regional, plant-based alternatives	Germany
Lebe Gesund	Germany	Coffee	Sweet lupins	Regional, plant-based alternatives	Germany
Nestlé (Caro Kaffee)	Switzerland/ Germany	Coffee	roasted barley, barley malt, chicory, and rye	Regional, plant-based alternatives	Europa (Germany, neighboring countries)
Minus Coffee	USA	Coffee	date seeds, chicory, sunflower seeds, carob, lentils, grape seeds, and millet malt	Upcycled, plant-based ingredients, microbial fermentation for coffee aroma	/
Prefer	Singapore	Coffee	soy pulp (okara), broken rice (previously, day-old bread and spent barley grains). Also, caffeine powder (often from green tea)	Upcycled, plant-based ingredients, microbial fermentation	Local food industry (Singapore)
Röstfein (Im Nu Malzkaffee)	Germany	Coffee	barley, rye, barley malt	Regional, plant-based alternatives	Germany and Europe

Naturata	Germany	Coffee	Coffee from malt, chickpea, chicory, grain, lupin, spelt	Regional, plant-based alternatives	Germany, Europe, Turkey
Mount Hagen	Germany	Coffee	Malt, spelt, grain	Regional, plant-based alternatives	Germany
Alnatura	Germany	Coffee	Malt	Regional, plant-based alternatives	Germany, Poland
Sonnentor	Germany	Coffee	Dandelion root	Regional, plant-based alternatives	Countries within and outside the EU
Lievie	Germany	Coffee	Dandelion root coffee, acorns, chanterelles, lion's mane mushrooms, burdock roots, chicory, caramel barley malt, spices, coffee cherry tea	Regional, plant-based alternatives	Lithuania
Mayrlife	Austria	Coffee	Dandelion root	plant-based alternatives	/
Teeccino	USA	Coffee	Adaptogenic Herbs (Tulsi leaves, Rhodiala root, Ashwagandha root, Schisandra berries, Astragalus Root, Eleuthero Root, Maca Root, Almonds, Barley, Carob, Chirocy Root, Dandelion Root, Dates & Figs, Mushrooms, Natural Flavors, Ramón Seeds, Prebiotics	Plant-based alternatives	USA, EU, India, Guatemala,
Dandy Blend	USA	Coffee	Dandelion roots, chicory roots, barley, rye	Plant-based alternatives	Poland
A. Vogel (Bambu)	Switzerland	Coffee	Chicory, wheat, malted barley, figs, and acorns	Plant-based alternatives	Turkey, Greece, Poland, rest of Europe (undefined)
Another Food Pte. Ltd.	Singapore	Coffee	Cell-based coffee	Cell cultivation, biotechnology	/
Voyage Foods	USA	Coffee, (Chocolate, peanut butter)	Roasted chickpeas, rice hulls, natural flavors, and caffeine derived from green tea	Plant-based alternatives, partly Upcycling, Fermentation, roasting, Reverse Engineering (molecular decoding) and replication	North America, Europe
Nature's Fynd	USA	coffee	Mycelium-based fungal biomass	Microbial fermentation / biomass cultivation	/ (North America)

3.2 Cocoa substitutes

Table 2 Overview over identified cocoa substitute producers (Source: authors)

Company name (brand)	Country of origin company	Substituted raw material	Alternative raw material	Processing method	Country of origin substitute material
Planet A Foods (Choviva, Nocoa)	Germany	Cocoa (, Coffee)	Sunflower seeds, oats, grape seats	Fermentation, Roasting, Conching	EU, Bulgaria
Nukoko	UK	Cocoa	Field beans	Fermentation	UK, Europe
Win Win (formerly WNWN Food Labs)	UK	Cocoa	Barley, carob, tigernuts	Fermentation, Roasting, Blending	UK, Italy, Spain
Food Brewer AG	Switzerland	Cocoa	Cell-based cocoa	Cell cultivation, biotechnology	/
Koa	Switzerland/ Ghana	Ingredients for chocolate	Cocoa Pulp, Upcycling	Upcycling	Ghana
Voyage Foods	USA	Cocoa, (coffee, peanut butter)	Sunflower seeds, grape seeds, other plants	Plant-based alternatives, partly Upcycling, Fermentation, roasting, Reverse Engineering (molecular decoding) and replication	North America, Europe
Foreverland Food (Choruba)	Italy	Cocoa	Carob, Grains, Legumes (chick peas), pumpkin seeds	Fermenting, roasting	Southern Italy, Mediterranean
California Cultured	USA	Cocoa, (Coffee)	Cell-based cocoa	Cell cultivation, biotechnology	/
VTT Research Centre	Finland	Cocoa	Cell-based cocoa	Cell cultivation, biotechnology	/
The Kawa project	USA	Cocoa	Spent coffee grounds, aroma	Upcycling, defatted, roasted coffee paste	USA, food industry
Prefer	Singapore	Cocoa	soy pulp (okara), broken rice (previously, day-old bread and spent barley grains). Also, caffeine powder (often from green tea)	Upcycled, plant-based ingredients, microbial fermentation	Local food industry (Singapore)
Celleste Bio	Israel	Cocoa	Cell-based cocoa	Cell cultivation, biotechnology	/
Fermtech (Koji Cocoa)	UK	Cocoa	Byproducts of cocoa plant (cacao husks & shells) , koji mushroom, spent grains	Upcycling, solid-state fermentation	Cocoa supply chain and industry, regional breweries (UK)

4. Results – Market and Supply Chain Strategies

The analysis reveals the emergence of a growing ecosystem of start-ups and established companies developing alternatives to conventional coffee and cocoa products. These companies aim to address sustainability-related and industry-specific challenges while creating new economic opportunities. Compared with traditional coffee and cocoa supply chains, many identified companies rely on more regional raw material sourcing and production structures, indicating the potential to reshape established global value chains.

The analysis further reveals recurring patterns in production approaches and supply chain strategies. Based on these patterns, companies were grouped into distinct strategic categories. As some companies apply multiple technologies or combine different sourcing approaches, individual companies may belong to more than one category.

4.1 Regional Crop Substitution

Regional crop substitution represents the oldest and most established approach to coffee alternatives. Many products, including Caro Kaffee (Nestlé), Naturata, Mount Hagen, Sonnentor, Röstfein, Alnatura, Dandy Blend, and Bambu (A. Vogel), have been commercially available for decades. These products mainly use locally available crops such as barley, malt, rye, wheat, spelt, chicory, and dandelion roots, which are roasted, ground, and brewed similarly to coffee.

The main characteristics of this category are established agricultural supply chains, simple processing technologies, and cultivation of temperate-climate crops. Roasting is the key process for generating coffee-like aromas, making regional crop substitution a mature and commercially proven approach based on conventional food processing.

4.2 New Plant-Based Raw Materials for Coffee and Cocoa Substitution

Recent innovations increasingly explore novel plant-based ingredients beyond traditional cereal substitutes. Examples include sweet lupins (Loffee, Lupinello), chickpeas (Northern Wonder, Voyage Foods), sunflower seeds and oats (Planet A Foods), field beans (Nukoko), and carob (Foreverland Food, Win-Win). Additional ingredients include date pits, grape seeds, lentils, mushrooms, herbs, and spices.

Compared with traditional substitutes, these products select raw materials based on their functional, nutritional, and sensory properties. Roasting remains central, often combined with fermentation or flavour optimisation to recreate coffee- and cocoa-like characteristics. This approach enables the use of regionally cultivable crops and reduces dependence on tropical commodities.

4.3 Upcycling of Food By-products

Upcycling focuses on converting agricultural and food industry by-products into valuable ingredients for coffee and cocoa alternatives. Examples include date pits, grape seeds, sunflower seeds, rice hulls, spent grains, soy pulp (okara), and spent coffee grounds (Atomo Coffee, Minus Coffee, Prefer, The Kawa Project, Voyage Foods). Cocoa-related examples include cocoa pulp (Koa), cocoa husks, shells, and spent grains (Fermtech).

These materials are typically processed through roasting, fermentation, and flavour optimisation to generate coffee- or cocoa-like sensory properties. By valorising existing biomass streams, upcycling contributes to circular economy principles, reduces food waste, and creates additional value within existing supply chains.

4.4 Fermentation

Fermentation is an increasingly important enabling technology for next-generation coffee and cocoa alternatives. Companies such as Planet A Foods, Nukoko, Minus Coffee, Prefer, Northern Wonder, Voyage Foods, Win-Win, and Fermtech apply microbial fermentation to modify plant-derived ingredients, generate aroma compounds, and improve sensory properties.

Fermented substrates include legumes, cereals, seeds, cocoa by-products, and food industry side streams. Microorganisms such as yeasts, bacteria, or fungi transform carbohydrates and proteins into flavour-active compounds, often followed by roasting, blending, or further flavour optimisation. Fermentation therefore enables the development of coffee- and cocoa-like profiles from non-traditional raw materials.

4.5 Cellular Food Production

Cellular food production represents a fundamentally different approach by cultivating coffee or cocoa cells directly rather than replacing them with alternative crops. Companies such as Food Brewer, Coffeesai, California Cultured, VTT Research Centre, Another Food, and Celleste Bio use cellular agriculture and biotechnology to produce coffee- or cocoa-derived biomass in controlled bioreactor systems.

Because the biomass originates from coffee or cocoa cells, this approach may achieve flavour profiles closer to conventional products compared with plant-based substitutes. However, commercialisation remains limited due to challenges related to production costs, scalability, regulation, and consumer acceptance.

4.6 Molecular Decoding and Flavour Replication

Molecular decoding uses analytical approaches to identify the key compounds responsible for coffee and cocoa flavour and reproduce them using alternative ingredients. Voyage Foods represents the main example identified in this review, applying reverse engineering and flavour replication approaches.

The company combines plant-based ingredients such as roasted chickpeas, sunflower seed meal, grape seeds, rice hulls, and plant-derived caffeine with roasting, fermentation, and flavour engineering. This approach differs from conventional substitution by focusing on recreating sensory and functional properties at the molecular level. Although still an emerging strategy, molecular decoding illustrates the increasing role of food chemistry and product design in developing next-generation alternatives.

5 Discussion

The reviewed companies demonstrate that innovation in coffee and cocoa alternatives is developing rapidly across multiple technological pathways, including crop substitution, novel plant-based ingredients, upcycling, fermentation, cellular agriculture, and molecular flavour engineering. This diversity reflects both increasing pressures on conventional production systems and the demand for more resilient and sustainable food supply chains.

A key finding is that the main innovation often lies not in individual substitute ingredients but in the restructuring of supply chains. While conventional coffee and cocoa production relies heavily on tropical regions and is vulnerable to climate change, biodiversity loss, diseases, and market volatility, alternative approaches enable the use of regional crops, food industry side streams, or controlled biotechnological production systems. These strategies may increase supply chain resilience, diversify sourcing, and reduce dependence on climate-sensitive production regions.

However, the transition towards alternative products also raises socioeconomic challenges. Millions of farmers depend on coffee and cocoa production, and future developments should consider pathways that enable their participation in emerging value chains rather than creating additional inequalities. Sustainable transitions therefore require consideration of both environmental and social dimensions.

The commercial maturity of identified companies varies considerably. While some products are already available in B2B and B2C markets, others remain at the research or prototype stage. The disappearance or inactivity of some companies highlights challenges related to scalability, financing, regulation, consumer acceptance, and economic viability. Although many companies claim cost and sustainability advantages, these assumptions require independent validation through techno-economic analyses and life cycle assessments.

The current innovation landscape should be considered highly dynamic. Future research should therefore address not only technological performance but also market development, consumer acceptance, environmental impacts, regulatory aspects, and socioeconomic consequences.

6 Conclusions and Future Research

This review demonstrates that coffee and cocoa alternatives are evolving from traditional substitutes towards diverse technological approaches, including plant-based alternatives, upcycling, fermentation, cellular agriculture, and molecular flavour replication. These innovations indicate a broader transformation of food supply chains rather than merely the replacement of individual ingredients.

Despite rapid technological progress, important research gaps remain. Future studies should assess sensory quality, nutritional properties, health effects, environmental impacts, and economic feasibility through comparative life cycle assessments and techno-economic analyses. Consumer acceptance, communication strategies, and market adoption of novel food technologies also require further investigation.

Future developments should additionally consider the role of existing producers in coffee and cocoa-growing regions to ensure socially responsible transitions. Beyond coffee and cocoa, similar approaches may support the development of alternatives for other environmentally critical commodities, including palm oil, coconut, vanilla, seafood, egg proteins, milk proteins, and avocado.

The field remains highly dynamic and offers substantial opportunities for interdisciplinary research linking food science, biotechnology, sustainability, supply chain management, and consumer behaviour.

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MAPPING SHORE-BASED SKILLS AND ORGANISATIONAL CAPABILITIES FOR MARITIME DECARBONISATION

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Abstract

This paper investigates shore-based individual skills and organisational capabilities required to enable maritime decarbonisation across the UK maritime supply chain. While existing research focuses predominantly on technological solutions and seafarer skills, shore-based human and organisational capacities remain empirically unexplored. Drawing on dynamic capabilities theory and green human resources management concept, this study proposes a multi-dimensional framework and a survey-based instrument to measure the importance and availability of skills and capabilities across commercial maritime actors including ports, ship operators, agents, port agents and other relevant maritime logistics firms. An importance-availability gap analysis will identify priority development needs. The study provides one of the first empirical mappings of shore-based decarbonisation skills in the UK maritime sector.

Introduction

International shipping carries approximately 80 per cent of global trade by volume and accounts for approximately 3 per cent of total global GHG emissions (IMO, 2020).The 2023 IMO GHG Strategy commits to net-zero emissions by or around 2050, with interim targets of at least 20 per cent reduction by 2030 and 70 per cent by 2040 (IMO, 2023). The UK Maritime Decarbonisation Strategy (2025) aligns with the IMO ambition level, and sets domestic targets of 30 per cent reduction by 2030 and 80 per cent by 2040, and extends the UK ETS to shipping.

Despite the urgency of this transition, research has focused predominantly on technological solutions and seafarer training, leaving shore-based commercial actors including fleet managers, port operators, freight forwarders, port agents, and compliance officers empirically underexplored. These actors play a key role for the maritime decarbonisation transition as they accomplish key tasks such as procuring and selling low-carbon services, managing emissions reporting obligations and complying with regulations. Their skills and capabilities are foundational to any effective energy transition.

This paper proposes and operationalises a multi-dimensional framework of shore-based skills and organisational capabilities for maritime decarbonisation, grounded in dynamic capabilities theory (Teece et al., 1997), green HRM (Renwick et al., 2013), and green skills research (Fuchs, 2024). An importance-availability gap analysis identifies priority development needs, and regression analysis examines which capabilities predict decarbonisation performance.

Literature Review

The maritime decarbonisation literature has expanded considerably over the past decade, yet it remains heavily skewed towards technological and regulatory dimensions. The dominant research focus has been on alternative fuel pathways (Bouman et al., 2017), vessel design and efficiency measures, and the regulatory architecture established by the IMO. While this body of work is valuable, the human and organisational dimensions of decarbonisation are overlooked.

The most directly relevant strand of existing research concerns seafarer training and competencies. The DNV Maritime Just Transition Task Force (2022) produced a comprehensive study, estimating that between 310,000 and 800,000 seafarers will require additional training by 2050 depending on decarbonisation scenario. Jimenez et al. (2026) suggest that training of maritime professionals is as important as technological developments and identify that a significant gap exists between requirements of maritime decarbonisation and existing education programmes. According to the study, most significant gaps exist in alternative fuels, emissions measurement and reporting, energy-efficient technologies, digital analytics, and regulatory compliance. While these studies underline the necessity of maritime decarbonisation skill development, shore-based professional are either overlooked or not explicitly studied.

The port sustainability literature offers a second relevant stream. Steen et al. (2024) found that knowledge of decarbonisation

tools and technologies is one of the main drivers of port decarbonisation. Bjerkan et al. (2021) found through a survey of 96 Norwegian ports that organisational role and intermediation capacity — rather than technology alone — drive decarbonisation progress, with port authorities functioning as crucial intermediaries between transport and energy systems. This finding is significant because it suggests that capabilities of firms also play a key role. Alamoush (2024) similarly identifies governance, managerial attitudes, interorganisational relationships and organisational capacities as determinants of port decarbonisation.

Beyond the maritime-specific literature, logistics literature has also touched upon the necessity of skillset development for the sector's decarbonisation (McKinnon, 2022). Similarly, Royo et al. (2023) has identified the need for curriculum development for logistics decarbonisation. While the gap is underlined, the literature lacks empirical research to identify what skills should be prioritised.

A main gap across the literature is the absence of empirical measurement focusing on shore-based maritime skills and organisational capabilities. Studies consistently identify skills and capability as important for maritime decarbonisation without operationalising or measuring them. Where measurement attempts exist, they are either confined to seafarers limited to single organisation types or based on qualitative or expert judgement rather than systematic survey data. This study addresses that absence directly, drawing on green skills concept (Fuchs, 2024; Vona et al., 2018) and dynamic capabilities for sustainability (Amui et al., 2017) to develop and operationalise a framework that is both theoretically grounded and empirically testable.

Methodology

This study adopts a quantitative, cross-sectional survey design targeting shore-based professionals in UK commercial maritime organisations including ship operators, ports, freight forwarders, port agents, and maritime service providers. Respondents evaluate skills and capabilities within their team as a whole, following the key informant approach (Huber and Power, 1985). Data collection is conducted via LinkedIn outreach, direct email, and dissemination through industry networks, with a target of at least 150 completed responses to support exploratory factor analysis.

Survey items were developed through systematic literature review and expert validation, with all items reviewed for applicability across the full range of target organisation types. Analysis will employ importance-availability gap analysis to calculate gap scores by dimension and organisation type, visualised on an importance-availability matrix, and exploratory factor analysis to test the empirical factor structure of the instrument.

Table 1 Measurement dimensions

Dimension	Illustrative Item
A1. Decarbonisation Knowledge	Understanding of alternative energy solutions (e.g. ammonia, methanol, electrification, shore power)
A2. Safety for Decarbonisation	Awareness of operational readiness requirements for implementing alternative energy solutions
A3. Regulatory Compliance	Managing obligations under applicable emissions trading schemes (e.g. EU ETS, UK ETS)
A4. Financial & Commercial	Ability to assess the impact of carbon pricing mechanisms on business performance
A5. Digital Skills	Data analysis expertise for emissions management
A6. Transversal Skills	Applying critical thinking when evaluating sustainability solutions
B1. Value Chain Carbon Management	Analysing carbon emissions data to identify reduction opportunities
B2. External Collaboration	Jointly developing decarbonisation knowledge and solutions with external partners
B3. Funding & Resource Acquisition	Developing business cases to attract investment in decarbonisation
B4. Adaptive Capability	Adjusting business strategy in anticipation of emerging decarbonisation requirements
B5. Organisational Learning	Disseminating decarbonisation knowledge across departments to support decision-making

5. Discussion and Conclusions

This study responds to a well-evidenced gap in both the academic literature and UK maritime policy: while considerable investment has been made in understanding the technological pathways to maritime decarbonisation, comparatively little is known about whether organisations and shore-based personnel are actually equipped to implement these solutions in practice. As the UK Maritime Decarbonisation Strategy (DfT, 2025) sets ambitious domestic targets and brings shipping under the UK ETS, the question of organisational and workforce readiness becomes increasingly urgent yet remains largely unanswered by existing research.

The importance-availability analysis will provide a systematic and empirical picture of which individual skills are perceived as most important by shore-based maritime professionals across different organisation types. This distinction matters because, as identified in the introduction, large operators and major ports may have specialist teams while SMEs rely on generalist staff with limited exposure to emerging technologies and policy developments (Lloyd's Register, 2023). The analysis is therefore expected to reveal not only which skills are most critical overall, but also significant variation by organisation size and type.

The organisational capability dimensions reflect the recognition that decarbonisation is not simply a matter of individual knowledge but of firm-level capacity to plan, coordinate, invest, and adapt. This is particularly important given that training and certification in maritime decarbonisation are not keeping pace with rapidly developing technologies (DfT, 2023), and that skills and capability development more broadly lags behind technological improvement (Maritime UK, 2024). Organisations with stronger adaptive and learning capabilities are better positioned to respond to this dynamic environment, and the framework provides a basis for measuring and comparing those capabilities empirically across the UK maritime supply chain.

The practical outputs of this study are designed to be directly actionable. Evidence on priority skills and capability gaps will inform workforce development strategies for industry bodies, training providers, and policymakers. The findings are particularly relevant to the Maritime Skills Alliance, the UK Clean Maritime Research Hub, and the Department for Transport as they develop the next phase of workforce and training policy under the Maritime Decarbonisation Strategy. The validated framework can also function as a self-assessment tool for organisations seeking to benchmark their own readiness and identify priority development areas, addressing the need for accessible, inclusive, and targeted training interventions identified in the literature.

Several limitations should be acknowledged. The study relies on managerial perceptions as a proxy for team-level skills, which introduces the possibility of social desirability bias and limits precision at the individual level. The cross-sectional design captures a snapshot in a rapidly evolving regulatory and technological environment, meaning findings may require updating as the landscape changes. Future research should examine how gaps evolve over time, explore the perspectives of non-managerial shore-based staff directly, and extend the framework internationally to enable cross-national benchmarking of maritime workforce readiness for the net-zero transition.

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SPATIAL ACCESSIBILITY TO LOGISTICS EMPLOYMENT: EVIDENCE FROM A UK DISTRIBUTION CENTRE

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1. Introduction

The rapid expansion of e-commerce has transformed the spatial organisation of logistics systems across the UK, driving the proliferation of large-scale distribution centres strategically located between urban areas. These facilities, often situated along motorway corridors and in out-of-town industrial parks, have become key nodes in national and regional supply chains while simultaneously acting as major sources of employment. However, their location raises important questions about the accessibility of these jobs, particularly for lower-income workers who are more likely to depend on public transport.

These issues are particularly relevant given the distinctive characteristics of logistics labour. Distribution centres typically operate on a 24-hour, seven-days-per-week basis, with shift patterns extending into early mornings, late evenings, and overnight periods. Yet public transport networks remain largely oriented towards conventional commuting patterns. Previous research has shown that such conditions can lead to high levels of car dependency and create significant barriers for workers without access to private vehicles. However, existing evidence is largely based on case studies and worker-level analyses, limiting understanding of whether these dynamics are localised or systemic.

This paper addresses this gap by providing a scalable methodology for the analysis of the accessibility to distribution centres, which is applied to a selected distribution centre in South Yorkshire, UK. Drawing on secondary data sources, including transport networks and population distributions, the study evaluates the extent to which the site is accessible from surrounding residential areas within a maximum 30km radius of the site under realistic travel conditions. Particular attention is given to temporal accessibility, including early morning and late-night periods that are critical for shift-based work.

The paper contributes to debates on transport inequality, labour market access, and the evolving geography of logistics. It provides new evidence on whether the accessibility constraints identified in case-based studies reflect isolated conditions or structural features of the UK logistics landscape. In doing so, it advances understanding of how the spatial organisation of production interacts with transport systems to shape the conditions under which labour is accessed.

2. Relevant Literature

The evaluation of the social performances of transport systems has become an element of interest to many scholars and policy makers (see, for instance, Martiskainen et al., 2023). Specifically, it has been acknowledged that poorly designed transport systems may have the potential to create a detrimental effect on people's quality of life and employment opportunities (Jones and Lucas, 2012). In this context, Kenyon et al. (2002) defined the concept of mobility-related social exclusion in terms of the processes that prevent people from participation in the economic, political and social life of the community because of reduced accessibility to opportunities, services and social networks. With around 40% of households in the lowest income quintile, and two thirds of the job-seekers, having no access to a car, combined with rising costs of public transport, these access to work issues are becoming increasingly relevant across the UK. The lack of access to transport alternatives poses the risk of cutting-off at least half a million people from accessing work and employment opportunities (Sustrans, 2015; DfT, 2023). As revealed by PTEG (2015), about three quarters of the jobseekers outside London do not own (and do not have access to) personal motorised transport (i.e., car, van or motorbike); therefore, they can face significant barriers in finding work as a result.

As the economy transitions, local authorities continue to promote job creation in growing sectors such as logistics, yet significant access-to-work barriers persist. Reports indicate that for low-income and younger job-seekers, the cost of public transport fares, limited transport links to employment sites, and mismatches between shift times and available services

remain among the most significant obstacles to opportunity (Lucas et al., 2019, PTEG, 2015). According to research by O'Hara (2015), lack of affordable public transport is one of the main reasons for the unemployed turning down job offers, a situation that has significantly worsened in the last few years due to funding cuts to both local authority budgets and benefits induced by prolonged austerity regimes (Martiskainen et al., 2023). From May to July 2025 there were reportedly 1.69 million people claiming unemployment-related benefits.

Reductions in public transport services since 2019 have disproportionately affected early-morning and late-night routes that are essential for shift work (BBC, 2024), with night-time commuting studies highlighting distinct safety concerns, high taxi reliance, and a strong modal pull toward private vehicles in the absence of reliable public transport (Nettlefold and Boyer, 2021). These findings are consistent with the international academic literature stating the positive correlation between availability of public transport and employment rates in urban areas, with a special emphasis on deprived neighbourhoods (see, for instance, Ricciardi et al., 2015; Tyndall, 2015). Recent empirical work confirms a causal relationship between improved public transport job accessibility and higher employment probabilities in low-car-ownership areas (Mattioli et al., 2022), underscoring the economic and social stakes of aligning transport provision with the temporal and spatial demands of the logistics workforce.

The logistics and distribution industry is traditionally labour intensive, requiring high numbers of low-skilled workers to be employed as warehouse operatives working on round-the-clock shift patterns to facilitate a 24hrs a day, seven days a week business operation. For logistics companies, selecting a location for a new distribution centre is generally focused on adopting a site that provides a balance between the lowest costs and greatest efficiency in order to meet operational and strategic objectives (Thai and Grewal, 2005). Thus, large warehouses are usually located some considerable distance outside urban areas for ease of access to motorway networks and or port terminal infrastructure, as opposed to prioritising proximity to public transport for the workforce. Coincidentally these locations are also where local authority town planners encourage large developments due to the availability of cheaper land and the ability to segregate the visually intrusive warehouses from popular residential areas and green spaces. Continued growth of e-commerce has sustained the expansion of large, motorway-adjacent fulfilment centres (Savills, 2024; CBRE, 2023), often deepening the spatial mismatch between job locations and public transport networks.

While research explicitly examining the interaction between logistics distribution centres and workers' access to employment remains limited, a few emerging studies provide valuable insight. Tavasszy et al. (2014) found that areas with higher transport accessibility tend to attract more logistics employment, underscoring the importance of regional transport connectivity in shaping the geography of the sector. Nefs et al. (2023) questions the assumed wider economic benefits of very large distribution hubs, suggesting that while these facilities may catalyse local job growth, they can also create spatial-economic lock-in, with regional economies becoming overly dependent on logistics activity without guaranteed spillovers that improve access. Additionally, studies of employer-subsidised demand-responsive transport (DRT) demonstrate its potential to improve the perceived accessibility of employment for logistics workers at sites poorly served by conventional public transport (Calvert et al., 2022). These studies suggest that the spatial organisation of logistics facilities interacts with transport provision to shape labour market access and workforce experience; however, a significant gap in empirical research investigating these issues remains. This study addresses this gap by examining travel-to-work patterns and accessibility challenges for employees at a major logistics distribution centre, through a scalable approach based on publicly available secondary data.

3. Methods

This study adopts a spatial accessibility modelling approach to evaluate access to employment within the UK logistics sector. The analysis focuses on the relationship between the location of a major distribution centre and the availability of public transport connections from surrounding residential areas within a 30km radius of the site. By integrating geographic information systems (GIS) with public transport (bus and rail) timetable data, the study quantifies both spatial and temporal accessibility to logistics employment. The research design is informed by the premise that accessibility is not solely a function of distance, but of travel time, service availability, and alignment with working hours. In the context of 24/7 logistics operations, this requires consideration of both peak and off-peak periods associated with 24/7 operations and shift-based work. The data analysis centred on a single large distribution centre in South Yorkshire that serves e-commerce and forward retail distribution.

Population and labour supply data. Residential population data were obtained from the UK Census at Lower Layer Super Output Area (LSOA) level. For the LSOAs and the population estimates, the latest available data was used, which belongs to 2021 and 2024, respectively. To capture potential labour supply characteristics, indices of multiple deprivation (IMD) were also incorporated. The latest available indices, belonging to 2025, were used. These data enable the identification of areas where reliance on public transport is likely to be highest. Population centroids were used as origins in the accessibility analysis, providing a proxy for the spatial distribution of the potential workforce.

Public transport network data. Public transport data were derived from national datasets, including the UK Bus Open Data Service, Rail Data Marketplace, and General Transit Feed Specification (GTFS) timetable data for bus and rail services. These datasets were integrated to construct a multimodal public transport network. The network includes: walking links between origins and nearest transit stops; transfers between services; service frequencies and waiting times; temporal variations in service availability. To reflect realistic commuting conditions, the network was modelled for five time periods corresponding to the main shift start/finish times in the UK logistics industry.

Accessibility modelling. Accessibility was operationalised using a travel-time-based approach. For each residential origin, which is assumed the centroids of the LSOAs, the shortest travel time to the logistics distribution centre was calculated using Round-bAsed Public Transit Optimized Router (RAPTOR) algorithm, proposed by Delling et al. (2015). It is a dynamic programming-based algorithm and given an origin and a destination point, it finds the fastest route with at most k transfers, e.g., by taking at most k trips. In the experiments, the following assumptions have been made:

- Walking distance is estimated by multiplying haversine distances with a factor of 1.4.
- Walking time is calculated using a walking speed of 1.33 m/s.
- The algorithm searches the area within a radius from the origin point and identifies the nearest bus stop to start the journey. If there are no stops within an 800m radius, it returns “unreachable”.
- The number of transfers was not constrained by setting k to 8, e.g. the fastest route irrespective of the number of transfers is returned.
- For journeys that require changes between one bus/rail to another, the maximum walking distance allowed between two transit stops during an interchange was set to 1000 metres.
- A 60-second buffer is added to the first walking leg, e.g., to check belongings, lock the door etc. when leaving home. Note that this only affects the initial departure time and total journey time, e.g. by increasing by a minute, it does not affect the journey itself.
- A 2 hour time-window was set for the maximum period of time required to board the remaining transit vehicle in a trip chain. If the last required transit departure time falls outside the 2 hour window, the algorithm returns as “unreachable” result.
- For transfers to trains, a time buffer was added to every walking leg to provide additional time to locate the platform on arrival at the train station. This was set to 5 minutes and applies to same-station transfers.

4. Results

Journey times were calculated from all LSOA centroids to the facility; extensive computational results are reported in Table 1, this includes: percentage of reachable LSOAs; percentage of working population within the 30, 60, 90 minute catchment areas; proportion of LSOAs that are reachable in the 2 hour time window; percentage of more and less deprived LSOAs that are reachable in the 2 hour time window; total travel time; number of bus and rail transfers in one trip; percentage of waiting time within total journey time; percentage of walking time within total journey time; and percentage of journeys involving a rail leg. The analysis reveals highly variable public transport accessibility to the South Yorkshire distribution centre, with substantial differences occurring between shift times and journey directions.

The proportion of reachable LSOAs varies dramatically across shifts. For the early day shift (06:00 start), only 11.1% of LSOAs are reachable inbound, though outbound reachability at 14:00 reaches 81.5%. The standard day shift (08:00 start) shows 68.4% inbound and 79.3% outbound reachability. The late shift (14:00 start) achieves the highest inbound reachability at 90.6%, but outbound at 22:00 drops to 55.3%. The night shift shows 71.6% inbound (22:00) and 84.8% outbound (06:00). This asymmetry (particularly the collapse of evening services) highlights a critical temporal mismatch between shift patterns and public transport provision.

For the 30-minute threshold, accessibility is extremely limited across all shifts (1.0-3.3% of the working population), confirming that virtually no workers can complete a short public transport commute. At 60 minutes, coverage improves but remains modest (5.0-16.5%), with only the 14:00 inbound shift reaching 15.3%. Even at 90 minutes, coverage varies widely from 12.6% (06:00 inbound) to 49.8% (14:00 inbound), indicating that substantial portions of the working population cannot access the site even with extended commuting times. Median journey times are consistently high: inbound medians range from 51 minutes (06:00) to 94 minutes (08:00), while outbound medians range from 95 minutes (06:00) to 108 minutes (16:00). Maximum journeys extend to 137 minutes, representing over two hours of travel.

When disaggregated by Index of Multiple Deprivation (IMD), more-deprived LSOAs (deciles 1-5) consistently show higher reachability than less-deprived areas. For example, at 06:00 inbound, 14.7% of deprived LSOAs are reachable versus 5.5% of less-deprived areas; at 08:00 inbound, the figures are 76.7% versus 55.2%. This reflects the nature of urban located deprived neighbourhoods having greater access to public transport services, however the operating times and routes are not well aligned with logistics shift patterns that fall outside the traditional working day shift (08:00 - 16:00). This creates a double disadvantage with reliance on public transport combined with longer, more complex journeys to access work for other shift patterns.

Journey complexity varies considerably. Transfer counts range from 0-5, with outbound and late shifts requiring more transfers. The 14:00 outbound shows 569 journeys requiring one transfer, 440 requiring two, and 115 requiring three, compared to 75 zero-transfer journeys. Rail inclusion ranges from 0% (06:00 inbound) to 56.5% (16:00 outbound), with outbound journeys generally more rail-dependent. Waiting time constitutes up to 80.8% of total journey time (22:00 outbound) with typical medians of 12-22%. Walking time represents up to 78.6% of journeys (22:00 outbound) with median proportions of 14-26%. These components contribute substantially to more strenuous journeys and unreliability.

5. Discussion and conclusion

The findings from this single-site analysis reveal a pattern of public transport accessibility that is spatially uneven, temporally constrained, and characterised by long travel times, high journey complexity, and significant socio-economic differences. The lack of public transport service accessibility during early morning and late-night periods - precisely when logistics operations depend on labour reinforces car dependency and limits employment access for those without private vehicles.

These patterns challenge conventional interpretations of accessibility and transport planning as a technical or policy failure of transport systems. While limited public transport provision is often framed as an issue of service coverage, frequency, or planning inefficiency, the results suggest a more fundamental explanation. The observed constraints are not incidental but reflect the underlying spatial organisation of contemporary logistics systems: distribution centres are located to optimise flows of goods through motorway networks and intermodal terminals, while workforce accessibility is often not considered. The temporal mismatch between shift patterns and transport provision is not simply a failure of coordination but rather reflects the prioritisation of logistical efficiency over labour mobility.

This configuration has important implications for labour market dynamics. It contributes to the production of a car-dependent workforce, shapes labour force composition by favouring workers who can absorb rising mobility costs while excluding those without private transport. It also introduces a disciplinary dimension to labour, as unreliable transport increases risks of lateness or absence with consequences for job security in a sector characterised by precarious employment arrangements.

The findings also resonate with broader debates on the spatial organisation of capitalism. The clustering of logistics facilities in peripheral, infrastructure-rich locations can be interpreted as enabling firms to achieve operational efficiencies while simultaneously reshaping local labour markets. Transport systems thus become part of the mechanism through which labour is organised. These findings will be expanded through a large-scale analysis of major UK distribution centres to identify broader national patterns, potentially suggesting that accessibility constraints reflect a structural feature of logistics employment geography rather than isolated conditions.

From a Labour Process Theory perspective (Braverman, 1974), the peripheral siting of distribution centres combined with 24/7 operations embeds commuting within the labour process itself, with workers absorbing the time, cost, and uncertainty of transport accessibility, effectively externalising mobility costs from firms to workers. This theoretical lens will inform the interpretation of the broader analysis. Crucially, this interpretation reframes policy implications. Interventions aimed solely at improving public transport provision (through additional bus services or demand-responsive transport) may alleviate some constraints but are unlikely to address underlying structural drivers. Without integrated approaches considering the co-location of employment, housing, and transport infrastructure, inequalities are likely to persist. Planning frameworks that continue to prioritise large peripheral logistics sites risk reinforcing patterns of transport disadvantage and labour market exclusion. The paper contributes to a shift in perspective: from viewing accessibility as a question of transport provision to understanding it as a feature of the spatial organisation of logistics and production. The geography of logistics is not only a geography of goods movement, but also a geography of labour access, one that shapes who can work, where, and under what conditions.

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Shift		06:00 - 14:00		08:00 - 16:00		14:00 - 22:00		22:00 - 06:00	
		In	Out	In	Out	In	Out	In	Out
% Reachable LSOAs		11.10	81.50	68.40	79.30	90.60	55.30	71.60	84.80
Catchment of working population (%)	30 min	1.80	1.00	3.30	0.50	2.20	1.80	2.50	0.70
	60 min	8.20	10.20	16.50	5.00	15.30	10.50	13.90	9.40
	90 min	12.60	32.30	32.20	19.10	49.80	23.50	40.90	37.40
Reachability of deprived areas (%)	More-deprived LSOAs (decile 1-5)	14.70	85.60	76.70	83.70	92.50	58.40	75.90	87.40
	Less-deprived LSOAs (decile 6-10)	5.50	75.00	55.20	72.20	87.60	50.40	64.90	80.70
Total Travel time (min)	min	14	15	15	14	14	17	14	18
	max	81	134	130	134	137	134	133	133
	median	51	98	94	108	88	97	88	95
No. of vehicle transfers used		0→75, 1→81, 2→13	0→94, 1→569, 2→440, 3→115, 4→17	0→121, 1→260, 2→381, 3→225, 4→42, 5→8	0→41, 1→226, 2→530, 3→348, 4→56, 5→1	0→79, 1→365, 2→555, 3→331, 4→43	0→138, 1→519, 2→163, 3→19	0→82, 1→498, 2→401, 3→104, 4→1	0→109, 1→562, 2→502, 3→90, 4→23
Waiting time as % of total journey time	min	0.00	3.06	0.00	1.47	0.00	6.12	0.00	5.45
	max	26.09	53.76	68.42	67.86	57.94	71.74	60.00	80.77
	median	2.27	15.38	14.00	20.08	12.16	18.18	19.30	21.86
Walking time % of total journey time	min	7.94	4.17	5.05	4.90	4.92	4.63	3.85	4.39
	max	65.00	74.00	61.90	54.10	66.67	78.57	65.00	55.00
	median	26.42	18.03	15.32	14.43	15.38	18.18	15.47	14.98
Proportion of journeys including rail		0.00	23.81	50.63	56.49	56.08	35.16	47.15	35.30

Table 1 – Extensive computational results (Transfer counts are presented as [number of transfers] → [number of journeys]. For example, '0→75' indicates 75 journeys required zero transfers)

PATENT-BASED MAPPING OF MARITIME DECARBONISATION TECHNOLOGIES FOR SUSTAINABLE MARITIME TRANSPORT

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1. Introduction

Maritime training institutions must decide which decarbonisation technologies to build workforce capacity around, in what sequence, and with what urgency. Current regulatory milestones do not make this decision for them. The IMO 2023 Revised GHG Strategy sets a net-zero destination for or around 2050, but it does not specify which propulsion or fuel pathway will dominate, and Laskar et al. (2025) find no consensus among shipping companies, engine manufacturers, port authorities and investors on the pathway for 2030 or 2050 either. Training providers are therefore being asked to prepare a workforce for a transition whose technical shape is still being negotiated in the patent record and the newbuild order book, not in the regulatory text.

The training-capacity literature confirms this is a live operational problem rather than a future one. DNV's assessment for the Maritime Just Transition Task Force finds that the number of seafarers needing alternative-fuel training grows steeply well before 2050, and that safety-critical competencies are not yet embedded across the fleet at scale (DNV, 2023). Inal et al. (2021) show what building a single qualification looks like in practice: a dedicated STCW-aligned course on hybrid propulsion and alternative fuels for marine engineers, developed as a discrete 14-week programme. Translating a named technology into a deliverable qualification is a project measured in months, not a decision that can be made the week a fuel becomes commercially visible.

This paper treats that lag as the central design constraint. Rather than asking which fuel or propulsion technology will eventually dominate, it asks which technology clusters already show a firm-level combination of commercial conviction, durable patent quality, and current regulatory pull: the combination that should trigger curriculum investment ahead of, rather than behind, commercial deployment. We analyse maritime decarbonisation patents published between 2000 and 2025, organised into technology clusters using unsupervised natural language processing, and add two dimensions to the resulting lifecycle picture: a Commercial Readiness Signal built from patent quality indicators, and an explicit regulatory-status classification. Combined, these form a three-part prioritisation logic aimed directly at training institutions, flag states, and the IMO's Human Element and Training Sub-Committee.

Two questions guide the paper. First, do patent quality indicators, rather than raw patent counts, meaningfully separate technology clusters with real commercial backing from clusters that are patent-active but not yet commercially converging? Second, once lifecycle stage, patent quality, and regulatory status are combined, which technology clusters constitute genuine near-term training priorities, and which should be monitored strategically rather than resourced immediately?

2. Literature Review

2.1 The Maritime Training Gap in Decarbonisation

Decarbonisation training is already recognised as a bottleneck rather than a downstream detail. The Maritime Just Transition Task Force's DNV-led assessment models seafarer training needs against several decarbonisation scenarios and finds that the number of crew requiring new competencies rises sharply well before mid-century, identifying safety training for ammonia, methanol and hydrogen bunkering as a particular gap (DNV, 2023). Inal et al. (2021) translate this into curriculum design directly, mapping a proposed hybrid-propulsion and alternative-fuels course against specific STCW competency tables: useful evidence that course design, accreditation and delivery is itself a multi-month technical project once a target technology is chosen. Neither study, however, offers a method for choosing which technology to prioritise first; both assume the target technology is already known.

2.2 Patents as a Leading Indicator of Commercial Direction

Patent filing precedes commercial deployment by design: firms protect an invention before, not after, it reaches market, so patent records capture commercial conviction ahead of visible market signals (Gerken and Moehrle, 2015). Griliches (1990) establishes patents as a longitudinal, firm-level, publicly available record of inventive activity, distinct from and available earlier than market or deployment data. This property is exactly what a training-planning problem needs: an indicator that moves ahead of, not behind, the technologies it is meant to inform decisions about.

2.3 Patent Quality as an Underused Signal

Most patent-based technology forecasting treats a patent as a single unit of activity. A separate literature asks which patents actually indicate commercial substance. Higham, de Rassenfosse and Jaffe (2021) set out a systematic framework for patent quality spanning legal, technological and economic dimensions. Schmitt's (2025) systematic review of 762 studies confirms that forward citation count, patent family size and claim count are the most consistently used technological-quality indicators across the literature. These indicators are well established individually but, to the authors' knowledge, have not previously been combined into a single training-relevant readiness signal for maritime technology clusters.

2.4 The Research Gap

Existing maritime workforce-planning work is stakeholder- and expert-opinion-driven (Laskar et al., 2025), built on consultation with shipping companies, engine manufacturers and investors rather than on firm-level patent evidence. Existing patent-landscape work on maritime decarbonisation identifies technology clusters and their lifecycle stage, but does not connect that staging to training implications, nor does it weight clusters by patent quality. This paper closes both gaps directly, combining lifecycle stage, a new quality-weighted Commercial Readiness Signal, and regulatory status into a single prioritisation output aimed specifically at workforce planning.

3. The Planning Problem

A training institution allocating curriculum-development time and budget across a wide set of candidate technology clusters faces two distinct failure modes. The first is over-investment in visibility: a technology can dominate regulatory strategy documents and industry commentary while remaining, in patent terms, barely past the starting line. Hydrogen propulsion and fuel cell systems illustrate this directly: prominent in almost every long-range decarbonisation roadmap, yet, as Section 5 shows, still at an early stage of its patent-activity lifecycle with no inflection point yet visible. The second is under-investment in urgency: a cluster tied to a compliance requirement already in force can accelerate past the point where training capacity should exist, while institutions wait for a clearer signal that never arrives in time. Both failure modes share a common cause: regulatory attention and patent-based commercial attention are being read separately, when the planning decision requires reading them together, alongside a genuine quality check on whether the underlying patent activity reflects real technological investment rather than defensive or speculative filing.

4. Research Approach

4.1 Corpus and Cluster Structure

We analyse maritime decarbonisation patents collected from Lens.org using six Boolean search queries targeting the B63 CPC classification, covering publications between 2000 and 2025. Title and abstract text for each record was embedded using a sentence-transformer model, reduced in dimensionality with UMAP, and grouped using HDBSCAN density-based clustering; BERTopic's class-based TF-IDF procedure then labelled the resulting groups (Grootendorst, 2022). This process organises the corpus into 22 technology clusters across six domains: Alternative Fuels, Energy Efficiency, Electric and Hybrid Propulsion, Hydrogen and Fuel Cells, Wind and Renewable Energy, and Digital and Compliance. The classified corpus comprises 8,774 patents; unclustered records are treated as noise and excluded from cluster-level analysis.

4.2 Technology Lifecycle Staging

Each cluster's position in its commercial development trajectory is estimated by fitting S-curve models (Logistic, Gompertz and Richards specifications) to cumulative patent counts, selecting between them using the Bayesian Information Criterion. Following Andersen's (1999) five-stage classification, each cluster is assigned to Pre-emergence, Emerging, Growing, Maturing or Mature according to its position relative to the model's estimated carrying capacity. Lifecycle stage forms one of the three inputs to the prioritisation matrix below.

4.3 The Commercial Readiness Signal

Lifecycle stage alone does not distinguish a cluster with substantial defensive or speculative filing from one with durable commercial backing. This paper introduces a Commercial Readiness Signal (CRS) to make that distinction, built from the four patent-quality indicators most consistently used in the literature: forward citation count, simple patent family size, granted legal status, and independent claim count (Higham et al., 2021; Schmitt, 2025). Each indicator is normalised within the classified corpus and combined with equal weighting into a single per-cluster CRS score, giving a quality-weighted complement to the raw activity counts used in lifecycle staging.

4.4 Regulatory Status Coding

Each cluster is also coded against its relationship to compliance instruments currently in force, in three categories. Mandated clusters are those where a current legal requirement drives adoption, such as the Carbon Intensity Indicator and Energy Efficiency Existing Ship Index, in force under MARPOL Annex VI since 1 January 2023. Incentivised clusters are rewarded or indirectly required within an existing compliance calculation, such as wind-assisted propulsion under EEXI correction-factor provisions for innovative energy efficiency technologies and the FuelEU Maritime wind reward factor. Anticipatory clusters depend only on the long-range 2050 target with no current compliance trigger, such as hydrogen propulsion. This coding is independent of patent activity and is drawn from the regulatory instruments themselves.

4.5 Building the Prioritisation Matrix

Lifecycle stage, CRS, and regulatory status are combined into a three-tier output. Immediate Priority clusters are past or approaching their inflection point, show a credible CRS, and are Mandated or Incentivised. Strategic Preparation clusters are Emerging or Anticipatory but show a rising CRS. Monitor clusters are Emerging, show a low CRS, are Anticipatory, and show no near-term signal. The output is intended as a planning instrument, not a technology recommendation: it identifies where patent evidence and regulatory mandate align, not what training content should contain.

5. Preliminary Results

Table 1 sets out the prioritisation logic for four clusters that anchor the two failure modes described in Section 3: two already accelerating under a live compliance mandate, one accelerating under an incentive mechanism, and one still early despite its regulatory prominence. A citation and family-size proxy for CRS is included alongside lifecycle stage and regulatory status.

Cluster	Lifecycle Stage	Regulatory Status	Citation/Family Window	Preliminary Tier
Carbon Intensity Monitoring & CII/EEXI Compliance	Growing, 51.3% of estimated capacity	Mandated (MARPOL Annex VI, since Jan 2023)	approx. 6 years (median publication 2020)	Immediate Priority
Wind-Assisted Propulsion: Rotors, Sails & Kites	Maturing, 86.6% of estimated capacity	Incentivised (EEXI correction factor; FuelEU wind reward)	approx. 10 years (median publication 2016)	Immediate Priority
LNG & Methanol Dual-Fuel Systems	Growing, 46.4% of estimated capacity	Mandated (IMO 2020 sulphur cap; EU ETS Maritime)	approx. 10 years (median publication 2016)	Immediate Priority
Hydrogen Propulsion & Fuel Cell Systems	Emerging, 12.5% of estimated capacity	Anticipatory (2050 target only)	approx. 2 years (median publication 2024)	Strategic Preparation

Table 1: Preliminary prioritisation logic for four selected clusters.

Citation/family window is the approximate number of years since each cluster's median publication year, a mechanical proxy for the time available to accrue forward citations and complete family filings, ahead of full CRS computation across the wider cluster set.

Fourteen of the 22 clusters in the corpus remain in the Emerging stage overall, meaning most of the maritime decarbonisation technology space does not yet warrant Immediate Priority status on lifecycle grounds alone. The four clusters above show why regulatory status changes that picture for some clusters and not others: two Growing-stage clusters and one Maturing-stage cluster are already tied to compliance instruments in force today, while the technology most frequently named in long-range strategy documents, hydrogen, remains Emerging with no compliance trigger before 2050 and a citation and family-filing window markedly shorter than the other three. On preliminary evidence, training institutions have a stronger near-term case for compliance-monitoring and wind-assisted-propulsion competencies than the volume of hydrogen-focused commentary in the sector would suggest.

6. Discussion

The corpus's most compressed case, Boil-Off Gas Management and Reliquefaction, is instructive here even though it does not appear in Table 1. This cluster moved from near-absent to 86.4% of its estimated carrying capacity in under five years, tracking the delivery of LNG vessels ordered from 2018. A dedicated STCW-aligned course, on the evidence of Inal et al.'s (2021) 14-week hybrid-propulsion programme, is itself a project of months once development starts, before accreditation and rollout are added. A technology cluster that can move from near-absent to near-saturated inside a five-year window can therefore complete its entire commercial emergence before a training institution that waits for an unambiguous market signal has finished designing the course. This is the practical argument for reading lifecycle stage, patent quality, and regulatory status together, now, rather than waiting for any single signal to become unambiguous on its own.

The wider pattern also has a resourcing implication. Regulatory strategy documents and industry commentary disproportionately foreground hydrogen and, more broadly, alternative fuels; the corpus shows Alternative Fuels and Energy Efficiency together accounting for the large majority of classified commercial activity, with hydrogen a small fraction of it. A training institution allocating scarce curriculum-development capacity by regulatory or media salience alone risks the first

failure mode described in Section 3: building capacity around a technology that is not yet commercially converging, while under-resourcing compliance-monitoring and wind-assist competencies that are both mandated now and moving quickly through their lifecycle.

Three considerations qualify these findings. First, the CRS reported here uses equal weighting across its four component indicators; alternative weighting schemes may shift borderline clusters between tiers, and sensitivity testing across the full cluster set is reserved for future work. Second, the analysis draws on a single patent database, Lens.org; coverage gaps in specific jurisdictions could affect cluster-level estimates unevenly. Third, patent activity remains a leading but imperfect proxy for commercial deployment, and the prioritisation output should inform, rather than replace, direct consultation with training providers and flag states.

7. Conclusions

This paper proposes a training-relevant prioritisation framework for maritime decarbonisation technologies, combining lifecycle stage, a new patent-quality-based Commercial Readiness Signal, and regulatory status. Applied to four illustrative clusters, the preliminary evidence indicates that carbon intensity monitoring, wind-assisted propulsion, and LNG and methanol dual-fuel systems already combine credible commercial momentum with compliance instruments in force, supporting an Immediate Priority classification, while hydrogen propulsion, despite its prominence in long-range strategy, remains at an early lifecycle stage with no current compliance trigger and a short citation and family-filing window, and is better classified as Strategic Preparation. The broader corpus shows that most technology clusters, 14 of 22, remain Emerging, underlining that the maritime decarbonisation technology space is still resolving even as training decisions cannot wait for that resolution.

The framework is intended as a planning instrument for training institutions, flag states, and the IMO's Human Element and Training Sub-Committee: it does not prescribe training content, but identifies where patent evidence and regulatory mandate currently align, and therefore where planning should begin. It is transparent, reproducible, and updatable as new patent data becomes available. The next step is to complete CRS quantification across the full cluster set and test the resulting prioritisation matrix directly against training providers' own capacity-planning timelines.

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A FRAMEWORK FOR ANTIBIOTIC RESISTANCE-FREE SEAFOOD SUPPLY CHAIN: AN ANALYSIS OF SHRIMP SUPPLY CHAIN IN BANGLADESH

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Purpose

Seafood supply chains, particularly those involving shrimp, are increasingly recognised as important contributors to antimicrobial resistance (AMR) in Bangladesh. However, limited research has examined how supply chain actors, their interactions, and stage-specific operational practices shape antimicrobial use and its associated impacts. This study addresses this gap.

Research approach

Sixty-two peer-reviewed use cases were analysed to examine supply chain actors, antimicrobial use practices, and related AMR contamination risks. An antibiotic resistance-free shrimp supply chain framework was developed and subsequently refined through inputs from academic and industry experts.

Findings and originality

The findings show that antibiotics are widely used across broodstock, hatchery, and grow-out operations to enhance breeding, improve larval survival, promote growth, and prevent disease. Inappropriate use includes administration without diagnosis or authorisation, and the use of banned or critically important antibiotics such as nitrofurans. These practices increase AMR contamination risks across aquatic environments and downstream food chains. Up to 95% of administered antibiotics may enter the environment through untreated, often un-metabolised effluents, while horizontal gene transfer further accelerates resistance spread. The study proposes evidence-based prescribing, improved diagnostics, digital traceability through IoT, blockchain and digital product passports, wider use of probiotics and vaccines, stronger product stewardship, PBT monitoring, and greater AMR awareness across supply chain actors.

Research impact

The study advances understanding of how AMR contamination risks spread across seafood supply chain stages, how stakeholder behaviour influences these risks, and which interventions may mitigate them.

Practical impact

The findings can help shrimp producers, exporters, and aquaculture professionals manage AMR-related economic and environmental risks. Shrimp aquaculture professionals can also benchmark their processes against those in the proposed framework to identify gaps in resources, capabilities and controls.

Keywords

Antimicrobial Resistance, Antimicrobial Usage Practices, Shrimp Supply Chain.

Introduction

Antimicrobial resistance (AMR) is a major public health, environmental, and economic challenge that reduces antibiotic effectiveness, increases treatment failures and healthcare costs, and threatens food security and ecosystems (Salam et al., 2023). Aquaculture systems, including shrimp farming, are increasingly recognised as important contributors to the emergence and spread of AMR (Almansour et al., 2023). As shrimp production has intensified, antibiotic use has become more widespread across hatcheries and other production stages, often with limited diagnostic, professional, and regulatory oversight (Devadas et al., 2024b).

Bangladesh's shrimp supply chain involves several actors whose practices collectively shape AMR risks (Alam, 2024b). However, existing studies mainly examine antibiotic residues, resistant bacteria, and antimicrobial resistance genes at individual production stages, providing limited insight into how stakeholder behaviour, governance, waste management, and contamination pathways interact across the wider shrimp supply chain. This study addresses this gap by identifying critical risk points and developing evidence-based operational and policy recommendations for an AMR-free shrimp supply chain. By integrating supply chain management, environmental risk analysis, and aquaculture governance, the study aims to strengthen antimicrobial stewardship, biosecurity, traceability, environmental monitoring, and sustainable shrimp production in Bangladesh and other aquaculture-dependent economies.

Literature Review

Antimicrobial use in shrimp aquaculture

Diseases including vibriosis and other bacterial infections cause significant economic loss in shrimp farming in many developing countries, and consequently a variety of antibiotics such as oxytetracycline, erythromycin, ciprofloxacin, amoxicillin, chloramphenicol and nitrofurans are widely used (Devadas et al., 2024a) across multiple stages including hatchery operation, larval rearing, nursery management, grow-out farming, and post-harvest handling and transportation (Chowdhury et al., 2022). While the exact antibiotics used could differ across production systems and regulatory environments (Devadas et al., 2024b), some are either banned or tightly regulated in international food trade because of concerns about residues and AMR (Zhao et al., 2021).

The use of antibiotics is driven not only by disease outbreaks but also by uncertainty about disease causes, poor water quality, inadequate biosecurity, limited access to aquatic-animal health expertise, and pressure to maintain productivity (Chowdhury et al., 2022). In many low- and middle-income countries, antimicrobials can be obtained from feed and drug sellers without prescriptions, laboratory diagnosis, or professional oversight. This may encourage antibiotic use without diagnostic confirmation, inappropriate dosing, excessive use, and the substitution of antibiotics for improved husbandry and preventive disease management. Similar patterns have been reported across wider food systems, where limited knowledge, weak management, and poorly regulated access to antimicrobials contribute to inappropriate use and promote the emergence of resistant microorganisms (Samtiya et al., 2022).

These challenges are particularly evident in Bangladesh, where shrimp aquaculture is an important source of rural livelihoods and export earnings but is constrained by frequent disease outbreaks, inadequate biosecurity, and inadequate access to specialised aquatic-animal health services (Alam, 2024a). Antibiotics are therefore used prophylactically or therapeutically without diagnostic confirmation, adequate record-keeping, or consistent professional supervision (Chowdhury et al., 2022). Such practices can promote the emergence of resistant bacteria within production systems while also creating pathways through which antimicrobial residues and resistance determinants enter the wider environment and supply chain.

Environmental pathways of AMR emergence in aquaculture systems

AMR in shrimp aquaculture cannot be understood solely at the farm level because production systems are closely connected to surrounding environments through water exchange, pond drainage, sediment movement, effluent discharge, and the handling of feed, sludge, and stock (Reverter et al., 2020). Antibiotics that are not fully metabolised may enter pond water, sediments, or sludge, where they can persist and exert selective pressure on environmental microbial communities (Zhao et al., 2021). Routine practices such as water exchange, drainage, and sediment removal may then transport antibiotic residues, resistant bacteria, and antimicrobial resistance genes (ARGs) beyond farm boundaries.

Once released, these contaminants may alter microbial communities and support the persistence and spread of resistant strains and antimicrobial resistance genes (ARGs) in receiving waters and sediments (Sabri et al., 2020). Horizontal gene transfer further amplifies this process by enabling resistance genes to move between bacterial populations through plasmids, transposons, and other mobile genetic elements (Ifedinezi et al., 2024). Water, sediment, sludge, feed-related materials, and biological waste can therefore function as reservoirs and transmission interfaces linking aquaculture, food, human, animal, and environmental systems.

These pathways are especially important in coastal shrimp-farming regions, where shrimp ponds are often located near rivers, canals, estuaries, and mangrove ecosystems and can be direct or indirect recipients of farm effluents. Untreated wastewater, medicated pond water, and poorly managed sludge in such settings may carry AMR-related contaminants into natural environments and neighbouring food-production areas (Thornber et al., 2022). The resulting risks may extend beyond aquatic ecosystems, increasing human exposure to resistant bacteria through contaminated seafood, water, and other environmental pathways. The central concern is therefore not antimicrobial use alone, but how disease, water, waste, and production systems are managed within ecologically connected environments.

Shrimp supply chains as pathways of AMR risk transmission

Aquaculture AMR research has largely focused on farms, hatcheries, and specific microbial hazards, but shrimp production operates through a wider supply chain in which multiple actors influence antimicrobial use, disease management, product handling, and environmental risk. A supply-chain perspective is therefore needed to understand where AMR risks originate, how they move between stages, and where they may be amplified or controlled.

Bangladesh's shrimp supply chain includes hatchery operators, nursery owners, grow-out farmers, feed and drug sellers, transporters, intermediaries such as farias and aratdar, processors, wholesalers, exporters, and retailers (Alam, 2024b). Their roles create different points of AMR risk. Hatcheries and nurseries influence seed quality and early disease management; farmers determine antibiotic use, water exchange, sludge disposal, and harvest timing; and feed and drug sellers shape access to and selection of antimicrobials, particularly where veterinary oversight is limited. Processors, wholesalers, and exporters influence post-harvest hygiene, traceability, and compliance with market standards. Across these stages, resistant bacteria, antimicrobial residues, and inappropriate practices may be introduced, transferred, or amplified. Farm-level analysis alone is therefore insufficient because AMR risks are shaped by interacting biological, environmental, social, and commercial factors. These risks may travel through seed sourcing, input supply, product handling, knowledge flows, incentives, and accountability across the chain (Love et al., 2021). This is particularly important in Bangladesh, where formal and informal relationships coexist and traceability, record-keeping, and regulatory enforcement vary across actors and regions (Alam, 2024b). Such fragmentation makes it difficult to determine where antibiotics were used, whether withdrawal periods were observed, how wastes were managed, and whether residues or resistant bacteria entered later stages. These uncertainties weaken food safety assurance, environmental management, export credibility, and the ability of regulators and industry to target effective antimicrobial stewardship interventions.

Governance gaps and the need for an AMR-free shrimp supply chain framework

While concern about AMR in aquaculture is growing, the evidence base is patchy. A lot of work has been done on antimicrobial residues, resistant bacteria and ARGs in aquaculture environments and antimicrobial resistant organisms in shrimp and shrimp farming systems (Khan et al., 2022a). These studies are valuable in that they demonstrate that AMR-related hazards exist and are potentially important. However, they tend to be limited to singular samples, particular bacterial taxa or specific stages of production. As a result, they do not always describe how decisions are made about antimicrobial use across the wider supply chain, how operational behaviours influence the risk of AMR, or where interventions might be most effective. This is a major limitation for policy and practice. If the risk of AMR is driven by several actors, repeated antimicrobial exposure, environmental release, and low coordination along the chain, microbiological detection alone cannot provide a sufficient basis for management. What is needed is a framework that links antimicrobial use practices with supply chain behaviour, environmental contamination routes and governance capacity. Such a framework could identify priority points for stewardship and monitoring and clarify responsibility distribution across the chain.

Current regulatory frameworks for aquaculture production focus primarily on food safety, export compliance, and product testing, rather than a comprehensive approach to AMR risk governance (Thornber et al., 2020). Although these are important steps, they may be insufficient to tackle the root causes of resistance, such as uncontrolled access to

antimicrobials, limited diagnostic capacity, poor waste management and inconsistent biosecurity practices at the farm level. Recent assessments have underlined that effective AMR mitigation in food systems require a combination of stewardship, surveillance, environmental controls, traceability and cross-sector governance, and not isolated technical solutions (Samtiya et al., 2022). This need is particularly acute in Bangladesh, where the shrimp sector is economically important, environmentally sensitive, export-oriented, and characterised by diverse actors operating under varying levels of knowledge, oversight, and commercial pressure. An AMR-free shrimp supply chain framework can organise evidence around actionable intervention points by linking antimicrobial use, contamination pathways, stakeholder roles, and governance measures. It can therefore shift the focus from merely documenting AMR to identifying how risks can be reduced across the entire supply chain.

Methodology

This study adopted a qualitative exploratory research design involving two sequential stages. In the first stage, peer-reviewed journal articles related to antimicrobial use in aquaculture, shrimp farming practices, AMR transmission pathways, environmental contamination, and seafood supply chain governance were systematically searched using major academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Following screening and eligibility assessment, a total of 62 peer-reviewed studies were selected and each of them was analysed as single use case. The findings were synthesised into a preliminary framework characterising the relationships among supply chain actors, antimicrobial practices, and AMR contamination risks. To strengthen the robustness and practical relevance of the proposed framework, an expert evaluation was conducted with specialists from academia and the seafood industry.

Findings and Discussion

The integrated conceptual framework for AMR management in shrimp supply chains developed from the analysis is presented in Figure 1.

AMU drivers

As shown in Figure 1, the main drivers of antimicrobial use (AMU) include high mortality during the early larval stage, disease outbreaks, limited access to diagnostic facilities, informal advice of AMU given by the feed and drug dealers, financial dependence (debt/loan) of marginal farmers on intermediaries, and regulatory gaps and weak enforcement (Khan et al., 2022b; Bell et al., 2023; Hinchliffe et al., 2021). One of the use cases highlighted the lack of appropriate diagnostic facility leaving no choice for the farmers except to administer antibiotics blindly, thereby increasing AMR risks (Khan et al., 2022b). Also, the fact that more than half the farmers rely on informal and often inappropriate advice from feed and drug dealers when using antibiotics (Chowdhury et al., 2022). This risk is compounded by informal credit arrangements between marginal farmers and intermediaries. Under pressure to protect harvests and repay loans, these farmers resort to low-cost antibiotics recommended by unregulated sellers, even when their use is inappropriate (Alam and Pokrant, 2009).

AMU Practices

The review found that antibiotics are often used prophylactically rather than in response to confirmed clinical need, particularly during the sourcing phase (early broodstock and hatchery operations) (Devadas et al., 2024a). This pattern is also evident in other contexts: for example, 86% of antibiotic users in Thailand reportedly used them for preventive purposes (Hinchliffe et al., 2021). Antibiotics are also administered through medicated feed, sometimes without farmers' full awareness (Hirshfeld et al., 2023). Other concerning practices include the use of antibiotics for growth promotion, and the use of banned antibiotics because of their lower cost, both of which increase AMR risks (Akter et al., 2025). Overall, use of antibiotics appears to be widespread, with 71–77% of farmers reporting their use at least once during a production cycle (Bell et al., 2023).

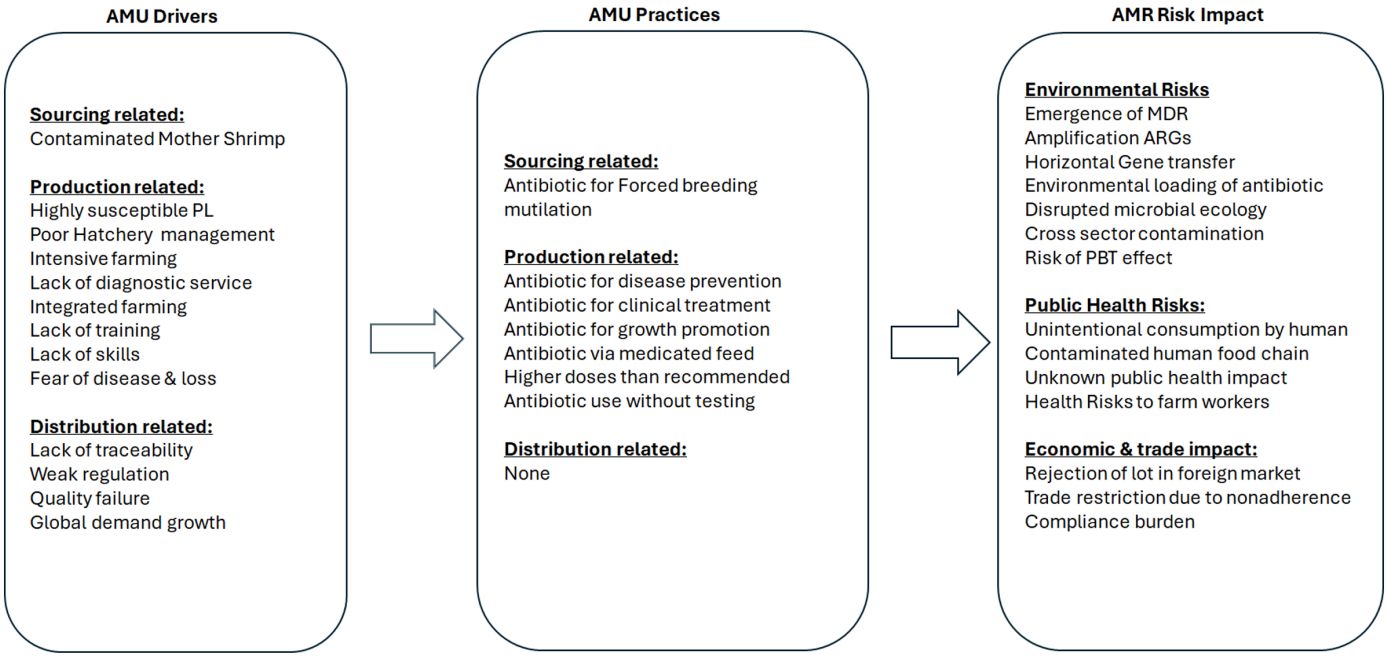

Figure 1. A framework for AMR free seafood (shrimp) supply chain.

AMR Risk Impact: As illustrated in Figure 2, AMR risks emerge across all major supply chain stages and affect human, animal, and environmental health. Although the production stage (grow-out ponds) represents a major point of exposure, the second stage (broodstock and early post-larval) are also critical because resistance may emerge and spread from these stages into later production and distribution activities (Eleonor and Leobert, 2001). This includes the transmission of specific resistance determinants, such as tetracycline resistance genes.

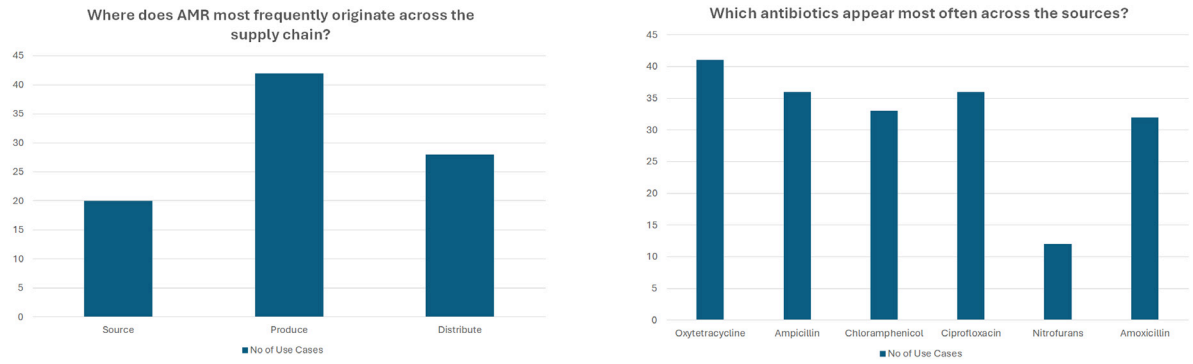

Figure 2: AMR Origins Across the Shrimp Supply Chain and Frequently Reported Antibiotics

Un-metabolised antibiotics released through pond discharge and surface runoff may persist in the environment, bioaccumulate, exert toxic effects, and disrupt local ecosystems before entering water and food systems (Deepti et al., 2026). This creates potential routes of human exposure through contaminated water and food, although the long-term health effects remain uncertain (Seong et al., 2021). The risks may be particularly severe for rural communities in Bangladesh that reuse river and canal water for domestic activities and crop irrigation (Kawsar, 2026). The use cases also indicate that domestic consumers may face increased AMR exposure when shrimp consignments rejected for export because of quality or safety concerns are redirected to local wet markets (Rheman et al., 2026). Finally, the cross-case analysis indicates that horizontal gene transfer (HGT) may represent a more significant mechanism of AMR dissemination across the supply chain than vertical gene transfer (VGT).

AMR mitigation: Key mitigation measures include biological alternatives such as probiotics and prebiotics; stronger antimicrobial stewardship through prescription controls, enforcement of withdrawal periods, and evidence-based prescribing; wider access to rapid diagnostics, including portable PCR kits; and improved supply chain traceability using blockchain, IoT, and digital product passports. Financial and educational support for marginal farmers and smallholders is also important because of their role in managing upstream risks. These measures should be evaluated through a One Health perspective that considers human, animal, and environmental impacts (Orubu et al., 2021; Akter et al., 2025). Implementation, however, remains challenging. Probiotic products may be difficult to assess because of inconsistent labelling and the possibility that they carry antimicrobial resistance genes (Hirshfeld et al., 2023). Enforcing prescription-only sales across a large and weakly regulated retail network, including an estimated 200,000 medicine outlets in Bangladesh, would also be operationally demanding (Orubu et al., 2021). Similarly, although laboratory testing of antibiotic residues could provide timely warnings, it requires substantial diagnostic infrastructure and resources (Beshiru et al., 2026).

Conclusion

This study develops a framework that enables practitioners, policymakers, and researchers to assess how antimicrobial use (AMU) practices influence AMR pathways and their human, animal, environmental, and economic impacts. It highlights the roles of key supply chain actors, including hatchery and nursery operators, farmers, intermediaries, wholesalers, processors, and exporters. The framework could support tailored information packs or guidance cards explaining the drivers of AMU, the emergence and spread of AMR, and the associated health, environmental, and economic consequences. It could also inform actor-specific AMR toolkits or checklists, allowing organisations to benchmark their practices and pursue continuous improvement through the Plan–Do–Check–Act cycle. For policymakers and regulators, the framework provides a basis for identifying priority intervention points, strengthening oversight, and clarifying responsibilities across production areas. This may include assessing the need for designated aquaculture prescribers, tighter control of antimicrobial sales, improved diagnostic support, and stronger integration of shrimp farming within a One Health governance framework.

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THE ROLE OF SUPPLY CHAIN MAPPING IN MEASURING AND MITIGATING UPSTREAM SCOPE 3 EMISSIONS IN THE AUTOMOTIVE INDUSTRY

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Abstract

Purpose: Upstream Scope 3 emissions make up a large part of the automotive industry's carbon footprint. Nevertheless, they remain challenging to manage since firms lack clear visibility throughout their supply chains and usually rely on limited data. This paper explores how automotive manufacturers measure and reduce emissions and how supply chain mapping can bridge the gap between measurement and action.

Research Approach: This paper uses both qualitative and quantitative data derived from publicly available ESG, sustainability, and annual reports of fifteen global automotive companies published in 2024 and 2025. The analysis is structured around three themes: (i) how companies measure their emissions, (ii) the level of visibility across their supply chain, and (iii) what are the relevant mitigation actions.

Findings and Originality: Findings indicate a clear discrepancy between measurement and action in efforts to mitigate upstream scope 3 emissions. Most companies report scope 3 emissions more transparently, yet they are finding it hard to transition from measurement to action. The supply chain mapping and data systems are not usually well understood and robust enough to facilitate data-driven decisions. An imbalance among measurement, visibility, and mitigation is observed, and this study highlights supply chain mapping as the key link that connects reporting and measurement to meaningful decarbonisation.

Research Impact: This study advances understanding of how upstream scope 3 emissions can be managed more effectively within complex supply chains, integrating measurement, visibility, and mitigation into a cohesive framework.

Practical Impact: The research suggests that automotive companies should develop more granular supplier data, improve multi-tier visibility, and apply supply chain mapping more systematically to support informed emission reduction decisions.

Keywords: Scope 3 emissions; Supply chain mapping; Automotive industry; Sustainability; ESG; Decarbonisation, OEM

1. Introduction

The automotive industry faces mounting pressure to reduce its Greenhouse Gas (GHG) emissions in line with global climate targets. While manufacturers have made measurable progress in cutting emissions from their own operations, a substantial portion of their carbon footprint lies beyond their direct control. These indirect emissions, known as Scope 3 emissions, are generated throughout the value chain and present a fundamentally different management challenge to Scope 1 and 2 emissions (GHG Protocol, 2011). In the automotive sector, upstream activities (including raw material extraction, component manufacturing, and inbound logistics) account for a disproportionately large share of total GHG emissions (Hettler and Graf-Vlachy, 2024). The urgency of addressing these emissions has been amplified by tightening regulatory requirements: the EU's Corporate Sustainability Reporting Directive (CSRD), which began applying to large companies from 2024, now mandates disclosure of Scope 3 emissions for in-scope firms, signalling a decisive shift from voluntary to obligatory reporting (Hettler et al., 2024).

Companies participating in leading carbon disclosure frameworks report upstream Scope 3 emissions averaging 26 times higher than their combined Scope 1 and 2 emissions (Wieland, 2025; CDP, 2024). This disproportion is particularly pronounced in the automotive sector, where manufacturers depend on an extensive, multi-tiered supplier base. The literature indicates that purchased goods and services are one of the highest contributors of emissions of automotive Original Equipment Manufacturers (OEMs), making suppliers an essential component of the decarbonisation process (Poligkeit et al., 2023). Although Scope 3 reporting is gaining attention in corporate reporting, it is still challenging to measure and manage upstream emissions. Automotive supply chains are generally multi-tiered, spanning several countries. As a consequence, many companies

still have information access only up to their first-tier suppliers and rely on estimates and secondary data to compute emissions inventories (Vieira et al., 2024). This means that it is challenging to identify emission hotspots and prioritise their reduction upstream. In recent years, many automotive companies have enhanced their sustainability and ESG reporting. But reporting emissions does not always result in effective emissions reduction. While companies can measure emissions upstream, it is often difficult to translate that data into meaningful action due to a lack of visibility across their supplier networks (Vieira et al., 2024). Additionally, research has emphasised the need for practical tools and implementable approaches that can enhance emissions measurement and mitigation in complex automotive supply chains (Wang et al., 2024).

A possible solution to this challenge is supply chain mapping. It can help organisations to see further upstream in their supplier chain, improve data collection and facilitate targeted mitigation measures. Thus, this paper aims to explore how upstream Scope 3 emissions can be measured and mitigated in the automotive industry with supply chain mapping. The study, based on publicly available ESG, sustainability, and annual reports of 15 global automotive companies, looks at emissions measurement, supply chain visibility, and mitigation practices. The aim is to examine whether supply chain mapping can serve as the link between emissions reporting and action for decarbonisation.

2. Literature Review

2.1 Supply Chain Mapping and Multi-Tier Visibility

Automotive supply chains are extensive, multi-tiered networks of suppliers spanning multiple countries and industries. Manufacturers typically know Tier 1 suppliers but have less visibility into Tier 2 suppliers. The lack of visibility can make it hard to understand supplier activity, manage risks and have a clear view of the broader supply chain (Fraser et al., 2020). The scale of this challenge is considerable: while 95% of companies report visibility into their Tier 1 suppliers, that visibility extends to Tier 2 or beyond for only 42% of organisations, with Tier 3 remaining largely opaque for most (EcoVadis, 2025).

To tackle this challenge, supply chain mapping has been identified as a key tool to enhance visibility. MacCarthy et al (2022) state that mapping can be used to gain an understanding of the relationship of the various parts of the supply chain, the material flows, and the general structure of the supply chain in the organisation. Mapping enables organisations to look beyond their direct suppliers and to gain an understanding of how suppliers are linked. This is particularly important since transparency is one of the main requirements of managing complex multi-tier supply chains (Fraser et al., 2020).

The need for visibility becomes even more important when organisations try to reduce carbon emissions. Yang et al. (2025) report that over 70% of emissions from most industries take place upstream within long supply chains. They also highlight that organisations aiming for net-zero targets are likely to need more visibility into Tier 1 and Tier 2 suppliers. Companies must be more aware of the deeper tiers of their supply chains in order to effectively manage Scope 3 emissions. Taken together, these studies suggest that supply chain mapping is more than an operational tracking tool, but it is a foundational capability for gaining the upstream visibility that effective Scope 3 emissions management requires.

2.2 Supply Chain Mapping and Scope 3 Measurement

For most organisations, the problem lies in the fact that most emissions in their Scope 3 are not directly generated by the company, making it difficult to measure them. Organizations need to know and be aware of their direct and indirect emissions throughout their supply chains to make effective carbon management decisions. Lee (2011) suggests that upstream/downstream indirect emissions are significant contributors to the carbon footprint assessment and should be taken into account for carbon performance management. But it is hard to get reliable emissions data because a lot of the data that is needed is beyond the control of a company.

Limited data availability and reporting quality exacerbate these measurement challenges. Many organisations continue to use industry averages and estimation methods, as it is not always possible to have primary supplier emissions data (Stenzel and Waichman, 2023). These methods of emissions reporting should not necessarily be representative of emissions produced throughout supply chains. Likewise, Klaaßen and Stoll (2021) point to consistency of reporting, completeness of boundaries and exclusion of activities as key reporting shortcomings in Scope 3 reporting. All of these can diminish the accuracy, comprehensiveness and comparability of emissions data.

The literature indicates that the right emissions measurement of the Scope 3 stage relies on knowledge of the position and location of the emissions along the supply chain as well as the calculation of the emissions. As illustrated in the literature, data availability and reporting obstacles point to the need for greater visibility throughout supply chain activities. To respond to this requirement, Lee (2011) points to the benefits of creating carbon process maps to identify the sources of emissions by the various stages of the supply chain and to measure carbon footprints. Therefore, supply chain mapping can help organisations to measure Scope 3 emissions by providing better visibility of the emissions sources, a better way to collect emissions data, and aid in the identification of upstream emission hotspots.

2.3 Supply Chain Mapping and Scope 3 Mitigation

Measurement is just the beginning of addressing upstream Scope 3 challenges. It is important for companies to also determine where the biggest emissions are taking place and to seek out practical methods for cutting them down. Emissions from purchased materials, supplier activities, and manufacturing processes account for a significant portion of emissions in the automotive sector. So, mitigating Scope 3 emissions is highly dependent on actions taken by the wider supply chain.

Research suggests that identifying emission hotspots is an important part of reducing supply chain emissions. Poschmann et al. (2023) identify battery cells, steel, and aluminium as major sources of upstream emissions in battery electric vehicle supply chains. This indicates that these are the materials and components that can deliver high emissions reductions for companies as they work towards decarbonisation.

But just finding the emission hotspots is not sufficient. Another thing that companies must do is to collaborate with their suppliers throughout the supply chain. The lack of visibility beyond Tier 1 suppliers makes sustainability management more complex as the lack of information about lower-tier suppliers is a challenge for firms, according to Adhikary et al. (2020). Similarly, Borchardt et al. (2025) have noted that stakeholder engagement is one of the key challenges in the management of Scope 3, as cooperation is limited to just one or two tiers of the supply chain. Another challenge that Wang et al. (2024) point to is the lack of emissions data and the inability to effectively manage Scope 3 emissions throughout supply chains.

These studies indicate that both visibility and collaboration are important to effective mitigation. Supply chain mapping can help companies identify emission hotspots and understand their supplier networks, which can help them to implement more effective mitigation measures in their supply chains.

2.4 Research Gap

While the literature addresses supply chain visibility, Scope 3 measurement, and emissions mitigation as individual topics, these areas are rarely examined together within a single integrated framework. Studies on supply chain mapping tend to focus on structural visibility without connecting this to emissions quantification, while research on Scope 3 measurement often treats data quality as a technical problem in isolation from the supply chain governance structures that generate it. Mitigation studies, meanwhile, frequently identify emission hotspots and recommend supplier engagement without addressing the visibility and data infrastructure required to act on those recommendations. This fragmentation is particularly consequential in the automotive sector, where the scale, geographic spread, and multi-tier complexity of supply chains make the interdependence of visibility, measurement, and mitigation especially pronounced. This study therefore, addresses this gap by examining how supply chain mapping can serve as the connecting mechanism across all three dimensions, enabling automotive OEMs to move from emissions reporting to informed decarbonisation action.

3. Methodology

The document-based comparative method is used in this study. It is based on publicly available annual, sustainability, ESG and climate-related reports published by 15 global automotive OEMs in 2024 or 2025. Document-based analysis of corporate sustainability reports is a method that has been used in similar OEM decarbonisation and Scope 3 management studies (Poligkeit et al., 2023; Vieira et al., 2024). The 15 companies were chosen based on geographic diversity and the availability of detailed enough reports. Evidence was limited to information that was clearly conveyed in the reports. Information that was not clearly identified in the reports was coded as "not evidenced" instead of as evidence of no action. This is because the study is based on reporting evidence that is disclosed, and not on internal company practices, which may not be reported.

Three matrices were used for the qualitative analysis. In matrix 1, scope 3 measurement approaches were compared to evidence of supply chain mapping. In Matrix 2, the mapping depth was compared to mitigation framing. In Matrix 3, the main reporting focus was compared to the value-chain focus. The following matrices were used to determine if OEMs linked emissions measurement, supplier visibility and upstream mitigation in their reporting.

The quantitative analysis evaluated each OEM on three components: T1 measurement and disclosure, T2 supply chain mapping and data infrastructure and T3 upstream mitigation action. T1 evaluated if each OEM reported their total Scope 3 emissions, if they purchased goods/services (category 1) and if they provided category-level or method-level information. Category level information refers to emissions being broken down into the categories of Scope 3. Method-level information refers to the information that provides an explanation of how emissions were calculated.

T2 evaluated evidence of supplier engagement, key material focus and data infrastructure. This included Life Cycle Assessment (LCA), the International Material Data System (IMDS), supplier-level data or parts-level data. LCA is the assessment of environmental impacts that are analysed throughout the life cycle of a product. IMDS stands for the automotive industry database for the collection of material and parts information from suppliers. The evidence of upstream mitigation action was assessed by T3. These encompassed supplier decarbonisation initiatives, low-carbon material strategies and specific upstream reduction initiatives. Supplier decarbonisation programmes are activities that help suppliers to reduce emissions. Low-carbon material strategies are based on the use or development of lower-emission materials such as low-carbon steel, recycled aluminium or lower-carbon battery materials. Specific upstream reduction actions are specific actions which are connected with suppliers, materials or upstream production.

There were three binary variables for each dimension. A score of 1 was awarded if there was clear evidence of it in the report, and a score of 0 if there was no clear evidence of it in the report. General narrative statements (not supported with numerical data, system-level evidence or operational action) were coded as 0. So each dimension was rated on a scale of 0-3. The overall maturity score was calculated by summing the scores for T1, T2 and T3 and was between 0 and 9.

Company	Geography	Business focus	Report used in this study
Toyota Motor Corporation	Japan / Asia-Pacific	Passenger and commercial vehicles	Toyota Integrated Report 2024
Volkswagen Group	Germany / Europe	Passenger and commercial vehicles, mobility and e-mobility	Volkswagen ESRS Sustainability Report 2024
Hyundai Motor Company	South Korea / Asia-Pacific	Passenger vehicles, trucks, buses, EVs and hydrogen vehicles	Hyundai Motor Company Sustainability Report 2025
Stellantis N.V.	Netherlands / Europe	Passenger vehicles, commercial vehicles	Stellantis Expanded Sustainability Statement 2024
General Motors Company	USA / North America	Passenger vehicles, trucks, SUVs and EVs	GM 2024 TCFD Report
Ford Motor Company	USA / North America	Passenger vehicles, trucks, vans, commercial vehicles and EVs	Ford 2025 Integrated Sustainability and Financial Report
Honda Motor Co., Ltd.	Japan / Asia-Pacific	Automobiles, motorcycles and power products	Honda Sustainability Report 2025
Nissan Motor Co., Ltd.	Japan / Asia-Pacific	Passenger and light commercial vehicles, EVs and e-POWER hybrids	Nissan Sustainability Data Book 2024
BYD Company Limited	China / Asia-Pacific	New energy vehicles, batteries and commercial vehicles	BYD Annual / ESG Report 2024
BMW Group	Germany / Europe	Premium cars, motorcycles and mobility services	BMW ESG Overview FY 2024
Mercedes-Benz Group AG	Germany / Europe	High-end passenger cars, premium vans and financial services	Mercedes-Benz Annual Report 2024
Tesla, Inc.	USA / North America	Battery-electric vehicles, energy generation and storage	Tesla Impact Report 2024
Jaguar Land Rover Automotive PLC	United Kingdom / Europe	Luxury and premium vehicles	JLR Annual Report 2025
Volvo Group	Sweden / Europe	Trucks, buses, construction equipment and industrial engines	Volvo Group Annual Report 2024
Renault Trucks	France / Europe	Trucks and transport solutions	Renault Trucks CSR / Sustainability Report 2024

Table 1. Study the sample profile of the 15 automotive OEMs (Prepared by the author using the 15 company reports included in the study.)

Note: Size categories are used descriptively to show sample diversity rather than as exact production rankings. Renault Trucks is treated as a brand-level case because it is part of the Volvo Group but provides separate sustainability reporting and a commercial vehicle focus.

4. Findings

The results are presented in the three areas analysed: emissions measurement, visibility in the supply chain, and mitigation actions. These regions are related to the three scoring dimensions. T1 presents examples of how companies measure and report upstream Scope 3 emissions. T2 indicates the evidence of supply chain visibility and mapping. The amount of upstream mitigation action is indicated on T3. The results for these three dimensions are combined in Figure 1.

4.1 Emissions Measurement

The first result is that the measurement of emissions is the most mature part of the sample. Most of the OEMs selected have some evidence of Scope 3 measurement and disclosure. This comprises the total Scope 3 emissions, category 1 purchased goods and services, and category-level or method-level information. But not all of this evidence is of the same quality in the reports. Some OEMs offer more detailed information at the category level and describe how the measurement was done. Other reports that give only partial or general Scope 3 data. This is an indication that emissions measurement is becoming a more prominent part of automotive reporting, but the level of detail is not uniform.

4.2 Supply Chain Visibility

The second is that supply chain visibility is less advanced than emissions measurement. The T2 results demonstrate that fewer OEMs have strong evidence of supplier engagement, key material focus, traceability, LCA, IMDS, supplier-level data or parts-level data. This indicates that there are some companies reporting emissions, but fewer companies reporting emissions in a way that clearly demonstrates the tracking of emissions through suppliers, materials or data systems. This is relevant since Scope 3 emissions are found throughout a supplier network. The emissions data is less tied to the actual supply chain structure if it is not reported at the supplier level.

4.3 Mitigation Actions

The third finding is that the level of mitigation action taken is also not uniform across the sample upstream. The T3 results indicate that fewer OEMs have clear evidence of supplier decarbonisation programmes, low-carbon material strategies or specific reduction actions in the upstream. These reports provide a more detailed list of actions associated with suppliers, materials or upstream activities. Other reports refer to mitigation in a more general way and are less clear about implementation at the supplier level. This implies that there is not always an obvious link between mitigation and action upstream in the supply chain.

4.4 Summary of Accumulated Results

In general, Figure 1 indicates that the three areas are not equally developed. There is more robust evidence of measurement than evidence of visibility and mitigation. A few OEMs demonstrate improvement in one or two dimensions, with fewer exhibiting strong evidence in all three dimensions. The overall finding is that there is no direct link between emissions disclosure and upstream scope 3 maturity. The stronger the link between emissions measurement and supply chain visibility and targeted mitigation actions, the stronger the maturity seems to be. This illustrates the significance of supply chain mapping. It can bridge between what companies measure and where emissions are generated and what can be done upstream.

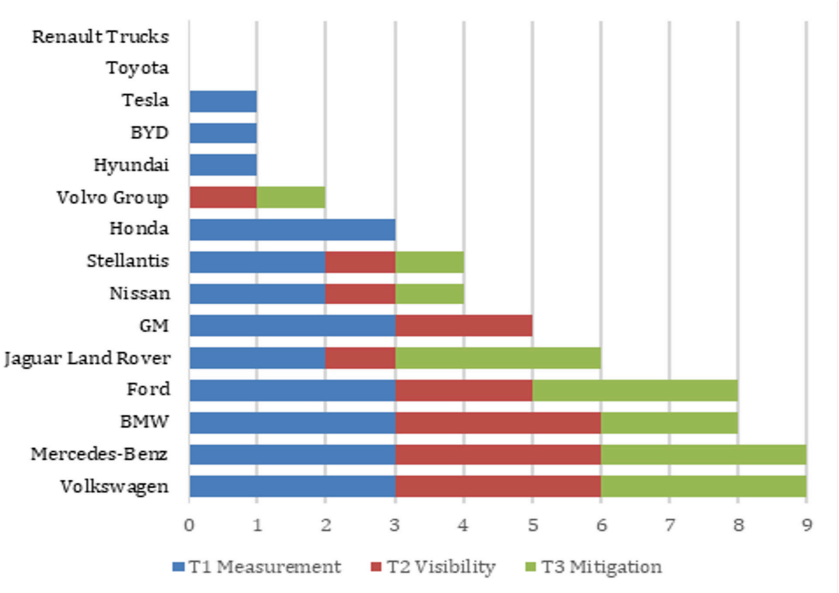

Figure 1: Accumulated findings across three dimensions(Prepared by the author using the scoring results from the 15 company reports included in the study).

5. Discussion

The results indicate that upstream management of Scope 3 is not solely about emissions reporting. As seen in Figure 1, there is a greater amount of development in measurement than in terms of supply chain visibility and mitigation in many OEM reports. This can result in some companies being able to report emissions, but with less evidence of how emissions are tracked through suppliers, materials and data systems.

This illustrates the importance of supply chain mapping. Measurement shows the scale and categories of emissions, while mapping helps identify where those emissions occur in the upstream supply chain. This is important in the automotive industry because upstream emissions are linked to complex supplier networks and high-emission materials.

Overall, the findings indicate that there is a need to link measurement, visibility and mitigation. Greater upstream Scope 3 maturity seems to occur when emissions disclosure is backed up by supplier visibility and targeted emissions reduction measures. This fills the research gap by demonstrating the potential of supply chain mapping as a link between measuring and reducing upstream emissions.

6. Conclusion

This research focused on the role of supply chain mapping in upstream Scope 3 emissions management in the automotive sector. Analysis of 15 OEM reports reveals some mixed progress in public reporting across measurement, supply chain visibility and mitigation. This indicates that Scope 3 management is not just about reporting emissions totals, but also about gaining greater visibility over suppliers and improving data-material-action connections. The study adds value by demonstrating that mapping the supply chain can be useful to link emissions measurement with actionable mitigation efforts upstream. The findings, however, are limited to those publicly reported and do not necessarily represent the actual practice of the company. This study could be expanded by conducting interviews and/or supplier-level data analysis or longitudinal analysis to determine if there are measurable emissions reductions over time as a result of stronger mapping practices.

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MODELLING COLLABORATIVE TRANSITIONS TO GREEN AND SMART PORT INFRASTRUCTURE

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Introduction

The steady rise in global temperatures since the First Industrial Revolution, driven by deforestation and the widespread use of fossil fuels for production, energy, and transportation, has made the transition to a global decarbonised economy increasingly urgent (Kumar et al., 2024). Within this context, the maritime industry holds particular significance. It accounts for 84% of global trade volume by tonnage (Gerrero-Molina et al., 2024) yet faces mounting challenges in maintaining efficient supply chain operations whilst meeting Net Zero goals. (Alzate et al., 2024; Owowo et al., 2024; González-Cancelas et al., 2025a).

Ports occupy a pivotal position in this transition. As central nodes in the maritime supply chain, they are at the forefront of the Fourth Industrial Revolution (I4.0) (Alzate et al., 2024). Recognising the environmental pressures associated with port activity, the United Nations launched the Green Ports Initiative in 2009 at the UN Climate Change Conference in Copenhagen, signalling a global commitment to reducing ports' environmental impacts through innovative decarbonisation strategies (Fei, Shi and Pan, 2025).

Effective cooperation between port authorities, industry partners, local and national government bodies, and technology providers is essential for overcoming implementation challenges and realising the full potential of I4.0 innovations (Liu et al., 2025).

This research paper develops a system dynamics model to examine how collaborative initiatives can accelerate the adoption of I4.0 technologies within ports. The proposed model illustrates how collaborative governance structures and innovation partnerships can strengthen environmental programmes, support the evolution of smart and green ports, and ultimately drive decarbonisation across the maritime supply chain.

Literature Review

Academic literature on smart ports concentrates on their technological development and architectural design. The dominant argument is that ports must adopt emerging technologies like AI, IoT and Cloud Computing to address rising operational demands, improve efficiency, and mitigate environmental impacts (Min, 2022; Alzate et al., 2024; Gerrero-Molina et al., 2024; González-Cancelas et al., 2025a). Within this context, smart ports are positioned as central enablers of the I4.0 transition, functioning as innovation hubs that enhance safety, efficiency, and sustainability across both the maritime and wider logistics sectors (González-Cancelas et al., 2025a).

I4.0 has transformed manufacturing, transportation, and logistics by deploying IoT, cloud computing, big data analytics, cyber physical systems, and AI to streamline processes and enhance decision making (Gerrero-Molina et al., 2024; Kumar et al., 2024; Owowo et al., 2024; González-Cancelas et al., 2025b). These technologies also underpin the transition toward 'sustainable ports', enabling energy efficient and environmentally responsible practices (Su et al., 2024; Fei, Shi and Pan, 2025). As operational efficiency increases, emissions and resource consumption decline correspondingly (Alzate et al., 2024; Fei, Shi and Pan, 2025), while the adoption of green energy technologies further accelerates port decarbonisation (Paulauskas et al., 2024).

Smart port development requires coordinated investment and collaborative governance. Significant capital is needed to support digitalisation (Liu et al., 2025), and fragmented, uncoordinated adoption risks undermining competitiveness (González-Cancelas et al., 2025a).

When looking at multimodal and hinterland transport the literature has focused on the idea of modal shift. Intermodal transport is responsible for the majority of GHG emissions, congestion and traffic accidents (Liu et al., 2021, Guo et al., 2023 and Zgonc and Jakšič, 2025). Roads are the most utilised in hinterland transport and are the least efficient method (Guo et al., 2023). The European Union (EU) have initiated a transport policy which is aimed at shifting road transport to a more efficient and less polluting alternative (Zgonc and Jakšič, 2025). The choice of transport mode is very dependent on the region and the availability of transport options (Liu et al., 2021 and Zgonc and Jakšič, 2025). Policy has been examined as a good way to foster modal shift or the use of multimodal transport to the hinterland (Zgonc and Jakšič, 2025).

The International Maritime Organisation's 2023 GHG strategy pushes global shipping to net zero emissions by 2050, with interim milestones for 2030 and 2040 (IMO, 2023). This, alongside the UN Green Ports Initiative, has prompted governments to align their regulatory frameworks with international decarbonisation goals. The UK's Maritime Decarbonisation Strategy sets a net zero target for 2050 and places responsibility on ports to support alternative energy options for vessels (DfT, 2025). The expansion of the UK Emissions Trading Scheme to include maritime activities from July 2026 further embeds decarbonisation into port operations (UK ETS, 2026). Similarly, the EU's AFIR and FuelEU mandate the provision of onshore power in EU TEN-T ports by 2050 (AFIR, 2023; FuelEU, 2023).

The circular economy (CE) is seen as a productive way to decarbonise and manage resources. This approach in ports involves systems such as waste to energy processes, industrial symbiosis that converts by products into new inputs, and the development of renewable infrastructure. The aim is to reuse, recycle, and remanufacture resources to keep them in circulation for as long as possible (Andriamanantena et al., 2025; Schulz et al., 2025). Successful CE implementation relies heavily on stakeholder collaboration (Andriamanantena et al., 2025), including shared resource networks that enable companies to exchange upcycled materials (Schulz et al., 2025).

Overall, the literature provides extensive insight into how I4.0 technologies enable the evolution of ports into smart and sustainable systems and how these developments contribute to global decarbonisation and more resilient supply chains. However, a critical gap remains focusing on how ports can achieve smart green status. This paper addresses this gap by proposing a system level model that integrates technological, organisational, and governance dimensions of smart green port development.

Methodology

This study conducted a systematic review of academic literature on smart green ports and adopted a system dynamics modelling approach to conceptualise an ideal port system that illustrates the links and interactions between ports and their wider stakeholders.

The scope for literature selection spans 2010–2026. This timeframe was chosen because the Green Port Initiative was formally introduced in 2009, allowing the review to capture the subsequent growth of research on smart and green ports. The selection criteria used to identify relevant literature are presented in Table 1.

Criteria	Reasoning
Literature Type	Literature from good quality journals and academic conferences that peer review articles and papers before publication.
Topic	Focus on green and smart ports development
Impact	Preference given to literature which is highly cited and influential in the academic community

Table 1: Selection criteria for academic literature (Source: Author)

The literature was sourced using several academic databases, including Web of Science and the Compendex and Inspec databases within Elsevier Engineering Information. A set of keywords was used to define the search parameters: "green ports", "smart ports", "collaboration", "cooperation", and "framework". These keywords were also combined in various ways to ensure a comprehensive and inclusive search. After screening the literature in accordance with the criteria outlined in Table 1, the selected publications were imported into NVivo for coding.

NVivo 15 software enabled the literature to be organised into codes, which were then used to identify key themes and topics across the articles, examine how these themes relate to one another, and support the definition of the overall system. This process facilitated the development of two system models: the current system and its operational characteristics, and the proposed system presented in this paper.

The literature selected for this study using the above criteria is presented in Table 2.

Authors	Title
Chandrasekaran, Zakaria and Arof	Challenges Faced by Seaports in Adoption of Industrial Revolution 4.0: A Review
Chen et al.	Constructing Governance Framework of a Green and Smart Port
Chengpeng et al.	A Novel Model for quantitative evaluation of green port development – A case study of major ports in China
Davarzani et al.	Greening ports and maritime logistics: A review
Fei, Shi and Pan	A Systematic Review of Green Port Evaluation: Methods, Subjects, and Indicators
Lam and Li	Green port marketing for sustainable growth and development
Lam and Notteboom	The Greening of Ports: A Comparison of Port Management Tools Used by Leading Ports in Asia and Europe
Le and Nguyen	The Development of Green Ports in Emerging Nations: A Case Study of Vietnam
Liu et al.	Smart ports for sustainable shipping: concept and practices revisited through the case study of China's Tianjin port
Paulauskas, Paulauskas and Markauskas	Port Green Transformation Factors Assessment
Sepehri et al.	Smart, sustainable, and circular port maintenance: A comprehensive framework and multi-stakeholder approach
Su et al.	Critical Success Factors for Green Port Transformation Using Digital Technology
Xu et al.	A systematic review of smart ports in global maritime trade: multi-dimensional evaluation framework and development trend analysis
Zhou, Xu and Wang	How to Complete Supply Chain Integration and Improve Supply Chain Performance Through Relationship Governance in the Digital Age

Table 2: Literature selected for Analysis (Source: Author)

Results

The critical analysis of the selected literature revealed several key factors shaping the system through which ports can progress toward the green port stage. These findings made it possible to model a system that supports the transition to smart green ports through coordinated and collaborative approaches. The proposed system, illustrated in Figure 1, demonstrates how strengthened stakeholder cooperation and shared investment mechanisms can overcome current barriers and enable ports to evolve into fully integrated smart green systems.

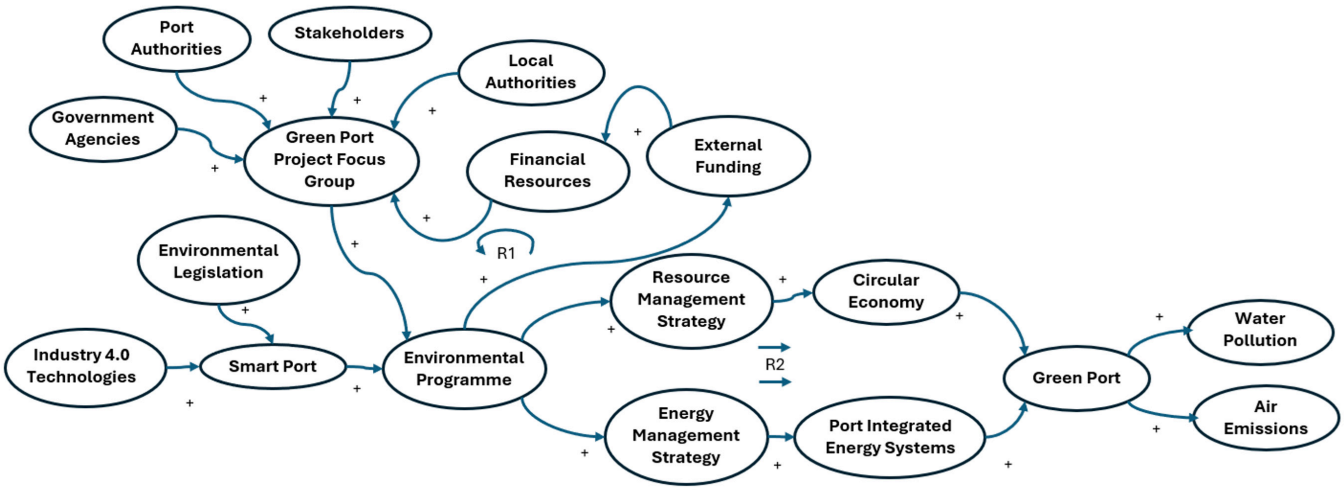

Figure 1: Proposed system on transition to green ports causality diagram. (Source: Author)

The first reinforcing loop (R1) is the key element of this proposed system. Each component of the loop strengthens the others. A robust environmental programme attracts greater external funding which increases available financial resources. This enhances the capacity and output of project focus groups, enabling further improvements to the environmental programme. As a reinforcing loop, R1 can strengthen rapidly when all elements are aligned, but it can also weaken if any single component underperforms.

As R1 strengthens, the environmental programme generates two core strategies: a resource management strategy and an energy management strategy. These strategies converge to support the development of the green port. This forms a second reinforcing loop (R2), which is directly influenced by the strength of R1. When R1 is functioning effectively, the environmental programme becomes more capable of reinforcing green strategies, thereby accelerating progress toward green port status. As the green port system strengthens, it produces measurable environmental benefits, including reductions in water pollution and air emissions.

Discussion

The analysis shows that the green port transition is shaped by a combination of external and internal drivers. Together, these factors determine both the pace and the success of a port's progression toward green port status. To achieve a strong reinforcing system, ports of all sizes must work toward shared infrastructure development. Examples that demonstrate the effectiveness of such collaborative approaches are the MAGPIE project, PIONEERS project and the NatPower Marine–Peel Ports green corridor initiative.

The MAGPIE project in the EU illustrates how a consortium of ports can collaborate to accelerate the transition to greener operations. Funded by the EU since 2021 (CORDIS, 2026), MAGPIE aims to advance the use of alternative energy sources, improve multimodal hinterland connections, and integrate smart technologies into port operations (CORDIS, 2026; Magpie, 2026). The project brings together four ports, three major seaports and one inland port, alongside 32 private companies, nine universities and research institutions, and four additional organisations (CORDIS, 2026; Magpie, 2026). This extensive collaborative network mirrors the focus groups in the proposed system, spanning the Netherlands, France, Germany, and Spain.

This project is utilising many different technologies to assist in the implementation of the many environmental programmes being undertaken. Among these are the creation of several tools. The smart green logistics tool is designed for the optimisation of hinterland transport through the planning of arriving containers. The tool is a shared interface which will provide port authorities and shippers 24-48 hours operational transport planning. This tool has the scalability for tactical decision making by ports and provides clarity for the shipper when decision making, improving emission performance. The GHG tool will be able to estimate the impact of the reduction measures based on real-world data. This tool was targeted at port of Rotterdam but has the feasibility to be utilised in other ports with minor adjustments to hinterland transport data. This tool enables logistics supply chains to accurately monitor their reduction efforts and remain in line with legislation. The final tool is the energy matching tool which aims to assist ports to balance the energy supply and demands over a 24-48 hour period. This allows the port to reuse energy and

in turn reduce emissions. It has the scalability to work in any port outside the project (Magpie, 2026). These tools all rely on high collaboration between the port authorities, technology providers, research institutes and transport companies for a strong environmental programme around these strategies.

This project aims to improve the multimodal hinterland connections through several strategies. One of these is the green trucking. The aim of this strategy is to utilise new emerging battery and charging technologies can be applied to heavy duty electric trucks and used in regular logistics operations over longer periods. Alongside this there is a strategy to spread the road traffic with the aim to reduce improve the flow of goods through the port by road. This strategy is utilising computer data and is focusing on bottlenecks during the off-peak distribution to assist in alleviating 20% of road traffic by 2030. This is a collaboration of the port authorities, terminal operators, transport companies, research institutes, and technology providers to produce the environmental programme to reduce GHG of the hinterland transport (Magpie, 2026).

Another area of collaboration which showcases the feasibility of the proposed system in figure 1 is the zero-emission shunting locomotive being developed and demonstrated as part of the MAGPIE project. This strategy is to assist in decarbonising the port on-site last mile of the rail transportation side of the logistics, using zero-carbon transport. This is a collaborative project between the port of Rotterdam, Railway companies and technology innovators. Similarly, the Port of Rotterdam is working alongside research institutes, power companies and shipping companies to develop autonomous e-barges. This project intends to improve the hinterland transport by barge through shorter lead times to make inland shipping more attractive and stimulate modal shift (Magpie, 2026).

This case study of MAGPIE demonstrates how high level international collaboration strengthens the reinforcing loop (R1). The consortium's collective expertise and shared environmental objectives have accelerated the development of green port initiatives across the EU, including inland ports. A strong collaborative focus group has enabled the creation of robust environmental programmes, which in turn support effective resource and energy management strategies, ultimately reinforcing green port development. This also demonstrates how the proposed system shown in figure 1 will assist in the development of a green hinterland and supply chain.

The PIONEERS project, funded by the EU, is a collaborative group of 46 partners (CORDIS, 2026) involving four major EU ports, multiple transport companies, shipping companies, technology providers and innovators, and research institutes and universities. Its aim is to transform ports into green infrastructures by 2050 through clean energy production and supply, modal shift and flows optimisation and deployment of electric and alternative fuel vehicles CORDIS, 2026 and Pioneers, 2026).

In its aim to improve the logistics and transport of the port and its hinterland the PIONEERS project is developing and researching several I4.0 systems. One of these is IT platforms for planning multimodal transport. This system is designed for providing comprehensive multimodal transport visibility from the Port of Antwerp-Bruges to their hinterland destinations. Port of Antwerp-Briges is working with its freight transporter stakeholders, and technology innovators to foster a modal shift toward sustainable transport modes (Pioneers, 2026).

The PIONEERS project has several ongoing collaborative strategies to decarbonise the port on-site last mile. The Port of Venlo is working with its operators and innovators to electrify its terminal tractors to produce an emission free on-site last mile. For port operations the Port of Antwerp-Bruges is working with innovators and research institutions to investigate and develop alternative fuel straddle carriers and has implemented a hydrogen-diesel dual fuel straddle carrier as a first step. Along with this technology innovators and developers are working together to develop autonomous ground vehicles for container transport operations (Pioneers, 2026).

The Port of Antwerp-Bruges is collaborating with research institutions, technology developers and providers and shipping companies to develop automated vessels for improved container drayage and River Scheldt hinterland connections. These vessels are operated from a shore-based location and utilise AI to provide a safe and efficient service for container transport to the hinterland.

Optimising resource management through the implementation of CE is another aspect of the PIONEERS project. This strategy is a collaboration between the Port of Antwerp Bruges and construction companies for the utilisation of recovered sand from port operations to be used in the creation of concrete for construction in the port. This collaboration is assisting the resource management within the port and reducing waste materials (Pioneer, 2026).

This second case study into an EU collaborative project to generate smart green ports has also identified that the reinforcing loop R1 shown in figure 1 is a critical element in the whole proposed system. With high collaboration and a well-structured environmental plan funding will be generated, and this will lead to the development of strong strategies for environmental

improvement leading to the growth of a green port. Both these case studies within the EU have shown that the proposed system in figure 1 has the potential to develop green initiatives, not only for the ports but the wider supply chain, including transport systems.

A good case study from the UK which shows how the proposed system can be utilised is the NatPower Marine–Peel Ports green corridor initiative between the UK and Ireland. This collaboration focuses on developing charging infrastructure to support cold ironing for vessels and e charging for vehicles, with Heysham and Birkenhead as the first ports to receive upgrades. The project has also secured funding through the UK SHORE programme (NatPower Marine, 2025).

This initiative will aid the land-based side of port operations to take advantage of the emerging electrification of transport as the project is planning the installation of these charging points around the entire group (NatPower Marine, 2025). This will foster freight companies and shippers to potentially move to greener transport technologies as there will be re-charging infrastructure at the maritime junction. It is also fostering the decarbonisation of port operations through the implementation of electric vehicles for port with all Port of Heysham operational vehicles being electric or Hydrotreated Vegetable Oil (HVO) (Peel Ports, 2022).

This initiative highlights the importance of R1, and the project's success depends on strong collaboration between Peel Ports, NatPower Marine, and associated stakeholders. R1 strengthens through high collaboration, so too do the management strategies and the overall effectiveness of the green port transition. This case study also shows how a single environmental improvement in the port, such as the e-chargers, can also positively impact the wider land-based logistics.

Other academics have also conducted case studies into the decarbonisation of port operations which also show how the proposed system in figure 1 could foster greener infrastructure.

Sharfi et al. (2024) have conducted a study into the feasibility of electric trucks in Port Houston for Drayage operations and discovered that it had the potential to significantly reduce NOx emissions, plus over time reduce operational costs. It was determined in the study that for Port Houston the most economically efficient manner would be to convert the fleet into from full diesel to partial battery trucks due to this port's operational procedures and an assumption of the charging point location at the depot only. If a collaboration between the port authority and innovator and supplier could be established, much like the NatPower-Peel Ports initiative, this would strengthen the programme and lead to potential funding from external sources, such as US EPA Clean Ports programme (US EPA, 2026). With the funding R1 will start strengthening and lead to R2 growing and strengthening.

Reducing water pollution is another essential component of green port development. Conventional vessel antifouling coatings, typically composed of copper oxide, release harmful substances into the marine environment, posing risks to both ecosystems and human health (Kim et al., 2026). The IMO has issued guidelines urging decision makers to consider the environmental impacts of antifouling materials (IMO, 2023b). Understanding the ecological consequences of antifouling practices is critical, as green ports carry a social responsibility to protect and enhance the marine environment (Lam and Li, 2019; Fei, Shi and Pan, 2025).

Conclusion

This study has developed a proposed system designed to accelerate the transition toward smart and green port infrastructure. The analysis identifies legislation as one of the primary external forces compelling ports to modernise. These regulatory pressures create the conditions under which ports must adopt new technologies and environmental practices.

At the core of the proposed system is reinforcing loop R1, which highlights the critical importance of a collaborative focus group. This group, comprising stakeholders, port authorities, local authorities, government organisations, and industry specialists, forms the foundation of an effective environmental programme. It has also been shown how the proposed system will promote the development of a green port-hinterland connection as part of the green port development.

The study demonstrates that high level collaboration is essential: only when these actors work collectively can ports develop strong environmental strategies capable of driving meaningful change. The case studies from the EU and the UK illustrate how such collaboration strengthens R1, enabling ports to secure funding, implement advanced technologies, and progress toward green port status.

Future research could build on this study by conducting structured interviews with port authorities, policymakers, and industry stakeholders to validate and refine the proposed system. Such work has the potential to evolve the model into a practical framework that ports can use to guide their transition toward a smart and green future.

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DYNAMIC PILOT BOARDING RELOCATION DECISION-MAKING: A STATISTICAL AND OPERATIONAL ANALYSIS

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Introduction

Ports commonly assign a nominal pilot boarding point (PBP), a fixed charted position that serves as the default location for pilot embarkation. Because that point is static, it cannot reflect the sea state, traffic, or tide on the day of transfer. Pilots and masters therefore have to decide repeatedly whether to keep the nominal point or relocate the boarding position relative to it. That choice affects transfer safety, approach predictability, pilot boat deployment, and port logistics (IMO, 2011; Oraith et al., 2021). In practice, the decision is a direct trade-off between safer transfer conditions and extra delay. Since approach time feeds into berth planning and vessel turnaround, even small shifts in boarding position can create measurable logistics costs (Johnson and Styhre, 2015; Poulsen and Sampson, 2019).

A growing body of work has proposed dynamic relocation approaches that combine AIS streams, weather observations, and risk scoring to support these decisions (Tu et al., 2018). Even so, little is known about how experts actually decide when to move offshore, stay at the nominal point, move inward, or suspend the operation. This matters because recommendations that conflict with expert judgement are unlikely to be trusted or adopted on the bridge.

This study addresses that gap by analysing an international survey of marine pilots and shipmasters (N = 74). It has three aims: (i) identify the latent decision dimensions that shape relocation choices; (ii) estimate the probability of inward, nominal, offshore, and stop-operation responses under controlled scenarios; and (iii) translate those choices into indicative logistics effects using a distance–speed calculation.

Literature Review

Pilotage safety literature consistently recognises environmental forcing (wind, wave, visibility), traffic conditions, and vessel manoeuvrability as central determinants of transfer risk. Historical analyses of port accidents show that the approach and pilot transfer phases account for a disproportionate share of incidents in confined waters (Darbra and Casal, 2004). Human factors research also describes pilotage as a high-workload socio-technical activity in which environmental stressors and traffic complexity interact with situational awareness and communication demands (Ernstsen and Nazir, 2020; Oraith et al., 2021). More recent studies add machine-learning evidence on marine pilot occupational accidents (Camliyurt et al., 2023) and a network view of communication within VTS areas (Park et al., 2024). IMO Resolution A.1045(27) sets minimum transfer-arrangement standards but leaves the choice of boarding position to local judgement (IMO, 2011), and pilotage practice remains strongly district-specific (Lappalainen et al., 2014).

At the same time, logistics-oriented port studies emphasise that variation in approach time can disrupt berth planning, resource allocation, and schedule reliability. Shorter and more predictable time in port is therefore a lever for both efficiency and emissions reduction (Johnson and Styhre, 2015). The just-in-time arrival agenda likewise seeks better coordination between vessel arrival, pilotage, and berth availability (GEF-UNDP-IMO GloMEEP Project and GIA, 2020; Poulsen and Sampson, 2019). Port service attributes linked to navigation safety also shape carriers' perceptions of port performance (Hsu, 2012).

Emerging dynamic PBP research links AIS traffic indicators and metocean thresholds to location recommendations, exploiting the increasing accessibility of vessel trajectory data (Tu et al., 2018). While such methods improve situational responsiveness, many frameworks remain weakly connected to empirically observed expert behaviour. The result is a practical integration gap between algorithmic outputs and operational acceptance by pilotage stakeholders. This paper therefore makes three contributions: (i) it identifies the latent dimensions structuring expert PBP decisions from an international survey; (ii) it models choice probabilities across inward, nominal, offshore, and stop-operation decisions under controlled scenarios — including the suspension option that data-driven frameworks typically ignore; and (iii) it translates relocation behaviour into indicative approach-time and pilot boat utilisation impacts meaningful for port logistics planning.

Research Design and Data

Survey instrument and respondents

Data were collected through an international structured questionnaire targeting marine pilots and shipmasters. The instrument was developed in English using established scale-development principles (DeVellis, 2017), mapped to published pilot boarding criteria, and administered in English, Turkish, and Korean versions prepared from the English master instrument. During consolidation, each translated response option was mapped one-to-one onto a single English coding frame and a harmonised five-point scale before analysis. A total of 74 valid responses were obtained, and Table 1 summarises the respondent profile. The questionnaire comprised four blocks: (i) respondent profile (role, experience, port archetype, typical vessel and pilot boat capability); (ii) seventeen Likert-type items rating the influence of environmental, traffic, navigational-constraint, and situational-awareness factors on boarding decisions; (iii) six scenario vignettes; and (iv) personal capability thresholds (maximum workable wave height and wind, minimum visibility and under-keel clearance (UKC), and a traffic-density limit).

Characteristic	Distribution
Role	Marine pilot 63 (85%); shipmaster 11 (15%); 92% ex-master
Country	Turkey 54; South Korea 13; Kuwait 3; Qatar 2; USA 1; unspecified 1
Experience (interval midpoints)	Pilotage mean 8.9 years; command mean 7.3 years
Port archetype	Open coast 39 (53%); breakwater-protected 27 (36%); estuary/river 5; other 3
Pilot boat capability (max Hs)	1.5 m: 27 (36%); 2.0 m: 24 (32%); 2.5 m: 19 (26%); 3.0+ m: 3
Typical vessel type	Bulk carrier 23; tanker 22; container 18; other 11

Table 1: Respondent profile (N = 74)

The six vignettes, constructed following experimental vignette methodology (Aguinis and Bradley, 2014), were designed to span the documented operational envelope. Significant wave height ranged from 0.5 to 3.0 m, which brackets typical pilot boat working limits of 1.5–2.5 m. Wind and visibility were allowed to co-vary with sea state because that pairing reflects operational reality rather than an artificial orthogonal design. Scenario 6 combined mild weather with HIGH small craft activity so that the traffic effect could be separated from weather severity.

Scenario	Hs (m)	Wind (kt)	Visibility (NM)	Traffic density	Small craft	UKC margin
S1	0.5	8	3.0	Low	Low	High
S2	1.5	15	1.5	Medium	Medium	Medium
S3	2.0	20	1.0	High	High	Low
S4	2.5	25	0.5	Medium	Low	Low
S5	3.0	28	0.8	High	Medium	Medium
S6	1.0	12	2.0	Low	High	High

Table 2: Scenario vignette design (traffic density: vessels >300 GT within 2 NM; levels span the documented operational envelope)

Analytical strategy

Three analytical layers were used: descriptives, Exploratory Factor Analysis (EFA), and multinomial logistic regression (MNL). EFA was run on the twelve decision-driver items using principal axis extraction and varimax rotation, together with standard adequacy checks (Hair et al., 2019), because the correlated Likert items were expected to reflect a smaller number of latent constructs and no prior factor structure existed for this instrument. The MNL used the pooled scenario responses, namely 73 respondents × 6 scenarios, giving $N = 438$ choices, with the nominal charted point as the reference outcome. Because the outcome is an unordered choice among four discrete alternatives, MNL is the standard random-utility model for this setting (McFadden, 1974). Scenario attributes were reduced to three standardised indices: S for sea state (wave height, wind, inverse visibility), T for traffic (density and small craft), and U for UKC margin. Since responses are nested within respondents, standard errors are clustered by respondent throughout, and odds ratios (ORs) are reported per 1 SD of each index.

Operational time-impact model

The time-impact model was included to translate the decision patterns into logistics terms. It assumes that offshore relocation is roughly 3–5 NM beyond the nominal PBP, inward relocation is 1–2 NM inside it, ship speed is 8–12 kn, and pilot boat speed is 10–15 kn. Additional time is calculated as $\Delta t = \Delta d / v$. The calculation is deliberately illustrative rather than a route-specific simulation.

Findings

Descriptive patterns and capability thresholds

On the harmonised 1–5 scale, respondents gave the highest influence ratings to VTS communication (mean 4.45), speed and angle of approach (4.22), weather conditions (4.18), tidal and current data (4.07), and draft limitation (3.99). The lowest rating was for self-reported loss of situational awareness (2.30). Relocation is already part of routine practice: 58% reported changing the boarding point from the charted position at least "sometimes", and 78% agreed that dynamic, data-driven adjustment of boarding grounds would improve safety and efficiency. The stated thresholds were broadly consistent across roles: median maximum workable wave height 2.0 m (IQR 1.5–2.5 m), median maximum wind 25 kt (IQR 20–30 kt), minimum visibility most often ≥0.5 NM (51%), minimum UKC median 1.5 m, and a modal traffic-density limit of ≥5 vessels (>300 GT) within 2 NM (41%). Table 1 summarises the sample.

Latent decision dimensions

Sampling adequacy supported factor analysis (KMO = 0.75; Bartlett $\chi^2(66) = 277.0$, $p < 0.001$). A four-factor varimax solution explained 52% of common variance (Table 3). The dimensions can be read as: (F1) environmental and approach-condition sensitivity — tide/current, visibility, UKC influence, traffic encounter frequency, and vessel proximity ($\alpha = 0.80$); (F2) traffic-induced manoeuvring complexity — route adjustment flexibility, course-keeping, small-craft interference ($\alpha = 0.73$); (F3) transfer workload and situational awareness — weather impact and attention loss during transfer; and (F4) draft and UKC navigational constraint. F3 falls below the conventional 0.60 reliability threshold ($\alpha = 0.52$) and is treated as exploratory only, while F4 is dominated by a single item. The first two dimensions provide the most reliable compact behavioural representation of expert judgement that can be embedded as constructs in decision-support tools.

Item (abridged)	F1	F2	F3	F4
Tidal and current data importance	0.59	−0.14	0.10	0.10
Visibility impact on awareness	0.66	0.20	0.28	0.08
UKC influence on position	0.62	0.34	−0.06	0.33
Traffic density encounter frequency	0.57	0.36	0.28	−0.05
Proximity of other vessels	0.64	0.49	0.10	0.16
Small-craft complications	0.26	0.41	0.18	0.26
Route adjustment option importance	−0.01	0.80	0.21	0.18
Steady course-over-ground importance	0.14	0.60	0.08	0.08
Weather conditions impact	0.28	−0.02	0.45	0.14
Speed/angle of approach influence	0.10	0.22	0.39	0.06
Situational awareness loss frequency	0.04	0.13	0.70	0.04
Draft limitation criticality	0.21	0.31	0.21	0.91
Cumulative variance explained	17.6%	33.2%	42.7%	52.0%

Table 3: EFA loadings (principal axis, varimax; n = 72; loadings ≥ 0.40 define factors)

Relocation choice modelling

Scenario responses display a graduated, condition-sensitive pattern (Figure 1a). Under mild conditions (Scenarios 1, 2, 6) the nominal charted point dominates (63–71%), with a persistent inward minority (11–29%) and marginal offshore uptake. At moderate–severe conditions (Scenario 3: Hs 2.0 m, 20 kt, high traffic, low UKC) the expert community itself divides almost evenly between nominal (29%), inward (29%), offshore (22%), and stop (21%) — precisely the operating band where decision support has most value. Under severe conditions, suspension becomes the modal answer: 53% in Scenario 4 (Hs 2.5 m) and 73% in Scenario 5 (Hs 3.0 m). Offshore relocation never exceeds 22% of responses, indicating that beyond pilot boat capability limits experts prefer suspending transfers to moving them further to sea.

The MNL model (Table 4) is highly significant overall (likelihood-ratio $p < 0.001$; $N = 438$), with a McFadden pseudo-R^2 of 0.217 — within the 0.2–0.4 band conventionally regarded as good fit for behavioural choice models. Relative to remaining at the nominal point, the probability of offshore relocation increases significantly with sea-state severity (OR = 2.32 per SD, 95% CI 1.46–3.70, $p < 0.001$) and with traffic complexity (OR = 1.66, CI 1.20–2.32, $p = 0.003$). The stop-operation choice is dominated by sea-state severity (OR = 20.99 per SD, CI 10.45–42.15, $p < 0.001$) with a secondary traffic effect (OR = 2.02, CI 1.48–2.76, $p < 0.001$). Inward relocation, by contrast, is not significantly driven by the scenario indices: it behaves as a stable baseline preference (intercept $p = 0.002$) reflecting district practice and shelter-seeking habit rather than a reaction to the manipulated conditions. UKC margin adds no significant explanatory power once sea state and traffic are controlled — a pattern suggesting that experts treat depth as a binary feasibility gate resolved at the planning stage (median stated minimum 1.5 m) rather than a graded relocation driver, although the three-level UKC attribute may also have been less salient in the vignettes than the vivid sea-state cues. Predicted probabilities (Figure 1b) show the nominal–stop crossover occurring at roughly the sea-state level corresponding to the stated 2.0–2.5 m capability medians, an encouraging internal consistency between stated thresholds and scenario behaviour.

These estimates are robust. Re-fitting the model on the 53 Turkish respondents alone reproduced the same pattern (offshore: sea-state OR = 2.30, $p = 0.005$; traffic OR = 1.70, $p = 0.016$), and the 20 respondents from other countries showed the same significant offshore effects (OR = 2.89, $p = 0.017$ and OR = 1.80, $p = 0.037$), although the stop equation could not be estimated reliably in this small subgroup. Because wave height and wind are almost perfectly coupled in the vignette design ($r = 0.997$), their effects cannot be disentangled; substituting wave height alone for the composite index left the sea-state effects essentially unchanged (offshore OR = 2.29; stop OR = 18.6; both $p < 0.001$).

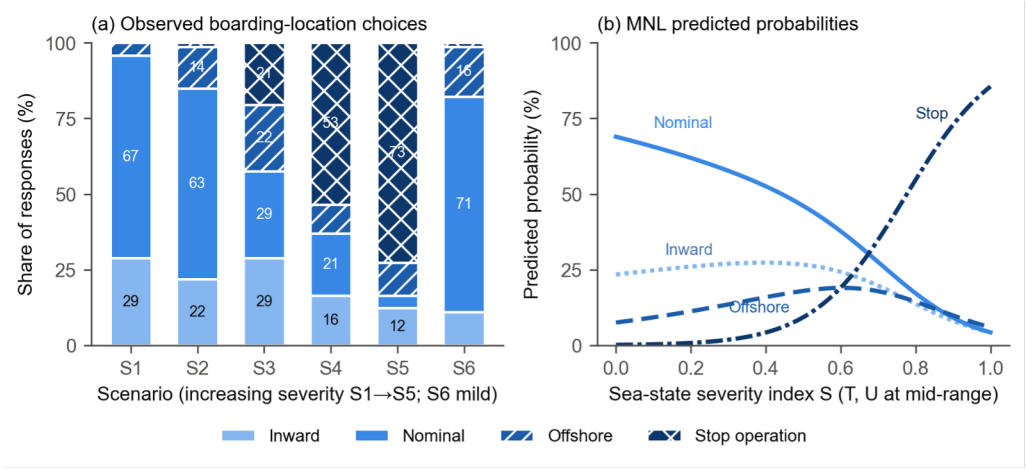

Figure 1: (a) Observed boarding-location choices across scenarios; (b) predicted probabilities from the multinomial logit versus the sea-state severity index (traffic and UKC indices at mid-range)

Outcome (vs nominal)	Predictor	(SE)	OR per SD	95% CI	p
Inward	Sea state (S)	0.35 (0.32)	1.42	0.76–2.66	0.268
	Traffic (T)	−0.03 (0.12)	0.97	0.77–1.23	0.820
	UKC margin (U)	−0.23 (0.24)	0.80	0.50–1.27	0.343
Offshore	Sea state (S)	0.84 (0.24)	2.32	1.46–3.70	<0.001
	Traffic (T)	0.51 (0.17)	1.66	1.20–2.32	0.003
	UKC margin (U)	0.26 (0.26)	1.30	0.78–2.17	0.310
Stop operation	Sea state (S)	3.04 (0.36)	20.99	10.45–42.15	<0.001
	Traffic (T)	0.70 (0.16)	2.02	1.48–2.76	<0.001
	UKC margin (U)	0.22 (0.25)	1.25	0.76–2.05	0.386

Table 4: Multinomial logit results (N = 438 choices; base outcome: nominal charted point; standard errors clustered by respondent; McFadden pseudo-R^2 = 0.217; LR test $p < 0.001$)

Indicative logistics impact

Table 5 translates relocation choices into indicative time effects. Offshore relocation of 3–5 NM adds approximately 15–38 minutes to a ship approach at 8–12 kn, and 24–60 minutes of additional pilot boat round-trip utilisation at 10–15 kn — a direct input for pilot boat rostering and berth-window planning. Inward relocation shortens the piloted approach segment by roughly 5–15 minutes but is selected mainly for shelter and manoeuvring predictability rather than time savings. Suspension converts transfer risk into schedule delay; its cost is bounded by the weather window rather than distance, which is why anticipatory relocation within the workable band matters.

Decision	distance	Ship approach effect (8–12 kn)	Pilot boat round trip (10–15 kn)
Offshore relocation	+3 to +5 NM	+15 to +38 min	+24 to +60 min
Inward relocation	−1 to −2 NM	−5 to −15 min	reduced accordingly
Stop operation	n/a	delay = weather-window duration	boat retained in port

Table 5: Indicative time impacts of relocation decisions ($\Delta t = \Delta d/v$)

Discussion

The results reinforce that pilotage decision-making is fundamentally socio-technical: experts combine environmental signals, traffic geometry, and vessel-state constraints in context-sensitive ways (Ernstsen and Nazir, 2020). Three findings are especially important for decision-support design. First, the response to worsening conditions is graduated but bounded: offshore relocation is a moderate-band tool, but once the pilot boat capability envelope is exceeded (median 2.0 m Hs) experts move to suspension rather than going further offshore; algorithms that recommend offshore boarding above that envelope would therefore clash with expert judgement. Second, inward relocation operates as a standing district preference shaped by shelter and local habit rather than as a reaction to conditions, so support systems should treat it as a per-district configuration. Third, the greatest expert disagreement appears in the moderate–severe band (Scenario 3), which is exactly where probabilistic advice adds more value than binary thresholds.

From a logistics perspective, relocation should be understood as controlled variability. Offshore relocation buys transfer safety at a known cost of 15–38 minutes of approach time and up to an hour of pilot boat utilisation, while suspension turns hazard exposure into schedule delay. Under uncertainty, accepting a moderate deterministic delay is preferable to reactive disruption, which is consistent with resilient-port thinking and the just-in-time arrival agenda (GEF-UNDP-IMO GloMEEP Project and GIA, 2020). Because 78% of experts endorse dynamic, data-driven adjustment, the main barrier appears to be alignment between algorithmic recommendations and the behavioural structure evidenced here.

Practical Implications

- Pilotage authorities and VTS centres should operationalise the four latent dimensions as watch-list indicators, adopt scenario-probability dashboards for inward/nominal/offshore/stop advice, and align relocation guidance with pilot boat capability envelopes (median 2.0 m Hs, 25 kt wind) together with UKC monitoring.
- Port and terminal operators should build relocation-driven delay bands (≈15–38 min per offshore event) and suspension risk into berth-window and resource planning, and should include pilot boat availability in short-term schedule optimisation.
- Digital system developers should calibrate AIS/metocean analytics against expert-derived choice probabilities and validate recommendations through iterative expert review to secure operational acceptance.

Limitations and Future Research

Vignettes simplify real bridge conditions. The sample, while international, is weighted towards Turkish respondents (73%); the subgroup re-estimation reported above reproduces the main effects, but wider replication is needed. The stop-operation option did not distinguish temporary postponement from outright cancellation, so the high suspension shares in severe scenarios should be read as deferral of the transfer rather than necessarily abandonment of the port call. Stated preferences may also diverge from revealed behaviour in individual districts: in sheltered, high-density ports, local geometry can make offshore transfers less practical precisely when traffic is heavy, so district-level calibration against observed AIS behaviour should precede operational use. The time-impact analysis is deliberately illustrative rather than route-specific. Future work should link the expert-derived model with historical AIS trajectories and recorded boarding positions, develop district-calibrated models, and trial real-time advisory prototypes with pilot organisations and VTS centres, including pilot boat resource constraints and seasonal weather regimes.

Conclusions

This paper provides an expert-informed statistical model of pilot boarding point relocation and connects it to operational time implications relevant to maritime logistics. Four behavioural dimensions structure expert judgement; scenario choice modelling shows offshore relocation rising with sea-state severity and traffic complexity, inward relocation acting as a district-level baseline preference, and suspension — not offshore relocation — dominating beyond pilot boat capability limits, with a nominal-to-stop crossover consistent with stated thresholds (median 2.0 m Hs, 25 kt wind). Offshore relocation carries an indicative cost of 15–38 minutes of approach time and up to an hour of pilot boat utilisation. Together, the latent dimensions, choice probabilities, and time bands offer a behaviourally credible foundation for next-generation pilotage decision support and for integrating planned pilotage flexibility into resilient port operations.

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PUBLIC SECTOR ROLES IN URBAN CONSOLIDATION SCHEMES: A COMPARATIVE STUDY AND BUSINESS MODEL PERSPECTIVE

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Introduction

Goods consolidation is a central concept in urban freight and refers to the bundling of shipments to reduce vehicle trips, improve load factors, and mitigate environmental and social impacts of urban deliveries (Kin et al., 2016). Among the various consolidation approaches discussed in the urban freight literature (Verlinde et al., 2012; Holguín-Veras & Sánchez-Díaz, 2016), Urban Consolidation Centres (UCCs) and microhubs have received increasing attention as mechanisms to improve efficiency and sustainability of last-mile logistics.

UCCs are logistics facilities located in proximity to the area they serve, such as a city centre, district, or specific development site, where shipments from multiple suppliers are consolidated before final distribution to receivers (Browne et al., 2005; Kin et al., 2016). Microhubs represent a more recent form of urban freight consolidation and are defined as small-scale logistics facilities located within or very close to the delivery area, enabling the transfer of goods from conventional freight vehicles to smaller, often electric or non-motorised vehicles for the final delivery leg (Katsela et al., 2022). Compared with traditional UCCs, microhubs operate within a smaller service area, and require less physical space.

Research on UCCs and microhubs has focused on issues such as facility location, routing, operational performance, and economic feasibility (Giampoldaki et al., 2023). While this focus has contributed to understanding technical and operational dimensions of consolidation schemes, stakeholder management, governance arrangements, and decision-making processes have received comparatively less attention (Lagorio et al., 2016). With this motivation, researchers have begun to examine urban consolidation schemes through a business models (BM) perspective (Björklund et al., 2017; Katsela, 2025), analysing aspects such as value propositions, stakeholder configurations, revenue mechanisms, and service offerings. These studies have highlighted the difficulties associated with developing financially sustainable BM and balancing the interests of multiple stakeholders.

However, the role of the public sector remains insufficiently understood within this literature. Existing studies typically conceptualise public authorities as external enablers that provide regulatory support, funding, or favourable policy conditions (Brettmo & Williamson, 2020). Such a perspective overlooks the diverse ways in which public actors participate in the development and operation of consolidation schemes. Municipalities and other public authorities may influence not only the institutional environment but also core elements of the BM, including value creation, resource allocation, risk distribution, and revenue.

Therefore, this study aims at examining the public sector role in UCC and microhub initiatives from a BM perspective. Specifically, the paper has two objectives: (1) to examine differences in the public sector role in the development of UCCs and microhubs; and (2) to propose a BM framework that clarifies how public and private actors can align their mandates, interests, and objectives. Drawing on 15 European cases, with particular emphasis on Swedish initiatives, the study contributes to the urban freight literature by providing a comparative analysis of public sector involvement across consolidation schemes and by developing a framework that conceptualises how different levels of public sector involvement contribute to overcoming BM barriers and aligning public and private objectives in urban consolidation schemes.

Relevant Literature

UCCs and microhubs aim to improve delivery efficiency while reducing congestion, emissions, and the use of urban space through the consolidation of freight flows before final delivery (Browne et al., 2005; Allen et al., 2012; Kin et al., 2016). Despite differences in scale, location, and operational design, both concepts rely on coordination among multiple actors and often require public sector involvement to overcome implementation barriers (Björklund et al., 2017).

The urban freight literature describes public authorities as enabling actors that shape the institutional and operational conditions under which consolidation schemes operate (Browne et al., 2005; Allen et al., 2012; Kin et al., 2016). Such involvement is often justified by the public benefits associated with consolidation, including reduced congestion, emissions, and demand for curb space (Katsela et al., 2022).

In addition, public organisations, such as municipalities, hospitals and universities, can as major receivers of goods and services, create demand for consolidation and influence how deliveries are organised (Balm et al., 2016). Public procurement can be used to specify delivery terms, vehicle standards, demand-planning routines, and incentives for more consolidated ordering, thereby affecting freight trips. Thus, the influence of the public sector extends beyond regulation and infrastructure provision to include demand-side interventions.

Although the importance of public sector involvement is recognised, existing studies tend to focus on individual initiatives, specific policy instruments, or specific forms of intervention. As a result, knowledge remains fragmented regarding how public sector participate in different types of consolidation schemes and whether their involvement differs between UCCs and microhubs. Moreover, while public sector actions are discussed as enabling factors (Björklund et al., 2017), less attention has been paid to how different forms of involvement influence BM of consolidation initiatives. A comparative perspective can increase understanding of the variety of public sector roles across consolidation schemes and their implications for long-term development and operation.

Problem Description

The long-term viability of UCCs and microhubs has been examined through a BM perspective. BM describe how organisations create, deliver, and capture value and are analysed through four components: infrastructure (actors, resources, and operational arrangements required to create and deliver value), finances (revenue streams, cost structures, and funding mechanisms), service offering (services provided through the consolidation scheme), and customers (target users and their relationships) (Osterwalder & Pigneur, 2010).

Previous research has shown that achieving viable BM remains challenging for both UCCs and microhubs. Several initiatives struggle to secure sufficient freight volumes, establish sustainable revenue streams, distribute costs among beneficiaries, and align the interests of stakeholders (Björklund et al., 2017; Katsela et al., 2022). To explain these challenges, Williamson & Moen (2022) propose that barriers to business model innovation (BMI) in urban freight can be understood through three categories: obstruction, confusion, and misalignment. Obstruction refers to barriers that prevent the implementation of new BM, confusion relates to uncertainty regarding how value should be created and captured, and misalignment arises when stakeholders hold conflicting objectives or expectations.

While the public sector support is recognised as important to overcome BMI barriers, public authorities are generally positioned outside the BM itself. Consequently, limited attention has been given to how public sector involvement influences the internal configuration of urban consolidation schemes, including the allocation of responsibilities, risks, resources, and benefits among actors.

As public authorities often participate directly in the implementation and operation of consolidation schemes (Björklund et al., 2017), they may shape BM components and influence how value is created, delivered, and captured. Understanding these interactions is therefore necessary to explain why some initiatives achieve continuity while others remain dependent on pilot funding or fail to scale beyond demonstration phases. This study combines the public-sector and BM perspectives by examining how different public sector roles influence BM barriers in UCCs and microhubs.

Methodology

This study adopts a qualitative multiple-case study design to examine public sector roles and BM characteristics in urban consolidation schemes. A total of 57 reports and academic publications were reviewed covering fifteen European cases, including nine UCCs and six microhubs, with a particular emphasis on Swedish initiatives. The sample included both long-established operations and temporary pilot projects, allowing the analysis to capture different stages of implementation and maturity.

Among the microhub cases, Lindholmsleveransen (Gothenburg, Sweden), Älskade stad (Stockholm, Sweden), and Urban Services JV (Stockholm, Sweden) were operating at the time of the study, whereas Nordstan Consolidation/Smoovit (Gothenburg, Sweden), SamCity (Malmö, Sweden), and Stadsleveransen (Gothenburg, Sweden) had concluded after pilot or demonstration phases. The UCC sample included long-running initiatives, such as Bath-Bristol UCC (UK), Consolidation Event Goods (Gothenburg, Sweden), Cityporto (Padova, Italy), Binnenstadservice BSS (Netherlands), and Certified Distribution / Cargohopper (Utrecht, the Netherlands), as well as more recent pilot projects, including NOHA Services (Stockholm, Sweden), REDIG (Gothenburg, Sweden), NOVELOG Co-Address Nordstan (Gothenburg, Sweden), and public-led UCCs in Sweden (e.g., Södertörn and Borlänge).

The selected initiatives represent a broad range of governance and operational arrangements. Some schemes were operated by a single private company, while others relied on public–private partnerships or collaborations among multiple private actors. Similarly, the cases differed in their financing structures and origins, including municipality-led initiatives, public–private partnerships, privately initiated schemes, EU-funded projects, and nationally funded pilots. The diversity of organisational forms, operational durations, and implementation outcomes enabled a comparative analysis of public sector involvement and BM development across different urban freight consolidation contexts.

The selected cases were analysed using a structured coding framework adapted from Giampoldaki et al. (2023). The coding scheme included four main themes. First, location characteristics captured the urban context of the initiative, including city size, catchment area, and distance between the consolidation facility and the market served. Second, public sector involvement documented the forms of participation by public authorities. Third, BM characteristics examined customer segments, financing arrangements, operational models, ownership and management structures, and service portfolios. Fourth, operational features included the use of digital infrastructure and fleet composition.

The coded material was analysed, and public sector roles were inductively derived from the cases and grouped into role categories. The analysis examined how these roles were associated with BM barriers across the infrastructure, service offering, customer, and financial components. Following Williamson & Moen (2022), barriers were classified as obstruction, confusion, or misalignment. The relationships between public sector roles and BM barriers were then interpreted and discussed through workshops, allowing the identification of mitigation mechanisms associated with different forms of public involvement.

Results

Six main roles played by public sector actors were found within the reviewed cases. Table 1 summarises definitions and attributes of the public sector roles in UCC and microhub cases.

UCCs	Microhubs
Privileged access granting	
Access regulation focused on supporting consolidated freight distribution into city centres through exemptions, dedicated lane access, and certification schemes. • Access to bus/taxi lanes (Bath-Bristol, Cityporto) • Granting unrestricting access to a limited traffic zone, exemption from restrictions for (un)loading (Cityporto) • Requiring use of electric vehicles in operating contract (Bath-Bristol)	Access regulation focused on enabling compliant last-mile operations using smaller or low-emission vehicles within restricted areas. • Granting access to road use and loading infrastructure in central areas (Stadsleveransen, Älskade stad). • Define freight distribution requirements through vehicle standards and delivery time windows (Lindholmsleveransen)
Public procuring / financing	
Operational subsidies, procurement contracts, incentives for fleet acquisition and staff funding. • Public tenders to operate UCCs (Bath-Bristol, BSS) • Public subsidies to cover operational costs, personnel and investment in fossil-free vehicles (Bath-Bristol)	Access to existing infrastructure (e.g. parking lots), pilot funding, and project management resources. • Free of charge leasing of public infrastructure (Lindholmsleveransen) • Project management funding (Stadsleveransen) • Subsidised services during pilots (Smoovit)
Initiator	
Project initiation, providing start-up funding, and institutional arrangements to support implementation. • Start-ups grants including support for vehicle acquisition (BSS, Cityporto)	Initiation and coordination, particularly in pilot and demonstration projects, later taken over by private actors. • Initiation funding through innovation calls (Stadsleveransen, Lindholmsleveransen) • Coordination and leadership in consortium formation (Smoovit / Smooth, SamCity)
Infrastructure owner	
Provision of logistics terminals within publicly supported intermodal infrastructure. • Public company owns UCC infrastructure (Cityporto, Swedish cases - Södertörn and Borlänge)	Public ownership was less common, with infrastructure more frequently owned by real estate actors. • Public company owns microhub infrastructure and contracts operators through innovation procurement agreements (Lindholmsleveransen)
Customer	
Procurement of distribution services directly from UCC operators, contributing to transport volumes and revenues. • Services purchasing from public agencies to UCC (BSS, Swedish cases - Södertörn and Borlänge)	Procurement of selected logistics services or municipal freight flows during pilot phases. • Dual role of public sector as project coordinator and customer (SamCity) • Waste management services as a return flow (Lindholmsleveransen)
Facilitator	
Stakeholders' coordination, facilitating governance and interaction. • Close interaction with UCC management and identification of new business opportunities (Bath-Bristol) • Definition of common operational rules and eligibility criteria for consolidation (Utrecht, BSS)	Knowledge sharing, and stakeholder coordination during pilot and implementation phases. • Support to organisational, administrative, and regulatory processes while facilitating dialogue and exchange of experiences among stakeholders (Älskade stad, SamCity, Stadsleveransen)

Table 1: Types of public sector role in UCC and microhub initiatives.

While both schemes involve public sector engagement across all six role types, differences were observed in the scope, and purpose of public involvement. In general, UCCs were more frequently associated with formalised operational arrangements, long-term service provision, and regulatory integration. Microhubs were more commonly linked to pilot-oriented initiatives, experimental governance arrangements, and flexible use of urban space.

The findings indicate that the roles assumed by the public sector differ not only in their function but also in the degree to which public actors become involved in consolidation schemes. Roles such as facilitation and privileged access granting influence the institutional environment surrounding the initiative. In contrast, procurement, customer participation, initiation and infrastructure ownership directly affect resources, demand, revenues, and operational continuity. This finding is further explored in the following subsection with particular attention to barriers in BMI that may be addressed by the identified roles of the public sector.

Roles of public sector in barriers to business model innovation (BMI)

The analysis identified barriers across all four BM components: infrastructure, finances, service offering, and customers. Following Williamson & Moen (2022), these barriers were classified as obstruction, confusion, or misalignment. The analysis explored in what way public sector roles were associated with BM components and how combinations of roles contributed to mitigating barriers. The findings suggest that public sector actors influence BM viability through different mitigation mechanisms that vary in function and involvement intensity.

Infrastructure: obstruction barriers constituted the largest group. These barriers included lack of incentives for property owners to provide logistics space, limited permits and infrastructure access, insufficient logistics expertise within the public sector, absence of data exchange standards, and unbalanced distributions of risks and benefits. The roles associated with these barriers were facilitator, infrastructure owner, and public procuring/financing. The association of these roles with infrastructure-related barriers suggests a mechanism of resource provision and capability development, where public actors contribute physical assets, financial support, institutional capacity, and coordination resources necessary to establish and operate consolidation schemes. Infrastructure-related confusion was primarily linked to uncertainty regarding governance arrangements, long-term ownership, contractual conditions, and political continuity. In these cases, the combination of facilitator, infrastructure owner, and initiator roles are interpreted as contributing to a mechanism of governance stabilisation, providing continuity, clarifying responsibilities, and reducing uncertainty regarding future regulations. Infrastructure-related misalignment was associated with conflicting stakeholder objectives, unclear responsibilities, and disagreements regarding risk allocation. For this group of barriers, the facilitation role contributes to a mechanism of stakeholder alignment, supporting dialogue, negotiation, and the establishment of common objectives.

Finances: obstruction barriers were associated with high start-up costs, additional handling costs, difficulties in demonstrating societal benefits, and uneven distributions of costs and benefits. The dominant roles were public procuring/financing, initiator and privileged access granting. These roles suggest a mechanism of economic viability support, where financial contributions reduce economic risk while regulatory incentives improve the operational attractiveness of consolidation services. Financial confusion emerged from uncertainty regarding revenue streams, long-term funding, cost allocation, and the transition from pilot permanent operations. Public procuring/financing and customer roles contribute to a mechanism of revenue stabilisation by providing predictable demand and financial continuity. Financial misalignment represented the largest group of barriers within this component and reflected situations where societal benefits accrued to municipalities and communities while operational costs remained among private actors. The combination of customer, facilitator, and public procuring/financing roles can therefore support a mechanism of cost-benefit balancing, helping redistribute costs and benefits among stakeholders.

Service offering: obstruction barriers related to difficulties in communicating the value proposition of consolidation services and coordinating service provision. These barriers were associated with facilitator and privileged access granting roles, which together contribute to a mechanism of service legitimisation by increasing the attractiveness, visibility, and perceived value of consolidation services. Service-related confusion emerged when actors lacked a common understanding of service scope, responsibilities, or the implications of introducing additional value-added services. The facilitation role supports a mechanism of service clarification through coordination, communication, and knowledge exchange. Misalignment within the service offering was associated with divergent expectations regarding service levels, contractual arrangements, and operational requirements. The combination of facilitator and customer roles contribute to a mechanism of value proposition alignment, supporting the negotiation of shared service expectations and acceptable service levels.

Customers: obstruction barriers were characterised by limited incentives to participate, reluctance to change established delivery practices, and difficulties in attracting sufficient demand. These barriers were associated with customer, initiator and facilitator roles, forming a mechanism of demand generation through procurement activities, stakeholder engagement, and demonstration of service benefits. Customer-related confusion was linked to uncertainty regarding demand, customer retention, and participation after pilot phases. Customer and facilitator roles contribute to a mechanism of demand stabilisation, signalling long-term commitment and reducing uncertainty among actors. Finally, customer-related misalignment reflected differences in priorities and expectations among stakeholders. The same combination of customer and facilitator roles contribute to a mechanism of demand alignment, supporting the reconciliation of service requirements and purchasing practices across stakeholder groups.

Discussion

The findings demonstrate that public sector involvement in urban consolidation schemes extends beyond an external enabler role. While previous studies have emphasised regulation, funding, and policy support as mechanisms through which public authorities influence UCCs and microhubs (Browne et al., 2005; Kin et al., 2016; Katsela et al., 2022), the reviewed cases reveal a broader set of roles embedded within BM of consolidation schemes. However, the six public sector roles identified do not contribute equally to BM development. Some roles, such as facilitation, primarily influence relationships between actors and the governance environment. Others, such as procurement, infrastructure ownership, and customer participation, directly affect resource allocation, revenue generation, and value capture. This suggests that public sector roles can be distinguished according to the degree to which they become embedded within the BM itself.

The comparison between UCCs and microhubs also indicates that public sector involvement differs in both form and intensity. However, both UCCs and microhubs relied on public intervention to address barriers that private actors alone may struggle to overcome. This finding supports previous arguments that urban freight consolidation generates societal benefits that are not fully reflected in private business incentives, thereby creating a rationale for public sector participation (Björklund et al., 2017).

Consistent with Williamson & Moen (2022), barriers were identified in relation to obstruction, confusion, and misalignment. The analysis further indicates that BM barriers differ in the type of intervention required for mitigation. Building on these findings, the paper proposes a public sector influence framework (Illustration 1) that conceptualises public involvement as a continuum of increasing influence over the BM.

	Public sector roles	Mitigation mechanisms	Barriers addressed	Business model focus
Low Involvement	• Facilitator	• Service clarification • Stakeholder alignment	• Confusion • Misalignment	• Infrastructure • Service offering
Moderate Involvement	• Facilitator • Initiator • Privileged access granting	• Governance stabilisation, • Service legitimisation • Demand stabilisation and generation	• Obstruction • Confusion	• Infrastructure • Service offering • Customers
High Involvement	• Facilitator • Public procuring/financing • Customer • Infrastructure owner	• Resource provision and capability development • Revenue stabilisation • Economic viability support • Cost-benefit balancing • Demand alignment	• Obstruction • Confusion • Misalignment	• Infrastructure • Finances • Customers • Service offering

Illustration 1: Public sector influence framework for BM viability.

At the lower level of involvement, public involvement is characterised by the facilitation role. Mitigation mechanisms at this level are instrumental for addressing uncertainty, conflicting objectives, or lack of shared understanding that hinders implementation. At an intermediate level of involvement, public actors contribute through initiation, facilitation, and privileged access granting. These roles support mechanisms that create conditions for consolidation schemes to emerge and develop by reducing uncertainty, enhancing the attractiveness of consolidation services, and supporting the formation of stable stakeholder relationships. At the highest level of involvement, public actors become embedded within the BM itself through public procuring/financing, customer, infrastructure owner, and facilitator roles. These roles contribute to mechanisms that enable public authorities to move beyond creating favourable conditions and actively participate in value creation, delivery, and capture.

The framework suggests that municipalities should avoid adopting a uniform approach to urban consolidation. Instead, public involvement should be matched to the barriers faced by a particular initiative. Where barriers are related to stakeholder coordination and governance, facilitation may be sufficient. However, where barriers concern access to resources, financial viability, or unequal distributions of costs and benefits, more direct forms of involvement may be required. The framework therefore provides a basis for selecting public sector interventions according to the specific BM challenges faced by UCCs and microhubs.

Conclusions

This paper examined public sector roles in UCCs and microhubs from a BM perspective. The study further examined how public sector roles relate to barriers to BMI. The results indicate that public sector involvement influences not only the external conditions under which consolidation schemes operate but also value creation, delivery, and capture.

The paper proposes a framework that conceptualises public involvement as ranging from facilitation-oriented activities to direct participation in BM components through procurement, infrastructure provision, and service purchasing. The framework contributes to literature by positioning public authorities not only as external enablers but also may actively shape the distribution of resources, risks, responsibilities, and benefits in urban consolidation.

It is suggested that public sector involvement should be matched to the barriers faced by a consolidation initiative addressing which forms of involvement are needed to support the long-term viability of UCCs and microhubs. In addition, public sector roles are not mutually exclusive, as roles accumulate as the level of public involvement increases. Facilitation remains necessary even when municipalities also act as customers, infrastructure providers, or procurers. Future research could further refine the proposed framework considering how public-sector influence mechanisms evolve over time as consolidation schemes move from pilot projects to mature operational models.

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Hydrogen Freight in High-Tech Industrial Clusters: Demand Conditions and Deployment Pathways

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1.Introduction

Climate change mitigation has become an increasingly important industrial and policy concern. Although transport decarbonization is central to long-term net-zero strategies, freight transport remains difficult to transform because logistics systems must maintain delivery reliability, route flexibility, payload capacity, speed, and cost efficiency. Low-carbon freight technologies must therefore demonstrate not only environmental benefits but also the capacity to support continuous production and time-sensitive supply-chain operations (IEA, 2023, 2024). Taiwan provides an important setting for examining this issue. Its high-tech economy is concentrated in science parks across northern, central, and southern Taiwan, where frequent truck movements connect factories, suppliers, logistics centers, ports, airports, and inter-park routes. These clusters are closely linked to global semiconductor and advanced manufacturing supply chains. Despite their technological sophistication, high-tech industries remain highly dependent on freight transport. Truck operations consequently represent a significant but relatively underexamined source of emissions within industrial supply chains. As manufacturing capacity and logistics demand expand, freight-related emissions may increase even where firms achieve improvements in production-side energy efficiency (ITF, 2023; Sugihara et al., 2024; Zhao et al., 2024).

Freight decarbonization in high-tech industrial systems cannot be treated solely as a fuel substitution issue. Transport disruptions may affect synchronized production processes, international delivery commitments, and customer relationships. Alternative energy systems must therefore meet operational requirements related to range, payload, refueling time, delivery reliability, cold-chain stability, and transport security. Hydrogen-powered trucks are relevant because they may provide a lower-emission option for heavy-duty and longer-distance freight operations while maintaining operational flexibility. This potential is particularly important in semiconductor, precision electronics, and advanced manufacturing sectors, where delays in material or product movement may generate substantial operational and economic consequences. The broader policy environment is also influencing firm-level freight decisions. Carbon pricing, carbon fees, ESG reporting requirements, and trade-related decarbonization measures increasingly affect supply-chain management and industrial competitiveness. The European Union's Carbon Border Adjustment Mechanism has reinforced the importance of carbon performance for market access and supply-chain legitimacy. Taiwan's 2050 Net-Zero Emissions Pathway similarly identifies transport transformation and industrial decarbonization as major policy priorities (European Commission, 2024; Transport & Environment, 2024). Hydrogen remains a promising but uncertain option. Fuel-cell trucks may be suitable for some heavy-duty and longer-distance operations because of relatively rapid refueling and potential range advantages. However, technical potential alone does not ensure adoption. Vehicle costs remain high, hydrogen supply systems are developing, and refueling infrastructure is limited. Adoption is likely to depend on technological feasibility, organizational readiness, infrastructure availability, and policy credibility (OECD, 2023; Müller, 2024).

Existing research has largely focused on hydrogen technology performance, national hydrogen strategies, and general transport decarbonization scenarios. Less attention has been directed towards firm-level demand for hydrogen freight in sector-specific industrial settings. This study addresses that gap by examining the demand conditions, operational suitability, and policy requirements for hydrogen-powered freight transport in high-tech industrial clusters. It investigates suitable freight applications, adoption barriers, and policy measures that may support an operationally and economically viable transition. The study combines the Technology–Organization–Environment framework with a sustainability transition perspective and draws on expert seminars and stakeholder consultations involving high-tech manufacturers, logistics operators, energy infrastructure providers, and policy-related stakeholders.

2. Literature Review

Research on freight decarbonization indicates that no single technology is likely to be suitable for all logistics activities. Battery-electric trucks are advancing in urban distribution and short-haul operations, whereas hydrogen fuel-cell trucks may be more relevant to longer-distance, heavy-load, or high-utilization freight tasks. The relative suitability of these technologies depends on route length, charging or refueling access, dwell time, payload requirements, and fleet utilization. Hydrogen may be particularly relevant where charging downtime imposes substantial operational costs or where large battery systems reduce payload efficiency (IEA, 2023, 2024; ITF, 2023; Churchman et al., 2025).

This study draws on the Technology–Organization–Environment (TOE) framework to examine hydrogen freight adoption. TOE suggests that adoption decisions are shaped by technological characteristics, organizational readiness, and external conditions. In the context of hydrogen freight, technological considerations include vehicle range, refueling time, safety, and infrastructure compatibility. Organizational factors include fleet strategy, capital availability, maintenance capability, supply-chain commitments, and managerial willingness to invest. Environmental conditions include subsidies, regulations, energy prices, carbon policy, technical standards, and customer expectations. This framework is useful because it recognizes that vehicle performance alone is insufficient to determine adoption; hydrogen trucks must also be compatible with firms' operational requirements and the wider policy and market environment (Cantillo et al., 2022; Sugihara et al., 2024). The study also applies a socio-technical transition perspective, particularly the multi-level perspective. Hydrogen-powered trucks may be regarded as a niche innovation seeking to develop within a diesel-dominated freight regime. Climate policy, energy security concerns, carbon pricing, and corporate decarbonization requirements create pressures for change, but emerging technologies require more than environmental advantages to gain market acceptance. Their development depends on policy support, demonstration projects, infrastructure investment, stakeholder coordination, and cumulative learning. This perspective therefore highlights the importance of coordinated institutional support during the early stages of hydrogen freight development (Müller, 2024; Yap et al., 2024). Energy policy instruments can substantially influence this transition. Infrastructure investment, carbon pricing, public procurement, fiscal incentives, and technical standards may shape both fleet investment decisions and the availability of hydrogen supply. Vehicle incentives are unlikely to be effective where refueling access remains inadequate, while infrastructure investment may be underutilized if fleet operators face excessive procurement risk. Policy coherence is therefore essential to reduce uncertainty and establish credible expectations of market continuity (Teng et al., 2024; Hyun et al., 2025).

Existing studies have focused mainly on Europe, North America, and China, with less attention given to export-oriented high-tech industrial clusters in East Asia. Many comparisons remain technology-centered and do not sufficiently distinguish between freight tasks, logistics conditions, or industrial supply-chain requirements. This study addresses these limitations by examining hydrogen freight demand in science-park-based high-tech industries and linking operational conditions directly to energy policy design (Churchman et al., 2025).

3. Research Methodology

This study employs a qualitative design based on expert seminars and document-informed comparative analysis. This approach is appropriate because hydrogen freight in Taiwan remains at an early stage of market development, with limited large-scale data on actual fleet adoption. Relevant evidence is therefore closely linked to stakeholder experience, operational knowledge, and policy interpretation. Qualitative methods are particularly suitable for identifying potential adoption pathways, implementation barriers, and policy priorities in emerging technology transitions (Müller, 2024; Yap et al., 2024). The empirical material was derived from an industry report and the expert consultations supporting that report. Seminar participants had expertise in high-tech manufacturing logistics, freight operations, energy technologies, infrastructure development, and public policy. The original Chinese-language materials were translated into English and organized into thematic units addressing freight demand, technology suitability, infrastructure conditions, policy measures, and implementation barriers.

The analysis used thematic coding to identify recurring issues related to operational suitability, economic constraints, refueling infrastructure, policy support, market timing, and industrial readiness. These themes were subsequently interpreted through the Technology–Organization–Environment framework and socio-technical transition theory. Analytical validity was strengthened through triangulation across seminar evidence, comparison of alternative freight energy pathways, and international policy benchmarking. The purpose was not to establish statistical representativeness, but to develop

contextually grounded insights into hydrogen freight adoption in high-tech industrial clusters. The study has limitations. It does not estimate firm-level adoption probabilities, price elasticities, or lifecycle emissions under alternative hydrogen supply scenarios. Nevertheless, the analysis clarifies the freight contexts in which hydrogen demand may emerge, the factors constraining adoption, and the policy conditions that may support transition in Taiwan's high-tech industrial system.

4. Research Findings

The seminar-based evidence indicates that hydrogen demand in high-tech industrial clusters is likely to be selective rather than widely distributed across all freight activities. Stakeholders associated hydrogen-powered trucks primarily with operations in which vehicle downtime is costly, delivery schedules are tightly constrained, and transport distances or payload requirements limit the suitability of battery-electric alternatives. Relevant applications include inter-park transport of high-value goods, freight movements between science parks and maritime gateways, and cold-chain or specialized logistics requiring high vehicle availability and route reliability. The initial market is therefore more likely to involve high-utilization fleets serving time-sensitive industrial logistics than occasional or geographically dispersed truck operators (Sugihara et al., 2024). Table 1 summarizes the stakeholder findings and their implications for hydrogen freight adoption in Taiwan's high-tech industrial clusters.

Infrastructure availability remains a major adoption constraint. Although stakeholders recognized the technical potential of hydrogen-powered trucks, they emphasized that fleet deployment would be difficult without reliable and accessible refueling facilities. Hydrogen demand is therefore likely to emerge through concentrated logistics corridors rather than dispersed national deployment. Early refueling investment should focus on recurring node-to-node freight flows connecting science parks, ports, logistics centers, distribution facilities, and major industrial users. This approach may improve station utilization and reduce the risk of underused infrastructure investment (Hall & Rodríguez, 2022).

Key finding	Evidence from stakeholder seminars	Implications
Selective demand potential	Hydrogen-powered trucks were considered most relevant where vehicle downtime is costly, schedules are rigid, and transport distances or payload requirements limit the suitability of battery-electric trucks. Relevant applications include inter-park transport of high-value goods, science park–port freight movements, and cold-chain or specialized logistics.	Early demand is likely to arise from high-utilization fleets serving high-value and time-sensitive industrial logistics rather than from dispersed or occasional freight users.
Refueling infrastructure constraint	Stakeholders recognized the operational potential of hydrogen trucks but regarded reliable and accessible refueling facilities as a prerequisite for fleet investment.	Insufficient refueling access may prevent adoption even where hydrogen trucks are technically suitable. Demand is likely to develop through concentrated freight corridors rather than nationwide deployment.
Economic and investment barriers	Concerns extended beyond vehicle purchase costs to hydrogen fuel prices, maintenance capability, infrastructure depreciation, residual-value uncertainty, and financial risks associated with early adoption.	Hydrogen trucks may be perceived as commercially uncertain unless firms can justify higher initial costs through long-term operational or market benefits.
Importance of policy credibility	Stakeholders emphasized the need for predictable infrastructure planning, green hydrogen supply, carbon pricing, technical standards, and sustained fiscal support.	Short-term demonstration programs may increase awareness but are unlikely to produce long-term fleet investment without credible policy continuity.
Need for a multi-energy transition strategy	Stakeholders did not consider hydrogen a universal replacement for diesel. Battery-electric trucks were viewed as more suitable for shorter, predictable, and urban routes, while hydrogen was associated with heavy-duty, longer-distance, and high-throughput operations.	Technology choice should reflect route characteristics, payload requirements, vehicle utilization, and operational constraints.

Table 1. Research Findings on Hydrogen Freight Adoption in High-Tech Industrial Clusters

Economic considerations also limit adoption. Stakeholders identified concerns regarding vehicle acquisition costs, hydrogen fuel prices, maintenance capability, infrastructure depreciation, residual-value uncertainty, and the financial risks of early investment. Firms may be more willing to incur higher initial costs when carbon-related costs increase, customers demand lower-carbon logistics services, and policy conditions provide credible long-term signals. Without such conditions, hydrogen-powered freight is likely to remain an uncertain investment rather than a strategic logistics option (Tian et al., 2025).

Policy credibility was regarded as equally important as financial support. Stakeholders required greater certainty regarding infrastructure development, green hydrogen availability, carbon pricing, technical standards, and the duration of fiscal incentives. Short-term demonstration programs may support learning and awareness, but they are unlikely to influence long-term fleet investment unless embedded within a stable transition framework (Teng et al., 2024; Hyun et al., 2025). Hydrogen should therefore be considered as part of a multi-energy freight transition rather than a universal replacement for diesel transport. Battery-electric trucks may be more appropriate for short-haul, predictable, and urban routes, whereas hydrogen-powered trucks may offer greater value in heavy-duty, longer-distance, and high-throughput operations. Within high-tech industrial clusters, freight decarbonization is likely to require a combination of near-term efficiency improvements, battery electrification where operationally feasible, and targeted hydrogen deployment in suitable logistics corridors (Müller, 2024; Zhao et al., 2024; Churchman et al., 2025).

5. Discussion, Policy Implications and Conclusion

The findings indicate that hydrogen freight transition in Taiwan depends on coordinated policy and market development rather than vehicle technology alone. Hydrogen-powered trucks may be suitable for long-distance, heavy-duty, and high-utilization freight operations, but adoption requires alignment among freight demand, hydrogen supply, refueling infrastructure, carbon policy, industrial strategy, and fleet investment capacity. Technological performance is therefore only one condition for market development.

The Technology–Organization–Environment framework helps explain these adoption conditions. Hydrogen trucks are most relevant where extended range, rapid refueling, and intensive vehicle use are operationally important. Adoption also depends on firms' financial capacity, maintenance readiness, operational capability, and confidence that low-carbon freight will be valued by customers. External conditions, including refueling access, regulatory certainty, carbon pricing, technical standards, and stable market signals, are equally important. Weakness in any of these areas may delay fleet investment.

Hydrogen freight remains at an early stage in Taiwan, while diesel-based transport continues to benefit from established fuel networks, maintenance systems, fleet practices, and cost structures. Policy must therefore support emerging technologies while reducing the continued advantages of conventional diesel operations. Relevant measures include carbon pricing, green freight accounting, zero-emission procurement, technical standards, and targeted infrastructure investment. The findings also indicate that hydrogen should not be treated as a universal replacement for diesel trucks. Its strongest potential lies in concentrated freight corridors involving high-value cargo, heavy payloads, long travel distances, and demanding delivery schedules. Battery-electric trucks may be more suitable for short-haul, urban, and predictable routes with sufficient charging access, while low-carbon fuels may remain relevant for other applications. Freight decarbonization should therefore follow a differentiated, multi-energy approach. Science parks provide suitable early deployment settings because they generate concentrated freight demand and recurring flows between factories, ports, logistics centers, distribution facilities, and industrial service providers. Refueling infrastructure should be prioritized along science park–port, science park–distribution center, and inter-park routes. Corridor-based development may improve station utilization, reduce investment risk, and create practical evidence for later expansion. Hydrogen sourcing and certification should also be incorporated into infrastructure planning to avoid emissions displacement from upstream production.

This study contributes to energy policy research by linking hydrogen freight adoption to the operational requirements of high-tech industrial logistics. The findings suggest that long-term policy consistency, public–private coordination, demand aggregation, strategic procurement, and targeted corridor investment are more likely to support adoption than broad and undifferentiated incentives. Hydrogen-powered trucks may make a selective contribution to freight decarbonization when deployment reflects actual logistics demand, infrastructure feasibility, and industrial conditions.

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HOW (DO) HEALTHCARE MANAGERS ASSESS SERVICE SOURCING RISKS IN THEIR SERVICE SUPPLY CHAINS?

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Introduction

Service supply chain risk management (SSCRM) and its practices plays a critical role in achieving resilience in service supply chains (SSCs) (Senna et al., 2023; Duong et al., 2025) and enhances the primary goal of delivering services to customers (Duong et al., 2025). Yet, SSCRM practices are mostly under-researched in the SSCRM literature with even less attention given to risk assessment, which is an essential aspect in SSCRM (Choudhary et al., 2023). Previous studies on SSCRM have focused mainly on risk identification. For instance, several risks have been identified in healthcare service supply chains (HCSSCs) such as health pandemics and epidemiological events (Hohenstein, 2022); counterfeiting risks (Wang et al.); as well as the quality, supply shortages, and distribution risks (Dogbe et al., 2023).

Unlike the traditional goods-dominant supply chains (SC)s, SSCs are vulnerable to disruptions from risks (Senna et al., 2023), thus, service sourcing ensures continuous flow of services and the delivery of core service offerings (Duong et al., 2025). Particularly in HCSSCs, the unique characteristics of service make healthcare service sourcing even more complex, in contrast to sourcing of goods. We therefore focus on risk assessment in this study with a focus on service sourcing risk assessment practices within the HCSSC context. In doing so, we addressed the following research questions:

RQ 1: How do healthcare service supply chain managers prioritise service sourcing risks in their service supply chains?

RQ 2: What approaches and tools are being used to assess service sourcing risks in healthcare service supply chains?

Literature Review and Theoretical Background

Service sourcing and risk management in healthcare service supply chains

In contrast to traditional SCs, service flows form the bulk of SC flows in SSCs as the prior flow to be managed. In HCSSCs, service offerings to patients from a healthcare service provider consist of a combination of core service and supporting services (Baltacioglu et al., 2007), where the core service offering is the healthcare treatment provided to patients while the supporting services that could include more tangible nature such as the diagnostic equipment, the laboratory test, drugs, etc that are required when delivering the core service. To meet the increasing demand of healthcare service, healthcare service providers tend to source both core and supporting service from their first-tier service suppliers, a process that often exposes them to potential risks in their HCSSCs. Considering the wide range of service characteristics and the various service sourcing processes, there has been a consensus among scholars in the service purchasing literature regarding the complexity of service sourcing (Hofmann et al., 2020; Heinis et al., 2022).

Although, studies on SSCRM with particular focus on HCSSCs represent a growing field, research have identified potential risk associated with service sourcing that could prevent healthcare service providers from achieving the desired service level outcomes thus leading to service failures (Wang et al.; Hohenstein, 2022; Dogbe et al., 2023; Senna et al., 2023). Thus, to manage risk in the SC, the Supply Chain Risk Management (SCRM) literature has distinguished the four main processes that managers employ namely risk identification, assessment, mitigation and monitoring. Most relevant to our research is the second process which involve assessing the likelihood of risk occurring during service sourcing and its impact on service operations in the hospital. So far, risk identification and mitigation within the healthcare context have attracted interest among scholars (Belhadi et al., 2021; Hohenstein, 2022; Senna et al., 2023). However, the phenomenon of service sourcing risk assessment has been largely unclear. In this study, we examine this phenomenon by exploring how healthcare service managers and their service suppliers prioritise service sourcing risk and the approaches or tools that they employ to assess these risks.

Exploring the service sourcing risk assessment at the dyadic HCSSC level is significant as it can help managers to classify and prioritise these risks based on their probability of occurrence and impact, thereby informing the implementation of appropriate risk mitigation actions on the most significant risks (Hohenstein, 2022).

Service sourcing risk assessment through the lens of Agency Theory

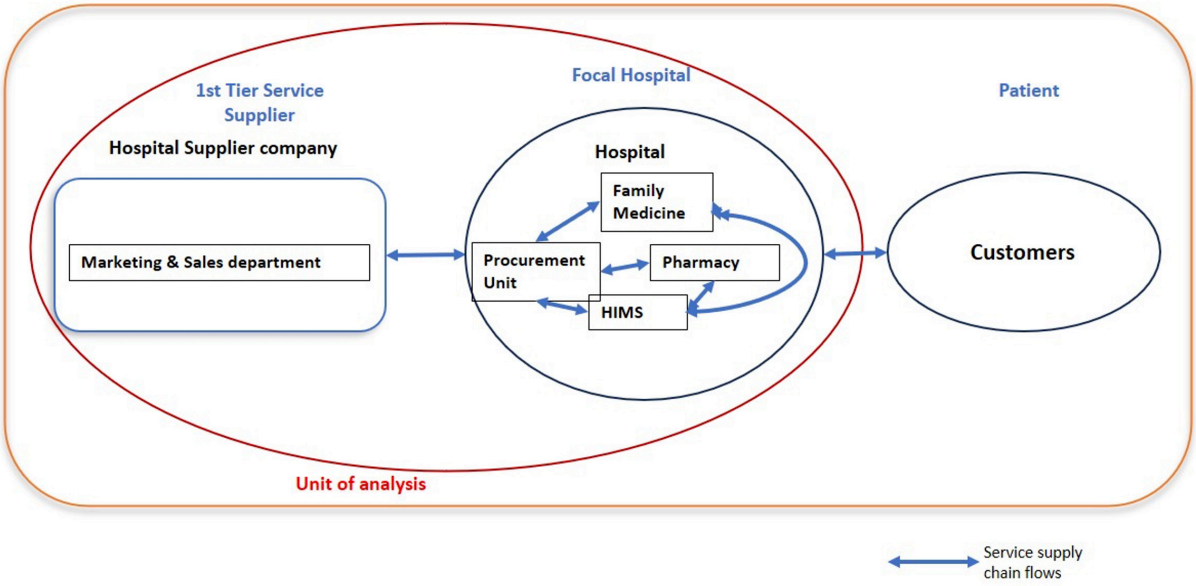
In HCSSCs, service suppliers play the important role of supplying services to healthcare service providers, the Agency Theory can offer the theoretical grounding for understanding how risk assessment influences the supplier-buyer relationship as it has been adopted by several scholars to understand the process of risk management in supply chains (Selviaridis and Norrman, 2014).

In SSCs, an important part of service sourcing process involves the stage where a formal contract is usually agreed between the service provider as the focal supply chain member (i.e. the principal) who procure services from the service supplier (i.e. the agent), creating a principal-agent relationship (Eisenhardt, 1989a). Challenges arising from the principal-agent relationship are often influenced by potential service sourcing risks. As such, risk assessment is seen as way in which service providers monitor risks during service sourcing particularly those emanating from their service suppliers in order to fully understand their likelihood and impact particularly on their hospitals (Zsidisin et al., 2004). Hence, approaches of assessing service sourcing risks in healthcare supply chains may be applied when sourcing for new suppliers or evaluating supplier relationship performance.

Methodology

Research Context

The study is situated on service sourcing risk assessment strategies in the Nigerian healthcare sector. With only 26.30 % of hospitals being privately owned and 73.7% being public owned (Federal Ministry of Health and Social Welfare of Nigeria (FMoHSW), 2024), the stratified nature of hospitals into tertiary, secondary and primary hospitals across the Nigeria's six geopolitical regions provided an appropriate and unique setting to gain in-depth insights in the phenomenon of service sourcing risk assessment practices.



Source: Authors

Figure 1: Healthcare service supply chain

In the healthcare service supply chain, hospitals serve as the focal supply chain members which purchase service from their first-tier service suppliers and provides healthcare service to patients as downstream partners (Figure 1).

Methods and Data Analysis

We employed a qualitative multiple case study approach (Stuart et al., 2002; Seuring, 2008; Yin, 2018) to elaborate theory (Ketokivi and Choi, 2014) on service sourcing risks assessment practices in HCSSCs. Multiple case study approach allows us to select cases based on replication logic in order to generalise theory within similar context (Eisenhardt, 1989b). Focusing on five case hospitals, each case represents at least two HCSSC stage (Seuring, 2008), i.e. healthcare services providers/hospitals as focal supply chain members and their first-tier suppliers, thus, ensuing richer insights were captured from relevant HCSSC partners. A purposive sampling approach was employed to select participants from the hospitals based on their experience, direct and indirect involvement in service sourcing processes and risk management practices in the hospital. In addition, the suppliers were selected based on a snowballing sampling approach mainly based on the references provided by the hospitals. Semi-structured interviews with procurement managers from the hospitals and their suppliers served as the primary data source. In addition, we conducted interviews with decision makers from various departments within the focal hospitals that collaborated with the procurement unit in the service sourcing process.

Overall, we conducted 28 interviews (19 hospital participants and 9 suppliers) between March 2025 and June 2025, utilising both face-to-face and online (via Microsoft Teams) interview approaches (Table 1). Secondary sources were also collected in the form of archival documents in combination with fieldnotes for triangulation purposes and to strength the validity of empirical data (Eisenhardt, 1989b; Yin, 2018). We analysed the data based on Braun and Clarke (2022) thematic analysis which begun with developing initial codes using an abductive approach i.e. combining insights from existing theory and new insights from our empirical data (Ketokivi and Choi, 2014) to elaborate on service sourcing risks assessment practices in HCSSCs. Both a single case and cross case analyses were conducted to identify similarities and differences in strategies relevant to risk assessment in the hospitals and their suppliers

	Case Hospital A	Case Hospital B	Case Hospital C	Case Hospital D	Case Hospital E
Level of care	Tertiary	Tertiary	Tertiary	Secondary	Secondary
Location	Northwest	Northcentral	Northeast	Northwest	Northeast
Participants interviewed	Procurement officer	Procurement officer	Procurement officer	Head of Procurement Committee	Head of Procurement
	Head of HIMS	Head of HIMS	Head of HIMS	Head of Medical Record	Head of Medical Record
	Head of Pharmacy	Head of Family Medicine	Head of Family Medicine	Head of Family Medicine	Head of Family Medicine
		Head of Pharmacy	Head of Pharmacy	Head of Pharmacy	Head of Pharmacy
Hospital Suppliers Interviewed	Head of Public private partnership (Equipment)	Procurement Manager	Marketing & Sales Regional Manager	Procurement Manager	Procurement officer
	CEO/Procurement Manager	Marketing & Sales Regional Manager	CEO/Procurement Manager	Procurement officer	
Data collected	**Primary data:** Interview transcripts, fieldnotes **Secondary data:** Public Policy documents, Law, Report, Brochure, Procurement Documents, and website materials				

Source: Authors

Table 1: Overview of cases and data collected

Findings

Service sourcing risk prioritisation in healthcare supply chains

Across the five case hospitals, evidence of risk prioritisation was observed among healthcare managers based on their own experiences and expert judgement about the identified risk. We categorised the risk priorities of healthcare managers using

the probability-impact risk matrix (Table 2). While high probability and high impact risks are mostly the concern for healthcare managers, interestingly, we observed that risk prioritisation were mixed across healthcare managers and their suppliers amongst the tertiary and secondary hospitals. Perhaps, this was due to the level of significant accorded to each identified risks relative to the service being sourced.

For instance, service sourcing risks with high likelihood of occurring but with low impact were given high priority by managers in the tertiary Hospitals Case. The participants reveal that tertiary hospitals struggled with challenges of communication and network infrastructure failures when employing their Electronic Medical Record (EMR) System which is mainly caused by frequent power outages or network downtime. As the EMR service is important to the hospital, suitable actions were taken to reduce the consequences of such risk. For example, when the risk occurrence was due to a power outage, the availability of backup Power Plant ensures that the hospital's service operations is immediately recovered after a power outage, as described by the head of HIMS department in Case Hospital_A: *"The one that is very high is when there is network failure concerning the electronic system. That one affects, you see everybody running Helter Skelter because but if it is power failure, the standby plants will not take more than 10-20 minutes, it will come back and everything will move ahead".* Similarly, the hospital suppliers prioritised medical product logistics associated transport risk as high, as highlighted by the marketing & sales regional manager of the pharmaceutical service supplier in Case B Hospital: *"I see the risks associated with transporting our goods from the warehouse to Hospital B as one of the major risk factors. Like I said, environmental factor in connection with the goods moving from Lagos to Abuja because it's going to pass through the Nigerian roads. The Nigerian roads is so volatile, the roads are not good, lot of risks associated with the road, there are arm robbers, there are, you know, bandits and what have you. So, we see that as one of the major risk. I categorise it as risk A".*

Examples of identified risks	Case Hospital A	Case Hospital B	Case Hospital C	Case Hospital D	Case Hospital E
High probability and Low-Impact risks					
Electronic Medical Record System Communication and Network Infrastructure Failures	×	×			
Lack of technical maintenance of medical equipment by the biomedical Department		×			
Medical product logistics associated transport risk		×			
High probability and high-Impact risks					
Supplier's incapacity to fulfil contractual obligations	×	×			
Unavailability of funds to pay suppliers	×			×	
Prolonged supplier payment delays			×		
Delayed supply of lifesaving health commodities				×	
Limited availability of essential medicines				×	
Healthcare workforce shortages affecting service delivery				×	
Low probability and Low-impact risks					
Internal challenges			×		
Low probability and High-impact risks					
Brand preferences by prescribers influencing demand				×	
Medical product logistics associated transport risk				×	
End-user incapacity to define service specification and complete requirements	×				
Unethical practices amongst hospital's employees affecting procurement and service delivery outcomes					

Source: Authors

Table 2: Service sourcing risk prioritisation across the case hospitals

In contrast, healthcare managers in the secondary Case Hospitals considered risk with low probability and high probability as high priority because of the potential consequences of such risks on service sourcing decisions. For instance, a high priority risk for Case Hospital_E is the unethical practices amongst hospital's employees affecting procurement and service delivery outcomes, as described by the head of procurement unit in Case Hospital_E: "Highest is the one that some attendant or clinicians collecting money at hand. The source of revenue, we get it hard to cater (account) for the revenue because we use central revenue, so we use receipt. Some, most of the workers they prefer collecting money at hand, then issuing receipts. So, there are there are loopholes [….] That's our problem". The severity of this risk is that the hospital has inadequate cashflow to make service procurement happen, thus leading to service delivery failure.

Overall, depending on the level of care, healthcare managers and their service suppliers focus on the most significant risks which they consider as high priority based on their practical knowledge about the livelihood of occurrence and level of the severity of the identified risk in the HCSSC. The significance of prioritising risks is to understand and prepare the most effective mitigation actions for each identified risk based on their importance.

Approaches for assessing service sourcing risks in healthcare supply chains

Our empirical findings show that several approaches and tools are employed by healthcare managers to assess risk associated with sourcing services across their HCSSCs. Interestingly, across the five case hospitals, the most common approaches are the use of technical and operational risk assessment practices (Table 3).

Examples of risks assessment approaches	Case Hospital A	Case Hospital B	Case Hospital C	Case Hospital D	Case Hospital E
Organisational risk assessment practices					
Formal risk assessment using Dedicated Monitoring and Evaluation Unit	×				
Dedicated Credit Control unit for financial risk			×		
Technical risk assessment practices					
Deployment of Gap Analysis		×			
Deployment of standardised risk checklists and historical data of risks occurrence		×			
Formal Risk documentation using Risk Registers		×			
Application of Strategic Risk Evaluation Framework e.g. SWOT Analysis			×		
Collaborative risk assessment practices					
Collective risk communication and decision-making approach during Management meetings				×	
Operational risk assessment practices					
Practical risks assessment				×	
Data Quality Assurance mechanism					×
Quarterly spot checks practices					×
Use of tally card for Inventory Tracking					×

Source: Authors

Table 3: Service sourcing risks assessment approaches/tools employed across the case Hospitals

On one hand, the hospital suppliers employ technical risk assessment practices such as formal risk documentation using risk registers, and the application of strategic risk evaluation framework e.g. SWOT analysis. For instance, the marketing & sales regional manager in the pharmaceutical service supplier in Case Hospital_C mentioned that the company employs SWOT analysis to evaluate the strength, weakness and opportunities of the company's vulnerability to exchange variations: "because exchange rate is an external factor, you know, we do a lot of SWOT analysis where you look at what are your strengths, what are your weaknesses, what are the threats that we have, so that at every point in time the company responds accordingly". On the other hand, the hospital participants employed mainly operational risk assessment practices such as quarterly spot checks practices and use of tally card for Inventory tracking. This finding reflects the level of competencies and capabilities to conduct risk assessment among managers in the HCSSC. It implies that healthcare managers in the hospitals rely more on their practical skills to assess risks during service sourcing rather than using a systematic and technological driven approach, as utilised by their service suppliers.

Discussion and Conclusion

Our study explores how healthcare service managers and their service suppliers assess service sourcing risk in their HCSSCs. This multiple case study of five case hospitals the Nigerian healthcare sector highlights several risks that were classified into four major risk prioritisation categories using the probability-impact matrix and identifies four distinct risk assessment approaches: organisational, technical, collaborative and operational risk assessment practices. We make several contributions to the SSCRM literature. The findings provide insights into the process of how risk assessment is considered as part of risk management practices in service supply chains. Building on limited pervious research on HCSSCRM risk assessment techniques, this study reveals risks prioritisation practices and identifies specific risk assessment procedures categorised as technical and operational risk assessment practices that are mostly employed by healthcare service managers and their service suppliers. This finding supports Harju et al. (2024), highlighting that the practice of risk assessment within the financial service sector were normally operational-oriented during service sourcing process. Thus, this study advances insights for healthcare service managers into approaches that their hospitals can implement to assess risks during service sourcing.

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INVESTIGATION OF HUMAN FACTORS IN TERMINAL ACCIDENTS AND THE ROLE OF IMMERSIVE TECHNOLOGIES IN TRAINING DE-FICIENCY

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Introduction and Problem Description

A significant transformation is currently taking place in the ports and terminal operations sec-tor, driven by digitalization, automation and the adoption of smart technologies (Development, 2025). As these environments become more dependent on technology, employees must in-teract with complex systems, adapt to rapidly changing operational conditions and continu-ously develop new skills (Suparman, et al., 2024). This trend is expected to accelerate further, as the automation of key port operations, particularly crane handling and docking activities, is projected to reduce global port sector employment by more than 8% by 2040 while increasing demand for advanced digital competencies (University, 2019). Meanwhile, maritime terminals remain dynamic workplaces where cargo handling, equipment operation, vehicle movement and human interaction occur simultaneously (Lopes, et al., 2025). As operations become more complex and technology-driven, the requirements for workforce competency continue to develop, creating an increasing need for continuous training, reskilling and safety aware-ness (Hussein & Song, 2022). However, workforce development often struggles to keep pace with technological advancements, resulting in gaps between existing competencies and emerging industry requirements (Lopes, et al., 2025). This has increased calls for more prac-tical and experiential training approaches to ensure workforce readiness and support safe and efficient operations within rapidly evolving terminal environments.

The increasing adoption of automation and digital technologies in ports and terminals is largely driven by the aim of improving operational efficiency and creating safer working environments. Nevertheless, accidents continue to occur throughout maritime operations, with human error being one of the most frequently reported contributing factors. Previous studies across differ-ent maritime sectors indicate that human factors account for approximately 70% of maritime accidents (Ishak, et al., 2019; Hussein & Song, 2022). These accidents are often caused by communication failures, fatigue, inadequate technical knowledge, and poor operational deci-sions. Although a study focusing specifically on container terminal operations reported that human factors contributed to around 27% of reported accidents, the underlying training relat-ed causes were not examined in depth (Lecue & Darbra, 2019). This means it is unclear whether such incidents are primarily linked to competency gaps, inadequate training or the limitations of current training methods. At the same time, digitalization and automation are changing the role of human operators in terminal operations. While reducing reliance on man-ual and routine tasks, these developments also introduce new challenges relating to the inter-action between humans and technology, and to decision-making (Água, et al., 2020). This raises questions about the adequacy of conventional training approaches for increasingly complex operational environments.

As maritime operations continue to evolve, concerns remain over whether traditional training methods are adequate for preparing personnel for increasingly digital work environments. Extended reality (XR) technologies have emerged as a promising alternative, offering immer-sive and repeatable training experiences that enable personnel to practice high risk opera-tional scenarios safely (Christopoulos & Stylios, 2024). Studies have reported performance improvements of up to 95% in XR based maritime safety exercises, highlighting their ability to support personalized learning by adapting training scenarios to individuals' needs and perfor-mance levels (Georgiou, et al., 2025). However, despite promising training outcomes, evi-dence demonstrating measurable reductions in human factor related incidents remains limited, with most validation studies confined to specific maritime terminal operational scenarios and activities. This study therefore combines a PRISMA based literature review with expert inter-views to bridge the gap between research and practice by evaluating the operational feasibility of XR technologies for addressing training deficiencies associated with human factors in mari-time terminal operations.

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Research Framework, Literature Review and Expert Insights

This paper focuses on the potential role of immersive technologies in addressing training re-lated contributors to human factor related accidents within maritime transportation. The sub-ject is examined from two complementary perspectives. Firstly, the literature on accidents, safety incidents, human factors, and training deficiencies was analyzed to establish the prima-ry causes and challenges affecting maritime operations (Corrigan, et al., 2020). Secondly, studies on immersive technologies in maritime transportation were reviewed to evaluate their adoption, application areas, and potential contribution to mitigating the identified human-factor and training-related issues (Kamis, et al., 2026).

A distinction was made between shipping applications, where immersive technologies are predominantly used for navigation, bridge operations, and onboard training, and port applica-tions, where their adoption remains comparatively limited and largely focused on specific op-erational and safety training scenarios. Consequently, this review investigates the extent to which immersive technologies have been applied to mitigate training related contributors to human factor related accidents in terminal operations. Based on the defined scope, the follow-ing claims are investigated:

I. There currently is no comprehensive academic literature base that systematically examines the relationship between immersive technologies, training deficiencies, and human factor re-lated accidents within maritime transportation.

II. Compared to conventional training approaches, immersive technologies offer significant potential for improving practical experience, operational preparedness, and competency de-velopment.

III. Contributing factor: Existing research on immersive technologies is predominantly focused on shipping related applications, while port and terminal operations are comparatively un-derrepresented.

IV. Contributing factor: When training related deficiencies are identified following operational incidents, industry responses primarily focus on modifying training content rather than recon-sidering the training methods and technologies used to deliver it.

This study was conducted using a two-stage research approach. First, a scoping review guided by the PRISMA framework (Page, et al., 2021) was conducted to identify existing evi-dence on human factors, terminal accidents, training deficiencies and immersive technologies. The review process is presented in Figure 1. Subsequently, expert interviews were conduct-ed to further explore the findings, validate the identified gaps and provide insights into the ap-plicability of immersive technologies for terminal training in the industry.

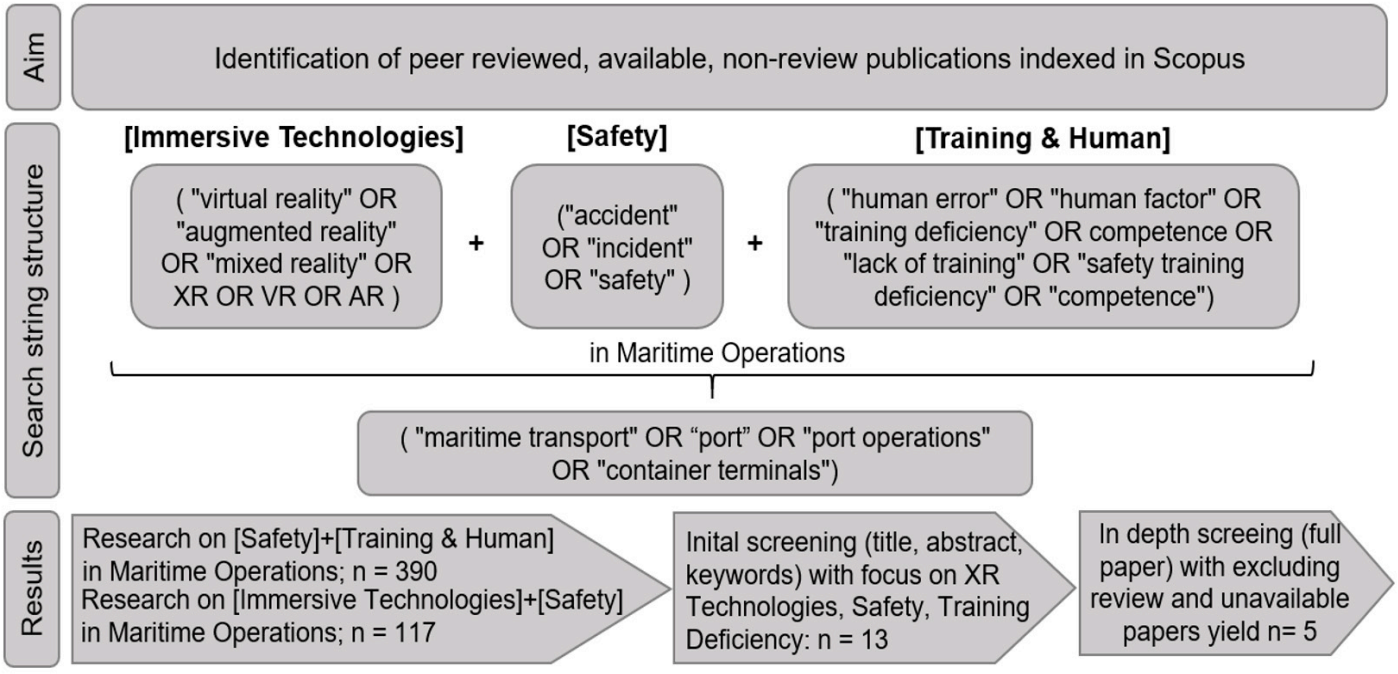

Figure 1. Review process including search string and result overview, own representation

A structured literature search was conducted using the Scopus database (search date: 1 June 2026), including all publications indexed up to the search date. To ensure consistency with the scope of this study, only publications addressing human factor related safety chal-lenges within maritime terminal operations were considered, while studies focusing on onboard vessel operations and navigation were excluded. The review followed a three-stage search strategy. The initial search identified 390 publications related to human factors, acci-dents and safety in maritime terminal environments. A second search, focusing on immersive technologies in terminal safety and training contexts, yielded 117 publications. Thirteen stud-ies were produced by combining both research streams, with the topics addressed being im-mersive technologies, human factors, training related deficiencies and safety. Following screening of titles, abstracts, and full texts, the five publications most closely aligned with the focus of this review were selected for detailed qualitative analysis (see Table 1).

Table 1. Overview of the publications most closely aligned with the scope of this review, own representation

Paper of:	Application Domain	Immersive Technology	Training & Human Factors	Training & Human Factors
Caballini et al. (2023)	Container Terminal	Augmented Reality (AR)	Hazard prevention; Worker safety	Situation awareness
Saager et al. (2021)	Port Operations	AR	Situational awareness	Decision support
Georgiou et al. (2025)	Maritime operations	Virtual Reality (VR)	Safety training	Human centered VR design
Miyusov et al. (2024)	Maritime operations	VR/XR	Learning safety	Competency development
Nazir (2026)	Maritime operations	Digital / XR - supported	Human performance	Competency assessment

The literature review findings were complemented by semi structured interviews (Vila-Henninger & Lara, 2025) being conducted with eight professionals working in maritime termi-nal operations. Participants were purposely selected to represent a variety of viewpoints on training and safety in the context of maritime terminal operations. The sample included both operational personnel and experts involved in training, safety and digitalization projects, with the aim of capturing practical and strategic viewpoints. The interviews explored current ap-proaches to accident investigation and training, as well as the development of competencies and perceptions of immersive technologies in training. Particular attention was given to how training deficiencies relating to human factors incidents are addressed in practice, and to the feasibility of using immersive technologies as a solution. The findings were then compared with the literature review and interpreted according to the participants' professional roles and areas of expertise. The collected data were analyzed using an iterative thematic coding ap-proach inspired by Braun and Clarke's Reflexive Thematic Analysis (Ahmed, et al., 2025). The analysis generated 72 initial codes, which were refined into eight categories and three overarching themes. These themes were subsequently used to identify recurring patterns, common challenges, and research gaps within the literature.

Result and Analysis

The literature review revealed two dominant research streams related to the scope of this study. The first stream investigates the human and organizational factors that contribute to safety incidents and accidents in maritime operations. The second explores the use of im-mersive technologies as preventive training tools aimed at improving safety performance and reducing risks related to human factors. While both topics have been widely discussed in the literature, only a limited number of studies explicitly link immersive technologies to the mitiga-tion of human factor related accidents through improved training practices. Furthermore, ex-isting research predominantly focuses on shipping and onboard operations, whereas com-paratively little attention has been given to port and terminal environments (Corrigan, et al., 2020; Giovannetti, et al., 2025).

Across the reviewed studies, human factors emerged as a major contributor to accidents, with common causes including inadequate training, communication failures, misjudgment and work-related fatigue (Giovannetti, et al., 2025). Open source accident reports and previous studies also suggest that incidents often involve falls, being struck by objects, being trapped, and the improper use of vehicles, machinery, and equipment. Recent research on occupa-tional safety and workforce training highlights a growing focus on competency development, upskilling the workforce, and integrating digital technologies to address evolving operational demands. However, despite the growing interest in innovative training approaches, there is still limited empirical evidence demonstrating measurable reductions in accident occurrence and long-term safety performance following the implementation of immersive technologies (Zain, et al., 2025).

Figure 2 presents representative examples of the coding process used during the analysis and illustrates how individual codes were grouped into broader categories and themes. The examples are intended to illustrate the coding procedure rather than provide a complete over-view of all identified codes. The following sections combine the themes that emerged from the interviews with the findings of the literature review. This provides a comprehensive overview of the current challenges in training, human factors and the role of immersive technologies in maritime terminal operations.

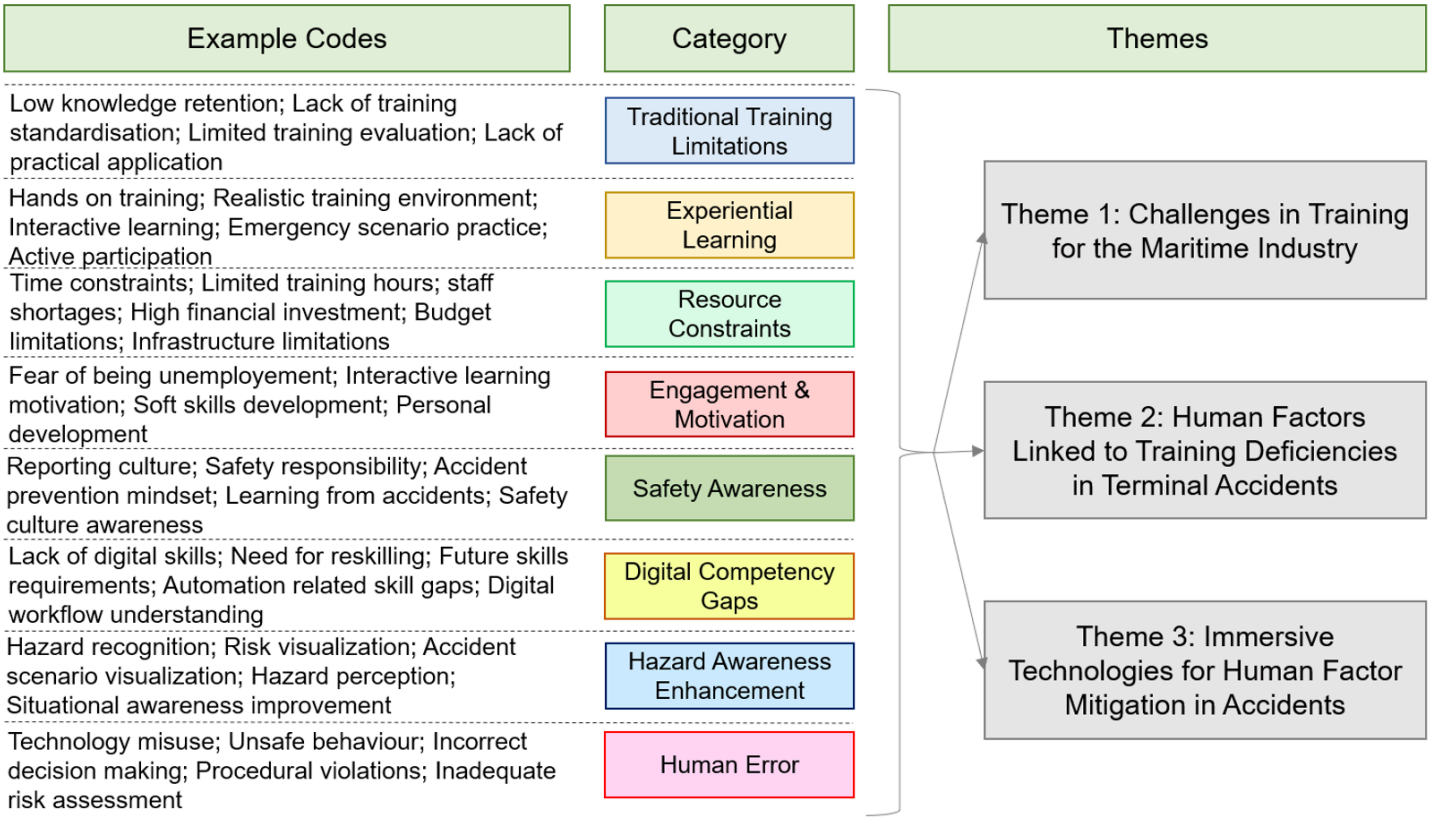

Figure 2. Illustration of the Coding, Categorization, and Theme Development for Interview Analysis, own representation

Theme 1: Human Factors Linked to Training Deficiencies in Terminal Accidents

Human factors were identified as a consistent contributor to accident risks in terminal opera-tions. Rather than attributing accidents solely to technical failures, participants emphasized that communication breakdowns, inadequate hazard recognition, poor decision-making and challenges in adapting to increasingly digitalized working environments often lead to an in-crease in operational risks. This highlights the limitations of current training approaches. Situa-tional awareness was identified as one of the most critical human factors. Participants ex-plained that employees working in dynamic terminal environments must continuously process information from vehicles, equipment, and digital systems. While digital technologies support operational efficiency, inadequate training can increase cognitive workload, reducing workers' ability to recognize hazards and anticipate unsafe situations. Research into maritime safety has also produced comparable results. A lack of perception, understanding and anticipation of events has been identified as a major cause of human error, especially as reliance on digital systems grows. (Grech, et al., 2002; Dominguez-Péry, et al., 2021). Participants identified communication breakdowns, coordination failures, resistance to technological change and a lack of digital skills as the main human factors that contribute to unsafe operational decisions. They also explained that accident analysis serves not only to identify the causes of incidents, but also to review procedures, compare findings with regulations and adapt training accord-ingly. These findings suggest that human factors related to accidents should not be viewed as individual failures, but rather as indicators of broader training and organizational deficiencies. This is consistent with previous maritime safety research (Sánchez-Beaskoetxea, et al., 2021). Consequently, participants emphasized that future safety training should strengthen communication, situational awareness, decision making, and digital competencies.

Theme 2: Challenges in Training for the Maritime Industry

Participants identified several challenges associated with current training practices in maritime terminals. Although traditional learning methods like classroom-based sessions or presenta-tions are still widely used, they are often considered inadequate for preparing employees for complex operational environments (Hussein & Song, 2022). A recurring concern was the diffi-culty of translating theoretical knowledge into practical workplace competence. Workforce diversity and learner motivation emerged as important challenges for maritime training. Differ-ences in educational background, language proficiency, digital literacy, and previous opera-tional experience influence how quickly employees acquire new competencies. Participants noted that individuals with prior exposure to the maritime sector, such as through family mem-bers working in the industry, often adapt more quickly than newcomers. Motivation also varied across employee groups. Experienced workers were sometimes reluctant to attend additional training, while younger employees generally preferred shorter training periods to enter the workforce sooner. These differences create varying learning needs and can affect engage-ment, knowledge transfer, and overall training effectiveness. Both the interviews and the lit-erature highlighted a growing gap between evolving operational requirements and existing workforce competencies. The increasing automation and digitalization of workplaces creates new competency requirements that existing training systems often struggle to address. This reinforces previous findings that rapid technological change requires continuous updates to training content and flexible learning approaches. (Esser, et al., 2020). Previous research similarly identifies changing skill demands, limited digital competencies among trainers, and insufficient investment in education and training as significant challenges to workforce devel-opment (Chang , et al., 2025). In the interviews, participants emphasized the need for broader training programs that combine technical knowledge with soft skills such as adaptability, criti-cal thinking, and digital competencies to reduce skill gaps and support employee reskilling in response to evolving operational demands.

Theme 3: Immersive Technologies for Human Factor Mitigation in Accidents

Across all interviews, immersive technologies were seen as a potential solution for enhancing safety training and mitigating the risk of accidents caused by human factors. Participants em-phasized that VR, AR and MR allow employees to experience hazardous situations that would be difficult or impossible to recreate safely in real terminal operations. By simulating emergen-cy situations, AGV operating areas, cargo securing procedures and other high-risk tasks, trainees can observe the consequences of unsafe actions, practice appropriate responses and learn from mistakes without endangering themselves, the equipment or the cargo. In addi-tion, participants explained that these realistic experiences improve hazard recognition and decision-making by demonstrating the consequences of unsafe behaviour. They also high-lighted that immersive technologies increase learner engagement by allowing repeated prac-tice of complex scenarios in a controlled environment. These findings are consistent with pre-vious studies showing that immersive technologies improve situational awareness and opera-tional preparedness in safety-critical settings (Saager, et al., 2021; Miyusov, et al., 2022). An-other recurring finding was the successful implementation of digital technologies. Participants emphasized that immersive applications should provide reliable, accurate and task relevant information in order to support operational decision-making. Unreliable systems or excessive information can undermine employee trust and hinder the acceptance of technology. Similarly, recent research in the field of maritime VR indicates that successful implementation depends not only on the technology itself, but also on system design that is centered on the user and on realistic training scenarios that reflect operational requirements (Georgiou, et al., 2025; Nazir, 2026). This finding is consistent with previous research indicating that context aware AR systems enhance the situational awareness of maritime operators only when information is presented clearly and without causing cognitive overload (Saager, et al., 2021; Caballini , et al., 2023). Participants also acknowledged that the effectiveness of immersive technologies has not yet been fully validated in real port operations. They implied on the need for iterative testing and close alignment between software design, training objectives and learner charac-teristics before wider implementation (Miyusov, et al., 2022). Finally, participants underlined the importance of using immersive technologies to complement, rather than replace, conven-tional training methods. They highlighted the need to integrate VR, AR and MR into broader training programs, as conventional training alone is increasingly insufficient to prepare em-ployees for digitalized terminal operations. Immersive learning, however, can accelerate work-force adaptation, support reskilling and reduce skill gaps by providing hands-on experience. This is consistent with previous research demonstrating that VR promotes embodied cogni-tion and improves knowledge retention by facilitating active learning rather than passive in-struction (Kato & Julius, 2026).

Discussion and conclusion

This study contributes to the growing body of research on human factors in maritime training by combining expert interviews with a systematic literature review. The review of accident reports and human factors studies identified communication issues, training deficiencies, and competency related problems as recurring contributors to safety incidents in maritime terminal operations. The interviews further highlighted digital transformation and evolving competency requirements as major challenges for terminal safety. Additionally, the review of immersive technology applications revealed that few studies have investigated their use in port and ter-minal operations. In contrast, including shipping in the search of accident and human factor related studies yielded more than 1,400 publications, indicating that existing safety research remains largely dominated by shipboard operations. The combined findings suggest that ad-dressing training deficiencies requires reconsidering not only training content but also the way training is delivered through immersive, learner centered approaches. Interview participants further emphasized that successful implementation depends not only on the technology itself, but also on trainers capable of effectively integrating immersive technologies into the learning process. Reliable system performance was also identified as essential, as technical failures may reduce user confidence and hinder technology acceptance. Ultimately, the success of immersive training depends on its integration into training practice, adaptation to different learner needs, and continuous refinement to promote safe operational behaviour. Although immersive technologies demonstrate significant potential for improving practical learning and supporting workforce adaptation, current evidence is largely derived from simulation studies, pilot implementations, and expert evaluations rather than long term applications in operational environments. Consequently, empirical evidence demonstrating measurable reductions in accident rates and sustained improvements in safety performance under real terminal condi-tions remains limited. Future research should therefore focus on large scale validation studies evaluating both training effectiveness and operational safety outcomes.

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WHEN DISRUPTION BECOMES THE BASELINE: BUILDING ADAPTIVE CAPABILITY IN FOOD DISTRIBUTION SUPPLY CHAINS.

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Key Words – Dual Hemisphere Sourcing, Cross functional alignment, Climate Action, Geopolitical risk, supply chain resilience & agility.

Introduction

The food supply chain plays a vital role in society, once the product is harvested it needs to be put through production, packaging, shipped and delivered to the end user in a timely manner (Zhong, Xu and Wang, 2017). In the last number of years multiple disruptions like Climate, Conflict and Economic Downturns have slowed down progress for development and advancement (FAO, 2021). Given the short window of opportunity to take the product from farm to fork it is imperative that the supply chain works seamlessly end to end. Any disruption within the supply chain puts both product and profit at risk. Climate change is one of the biggest threats to the supply chain as increased extreme weather events have had detrimental impacts on crops, infrastructure and availability (Schmidhuber and Tubiello, 2007). Geopolitical influence and turbulence have a significant impact on supply chains, they insert volatility and uncertainty into the chain along with significantly impacting prices, availability and security (Incekara and Incekara, 2024).

This study looks at the many challenges that exist within the food industry both internally and externally. Climate change is one of the most threatening phenomena that the food industry has to prepare for, within this study it will be assessed if geographical location determines climate action. The study will also look at internal mis alignment of key performance indicators (KPI's) and how they can inhibit the implementation of mitigation strategies. The study will also look to determine if there is one strategy that can mitigate against both climate and geopolitical challenges and how effectively it can be implemented.

Literature Review

Supply chain originally defined as trade between suppliers and customers, has in recent years been more clearly defined as a supply chain where multiple factors are considered (Blanchard, 2021). The supply chain is the most important element of any business as it is the method of getting goods from manufacturing through to the consumer. Blanchard also cited that the "best in class" supply chains have multiple common characteristics. The supply chain consists of two distinct elements which are the supply element and the management element (Chen and Paulraj, 2004). The critical part of a successful supply chain is where all elements are working together cross functionally. Cross functional alignment is typically at mid to senior level within an organisation (van den Adel, de Vries and van Donk, 2022). (Ambulkar et al. 2015) determined that this cross functional alignment within supply chains has been employed by organisations to improve their resilience to disruptions within the supply chain, and that firms that adopt this strategy are better placed to deal with disruptions but have acknowledged that it is dependent on the level of the disruption. In further publications (Ali, Mahfouz and Arisha, 2017) cited that sometimes when there are too many cross functional opinions that reaction to disruption can sometimes be hindered by the process of each department focusing on their main challenge rather than the overall view of reaction required.

Climate Change

Climate change is a very challenging phenomenon to clearly define as it is not something that is widely accepted as being a challenge in society (Werndl, 2016). It is however very important that we understand the concept of climate change and acknowledge that we accept observations of mean surface temperature changes as an indicator that there has been a shift in climate over the years (The House of Commons, 2006) if we are to be able to put strategies in place to not only provide robustness to our supply chains but to also make significant changes in production and manufacturing to lessen the burden on the environment.

One of the main considerations in the food industry when it comes to climate change is food risk and the security of food provision. In recent years we have seen significant impact on crops due to climate change, crops are highly sensitive to changes in climate and any deviation from optimal conditions can lead to crop failure of reduced yield (Mirón, Linares and Díaz, 2023). This in turn reduces the supply of product and increases demand which inevitably increases cost. Miron et al. (2023) concluded that food prices are a fundamental factor in food security and supply and since 2007 food prices have been on a constant incline. (Alexandratos and Bruinsma, 2012) concluded that with greater than 14% additional demand for food products in the world that now more than ever climate change and reduced yield from crops is an issue and that demand has now by far outweighed supply and has led to over 19% increase on average for the price of food products. (Lalit et al., n.d. 2022) have concluded that there needs to be an increase in food production and crop yield of 50% to meet the current demand. It has been widely agreed that dual hemisphere sourcing where possible is the best way for businesses to mitigate against shortage risk (Baozhuang et al., 2015). By having dual hemisphere sourcing the business increases the one harvest crop to now having two harvests per year, one in each hemisphere. This allows agility to switch between both supply options should one crop fail, or any other disruption occur. Baozhuang et al., (2015) discussed this in the context of the tech industry but the same concepts apply to crops. This theory has been supported by (Mena and Stevens, 2010) where they concluded that given the changes in the food supply demand coupled with climate challenges that having geographical diversification is key to resilience and agility in meeting consumer demand on food and price.

Mena and Stevens (2010) also concluded that global output has been growing at an average rate of 2.3% since 1961 which is outpacing the population growth, which was 1.7% in the same timeframe, this is in contradiction with Lalit et al., n.d. who concluded the opposite being the case where population was outpacing production. As much as there is contradictions within the industry regarding growth and demand Werndl (2016) also correctly concluded that until there is a consistent understanding of climate change and the impact it has on the food industry it will be difficult to see changes and the world will continue to see shortages of certain products and a continued upward trend on pricing.

Geopolitical Risk

Geopolitical risk can be defined as a branch of political geography which observes patterns and relationships between countries (Sun and Chi Wei Su, 2024). Geopolitical actions pose a very imposing risk on the food supply chain (Hendrix and Brinkman, 2013). Tariffs for example can move product imports from being competitive to be seriously uncompetitive and are usually politically driven rather than food related. Geopolitical impact on the price of food products has been extensively studied and according to (Chowdhury, Meo and Aloui, 2021) there is a direct link between geopolitical interference and food poverty. Within the food industry, one of the main factors to mitigate against geopolitical risk is to have multiple sources of supply from different geographical locations. This means that if one supply is hit with tariffs you can simply transition to another without financial impact on your supply chain (Kumar, 2022). Political interference and trade barriers are causing serious disruption in the food supply chain, although this is felt in price everywhere the main impact is felt in less wealthy nations where it creates further poverty (FAO, 2023). It is only by understanding the political reasons for actions that industry can put mitigating strategies in place.

Sanctions put on some countries like Iran have caused serious food insecurity as they no longer have access to open markets at prices they can afford, this has significantly increased poverty and malnutrition in the country (FAO, 2023).

The new political leadership in the United States has recently threatened significant tariffs on all products entering the US, although there is little academic literature on the topic to date if we look back to 2018 when the Trump administration implemented significant tariffs on Spanish olive oil (Bown and Kolb, 2025). This had a very negative impact on Spain in terms of exports; they continued to blend oil for the US but could not use oil of Spanish origin. On the other hand, it freed up a lot of stock onto the European market and reduced prices for European consumers. As much as this was a short term benefit the damage geopolitical intervention causes far outweighs any advantage.

Methodology

The research adopted an interpretivist paradigm in order to understand how people understand, interpret and react to disruptions within the supply chain. Interpretivism, also known as the constructivism, dictates that that the reality of what is happening is not objectively determined but constructed socially and subjectively interpreted (Schwandt, 1994). The use of this paradigm was particularly prevalent within the exploration of disruption within the food supply chain as each industry and country interpret the data based on previous experience to similar challenges. Given the complexity of food sourcing

and distribution it is vital to engage this paradigm to ensure that all opinion and strategies are explored (Golicic and Davis, 2012). This strategy will help ensure that there is a mutually shared understanding between the interviewer and participants given both parties work within the same industry. The interviewer has worked across all elements of the supply chain being reviewed making this approach the most appropriate.

Surveys were conducted with an Irish and International food distribution company with participants in the roles of Logistics / Warehousing, Procurement & Middle management all with non-decision-making roles. Interviews were conducted with the same roles but with decision making directors. This method was engaged to determine if there is a difference between Irish and International perception of threats and also to determine if there is a disparity between non-decision-making roles doing the day-to-day work and decision makers who set the KPI's and strategies.

Findings

The study conclusively showed that every person had experienced disruption within the last decade with the frequency of disruption becoming more challenging in terms of availability of produce and cost. One of the main strategies that was accepted across all functions was Dual Hemisphere sourcing can mitigate against both climate challenges and geopolitical turmoil, however when we look deeper with in depth interviews it becomes apparent that there are significant challenges with implementation. Looking at Dual Hemisphere sourcing when it comes to climate it is possible to not only mitigate against climate challenges but also have two crops instead of one in certain products. Taking Broccoli for example Ecuador is the cheapest but not the most reliable or consistent whereas Spain having a slightly higher priced product have consistency and reliability. Implementing dual hemisphere sourcing is however still a challenge when it comes to internal alignment and also from a price perspective, It is difficult to separate sustainable intention from actual sustainable action (Zanasi et al., 2017). There is no doubt that organisations are making moves towards being more sustainable with climate in mind, however, in reality as outlined by Zanasi et al, (2017) in a very competitive environment most companies will choose price over sustainability in a lot of cases. Despite the acceptance of the benefits of dual hemisphere sourcing from an internal perspective there is a battle between elements of the supply chain where warehousing KPI's lean heavily towards making sure days on hand are kept low and warehouse capacity does not exceed 85%, this is not possible when you are managing both long distance full container business parallel to short lead time pallet deliveries, so despite the benefits of having a dual source the internal struggle remains between departments.

One of the most startling findings from the study is the perception of the threat posed by climate change, from the Irish distribution business it was evident that the threat is front and centre in terms of focus and need to adapt to combat both the challenge and make changes to prevent future escalation, however when the International business were interviewed (United States based) they firmly believe that climate change is "pocketed" and see geopolitical turmoil to be a more immediate and greater scale threat. This would be very much in line with the theory of (Bas, 2025), where they discuss the impact that the political leadership within a country have on the public's perception of climate change. It would appear that the US distribution company are more focused on short term threats to the supply chain rather than longer term planning to ensure longevity of food security. The findings from this study would raise the question if political leadership of climate action should be removed as the political cycle is very short and climate action requires significantly longer-term planning; with each change of leadership there is a different focus either greater or less but certainly not consistent with making any real change.

Conclusion

The research aimed to determine how food supply chains can be more agile, resilient and ensure they are future proofing their business with adaptive strategies in terms of combating the impact of climate change and geopolitical turmoil. The findings showed that disruption is no longer a one-off event and seems to be more the baseline in today's society. This is in line with academic theories presented outlining the need to be more adaptable and include more strategic process to mitigate risk while becoming more sustainable, considering localised sourcing if only in part and to integrate circularity where possible into the supply chain (Antonius Setyadi, Suharno Pawirosumarto and Damaris, 2025). The study also outlines that despite the best strategies, mitigation and future planning, that without internal cross functional alignment it will not be possible to progress efficiently. Internal tensions make any implementation difficult and slow up the process to the point they are no longer viable. It is time for organizations to move into a proactive role rather than the current reactive role they hold today. Throughout the research on multiple occasions, it has been highlighted that Climate is the most threatening phenomenon facing our and future generations, unless every person and every industry take some proactive action to

mitigate against climate change, we will not see any improvement in the decades or centuries to come. Implementing strategies such as dual hemisphere sourcing and diversification of supply will not only protect the food industry but will also alleviate the significant pressures on certain regions. As a generation, we all acknowledge the issue it is now time for us all to play our part personally and professionally.

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GOVERNMENT-BASED ENERGY CONSERVATION CAMPAIGNS AT TIMES OF GEOPOLITICAL CRISIS: A COMPARATIVE CASE STUDY OF EGYPT, FRANCE, GERMANY, PAKISTAN, AND THE UK

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Abstract

Purpose

This paper focuses on conservation initiatives from a nationwide perspective during times of high geopolitical challenges. The paper explores the associated risks on the sustainable and timely flow of energy resources to meet economic, social, and developmental needs while implementing strategies towards energy efficiency and sobriety within the household sector, in addition to its reflection on cost and efficiency measures, sustainability, and consumer behavior.

Research Approach

This study uses an exploratory qualitative research approach to examine and compare how the countries under study from various continents with diverse contextual and geographical backgrounds respond to sudden threats and risks to the potential disruption in energy flows and the reduced access to its resources.

Finding and Originality

Key areas of findings were analyzed in light of an interdisciplinary lens guided by frameworks from management, humanities, and behavioral sciences fields, mainly Kotter's seminal eight-step process model and four principles of successful change management, and Aristotle's three appeals of human influence and persuasion. The findings also shed light on factors related to the (a) nature of the energy conservation campaigns, (b) involvement of public figures and advocacy groups, (c) use of technology and social media tools, (d) empowerment of the general public, and (e) empowerment of Gen-Z.

Research Impact

The findings of this study will contribute to the research theory and practice in areas related to energy efficiency, risk assessment, and energy management.

Practical Impact

This paper is significant for policymakers and practitioners in the field of energy management and efficient consumption. The paper highlights the overarching visions and practical roadmaps, as well as the implementable best practices that the countries under study employed while responding to the risks associated with the sudden disruption of energy flows during times of critical geopolitical tensions.

Keywords: Energy Conservation Campaigns, Geopolitical Crisis, Energy Disruption, VUCA, Residential energy consumption, Risk Assessment, Change Management.

Introduction

It is of no surprise that the world has been operating under a roller coaster mode of adverse events in recent years, most evidently depicted by the COVID-19 pandemic, the Russian-Ukraine war, the Israeli-Palestinian war, and lately the geopolitical tension between the U.S., Israel, and Iran. This certainly comes in addition to the environmental challenges related to global warming and its associated climate change. This definitely brings into mind that we are currently experiencing the concept of the VUCA world which is characterised by the occurrence of events that are unpredictably highly volatile, uncertain, complex, and ambiguous (Bennett & Lemoine, 2014; Bernstein, 2025). This risky mode of operation has obligated many countries around the globe to become constantly vigilant towards potential wide-scale impactful crises on their energy resources as well as on their supply chain flow, which opened the room for designing contingency plans that utilizes a sustainable and wise approach towards energy provision and consumption.

Problem Statement and Research Objective

Although governments across the globe have started to realize the impending need for rigorous energy conservation plans, there is an apparent lack of documented best practices or blue prints of such wide-scale initiatives that could eventually be used as an already tested plug and play viable collective contingency plan or implementation program that is both efficient and effective and also aligns with the demographic and cultural aspects/ considerations of their respective populations, but without hindering or challenging their social, economic, and developmental aspirations. Hence the need for exploring how different countries have been experimenting and implementing different programs in action in recent years. This paper is intended to portray an overview of these programs.

Literature Review

Energy consumption of individual residential household behavior is reported to represent around 20%-30% of the total energy consumption in various countries (Federal Ministry of Economic Affairs & Energy, 2025; International Emergency Agency, 2023), with major energy uses related to heating and cooling of spaces, water heating, electronic appliances, cooking appliances. Thus it is an important sector to consider in energy conservation plans initiated by governments. In fact, the International Energy Agency (IEA) has developed a list of 10 measures to reduce energy consumption worldwide, around 60% of which was directly related to the choices of individual behavior (International Emergency Agency, 2026).

Methodology

Conceptual Framework employed

This study uses an interdisciplinary lens guided by frameworks from the management, humanities, and behavioral sciences fields, mainly Kotter's seminal eight-step process model and the four principles of successful change management, and Aristotle's three appeals of human influence and persuasion to analyze the findings related to the various conservation campaigns.

Data Sources, Collection, and Analysis

Extant data that are publicly available and related to official reports, announcements, and audio-visual material published on official governmental websites and other social media accounts, as well as other relevant institutions were thoroughly examined. Several search words have been used to facilitate the data collection process (e.g., energy conservation campaigns, energy management, sustainability, energy conservation measures, energy consumption by residential sector, energy consumption by households, energy risk management, energy efficiency, energy waste reduction, energy consumption, energy waste prevention, renewable energy, solar energy, energy security). Thematic analysis was employed for deductive coding (Creswell, 2013).

Challenges and Limitations

Several challenges were faced while conducting this study. The first one was related to the data collection of non-English speaking countries, especially when an official governmental translation was not provided. To overcome this challenge, I had

to depend on automatic website translation tools. The second challenge related to restricting access to official governmental websites from outside the country for security reasons. For example, I was not able to access official governmental websites in Pakistan, to bypass this challenge, I attempted to collect data from their official accounts on social media. In addition, this study is limited to examining recent core government campaigns targeted towards private residential households that were triggered by the countries under study in response to the world crises that started unfolding in recent years.

Discussion and Findings

In this section, I discuss the key findings in light of Kotter's seminal eight-steps process model of change and transformation management through mapping the core actions adopted by countries under study to each step as well as the four interwoven essential principles that were addressed in the updated framework that facilitates successful change initiatives (Kotter, 2026; Kotter & Rathgeber, 2017).

Step 1 - Create a Sense of Urgency:

This step addresses the need for shedding light towards a looming and dangerous or risky situation or a great opportunity that if left unattended will have severe consequences on their economic, social well-being, and energy sustainability. Each of the five countries under study has successfully portrayed the crisis situation with their population and the associated threat that looms if no action was taken to address it promptly. By doing so, they were able to generate public attention, focus, and bring people together towards a common goal. However, a noticeable area of observation reveals that some countries around the globe might not have taken energy conservation initiatives in full power in response to global warming, climate changes, and the persistent call of environmental protection, sustainability, and the reservation of energy for future generations – not until the COVID-19 pandemic hit the world followed by several geopolitical tensions took place. This is when, in my estimation, countries and citizens joined forces to accelerate progress towards augmented energy saving plans, because they experienced the sense of urgency.

Step 2 - Build a Guiding Coalition:

This step represents a critical stage in successful change initiatives, where a diverse team of influential people with different backgrounds and skills are brought together to work on developing a strategic implementation plan. All five countries under study were able to form a representative team of key people with different backgrounds. For example, Egypt formed a Central Crises Management Committee where they were responsible to monitor the ongoing critical global event around the clock while assessing the risks and potential implications (State Information Service, 2026, Feb 28). Another example of building a guiding coalition was represented by the United Kingdom's Energy Efficiency Task Force to support the change towards an accelerated reduction of energy demand (GOV.UK, 2023). This step also witnesses Kotter's (2026) "Select Few and Diverse Many Principle: You need more eyes to see, more brains to think, and more legs to act in order to accelerate your change efforts" (Kotter, 2026, p. 14).

Step 3 - Develop a Strategic Vision and Initiatives:

This step in the change management process highlights the importance of having an applicable strategic plan for orchestrating the change with minimal side effects and maximum efficiency that will motivate people to take intended actions for a significant outcome. It is critically important to mention here that most of the countries had this vision of energy conservation for years - but perhaps was not put into full power by the public until after the recent catastrophic world events have unfolded. In fact this observation aligns well and is interpreted by Kotter's (2026) "Head and Heart Principle: You can't appeal to people with data and facts alone. You must also account for how people feel. Most people aren't inspired by logic alone, but rather by the fundamental desire to contribute to a larger case. If you can provide greater meaning and purpose to your effort, extraordinary results are possible" (Kotter, 2026, p. 9-17).

Step 4 - Communicate the Change Vision:

This step addresses the importance of effective communication with the general public on a larger scale, where it is highly important to solicit their buy-in and active contribution and support. This was highly evident while examining the different conservation campaigns conducted by the countries under study, with the apparent use of a wide array of mainstream media (e.g., TVs, radios, printed newspaper, highway billboards) as well as the efficient utilization of social media (e.g., Facebook, Instagram, LinkedIn), in addition to official governmental websites. In addition, the messages that was shared with the public were short but reflective of the meaning, for example, Germany have created an infographic style flyer with "25 Tips on Saving Energy" and translated it to several languages that reflect the majority of languages spoken by their residents (Federal Ministry of Economic Affairs & Energy, 2025, August).

Step 5 - Empower Others to Act:

Another critical step in change management is having the ability to actually involve people in the transformation process and eliminating potential obstacles that could hinder their positive contribution (e.g., mis-information, spread of negative vibes and rumors, acts of demolishing morale, etc.). This step was reflected in the slogan/ names of all the examined campaigns: Egypt's "Hand in hand, we'll conserve energy", France's "Every Action/ Gesture Counts", Germany's "80 millions working together for the energy shift", Pakistan's "Every Small Switch Adds Up", and UK's "It All Adds Up". In addition, Egypt took a further step by the empowerment of Gen-Zs enrolled in universities and educational institutions and soliciting their active involvement and participation through creative competitions and the use of digital tools which ultimately raises their awareness of the global crisis and encourages the implementation of energy saving habits at their schools and their homes which they can then spread into their communities (Ministry of Higher Education & Scientific Research, 2026). Hence this step reflects Kotter's (2026) "Have To and Want To Principle: Those who feel included in a meaningful opportunity will help create change… you need to give people a choice to participate and true permission to step up and act … [they will] provide the energy if you invite them" (Kotter, 2026, p. 9-20).

Step 6 - Generate Short Term Wins:

This step addresses the importance of continuously sharing the milestone results and impact of the actions that were taken to make the change happen, even if the final results were not attained yet. Alternatively, this step could also help decision makers in making alterations or amendments of actions that did not achieve the planned outcomes. For example, one of the measures taken by Egypt was the early closure of shops, malls, restaurants, and cafes by 9 pm (with an exception of weekends and touristic cities and sites). This mandate was called back after the pilot test stage of almost one month given that its unfavorable impact on the economy and tourism outweighed the intended benefits. In fact this action could be interpreted from the perspective of Sterman's systems dynamics model and how some decisions may not lead to the linear anticipated results, in fact, they may lead to counterintuitive side effects (Sterman, 2001).

Step 7 - Sustain Acceleration and Don't Let Up:

One of the greatest mistakes of all time is losing momentum or slowing down after achieving milestone successes. This is essentially true in change initiatives that involve a wide-scale public participation, especially when the main reasons that called for the urgency of the change have diminished, and hence a state of public complacency evolves. Thus, it is important at this step that the governments and decision makers associated with the energy conservation campaigns do not lose sight of the ultimate goals and keep on encouraging the general public for a sustainable action.

Step 8 - Institute Change:

The final step of the change management framework is to ensure that the new behaviors and actions are repeated long-term and are solid enough to replace old habits. This is the step where most change initiates fail to reach the final intended outcome due to the retreat that takes place when people start feeling more comfortable reverting back to their old behavior. In fact, Kotter (2026) addresses the importance of institutionalizing change in the "Management and Leadership Principle: As new ways of working become part of the fabric … the need for management and leadership is critical. Strong management is needed… and strong leadership is needed to capitalize on unpredictable winds of opportunities". (p. 31).

I also analyze the findings of this study from the perspective of Aristotle's three appeals of influence and persuasion: (a) Ethos, (b) Pathos, and (c) Logos (The Decision Lab, 2026). Table 1 represents a summarized version of how the different campaigns under study have utilized these techniques while attempting to convince the general public to change their behavior into a more sustainable and wise consumption of energy.

Influencing & Persuasion Appeals	Sample of how the Appeals were Reflected/ Employed in the Campaigns
Ethos	Leveraging such things as the credibility, ethics, authority, reputation, of the message sender. This was reflected in the use of stars and trusted public figures in various campaigns (e.g., Egypt, France, & the UK).
Pathos	Leveraging such things as emotions, feelings, values, and beliefs of the target audience. Also the use of patriotic or religious phrases or family oriented emotional themes or cultural proverbs or humor. Example: The utilization of humor in campaigns in France to raise public awareness regarding energy saving measures in a fun and light way (Egta, 2026 add to reference). Another example was from the campaign in Pakistan: "Use [energy] wisely to power a stronger, more resilient and self-sustaining nation" (NEECA, 2026, Apr 16).
Logos	Leveraging such things as reason, logic, and evidence of the intended message. This could be vivid when associating suggested change in day to day behavioral actions with potential statistics and major % decrease in energy consumption. An example was reflected in the German campaign as follows: "Most energy in the home is used for heating (71%) and hot water (15%). Consequently this is where the greatest savings potential is to be found" (Federal Ministry of Economic Affairs & Energy, 2025, August).

Table 1: A sample reflection of how Aristotle's three appeals were employed

Table 2 portrays a summary of the different energy conservation campaigns that were adopted by the countries under study and targeted towards private residential households and which involved a list of common minor behavioral action items that could yield major energy saving impacts while operating electronic devices at home and work.

Country	Key Initiatives
Egypt **Campaign Slogan:** Save It.. Light It: امرونت امرفـو **Hand in hand, we'll conserve energy:** ايا فـى ايا هنرشد اكيا **Target Plan:** Achieve a 10% saving in energy consumption by 2027 & 18% by 2035.	**Sample of Disseminated Guidelines** (North Delta Electricity Company, 2020). • Run washing m/cs with full loads. • Dry laundry under natural sunlight instead of electric dryers. • Use a water cooler dispenser in summer instead of having to open the fridge several times during the day. • Turn off electronic water heaters during summer time / when not in use. • Turn off light, TV, and A/C when you leave the room. • Set the A/C thermostat to 25°C. • Install curtains /shutters/ double glazing windows to reduce heat transfer. • Regularly clean the A/C filters. • Use a shower instead of filling the bathtub. • Use water heaters that run on solar energy. • Use gas instead of electric cooking furnaces. • Avoid operating electric devices during peak times of the day • Avoid using ironing machines during peak loads. • Use LED / fluorescent light bulbs instead of the traditional tungsten bulbs. • Add reflectors and use brightly colored paint to the interior walls of the building to minimize the dependence on extra light bulbs. • Utilize natural light as much as possible during the day. **A sample of other regulatory measures involved:** • Remote work system for 1 day per week across most sectors except essential & critical institutions (e.g., factories, schools, & hospitals). (SIS, 2026, Mar 28). • Reduction and/or turning off street & billboard advertising light to the minimum possible level without comprising public safety and security measures. (SIS, 2026, Mar 18). • Early closure of the government district offices at 6 pm (SIS, 2026, Mar 18). • Incentives to encourage switching to solar energy (SIS, 2026, Apr 26). • Published a daily real-time grid tracker reflecting the peak & minimum loads of electricity to guide citizens & other beneficiaries on the most suitable times to operate electronic devices during the day (Ministry of Electricity & Renewable Energy, 2025). • Published a smart meter connectivity tracker to help businesses manage & track their regular consumption of electricity & gas (Telecom Egypt, 2026).

France **Campaign Slogan:** Every Action/ Gesture Counts - I turn it down, I turn it off, I shift it: *Chaque geste compte - Je baisse, j'éteins, je décale* **Target Plan:** Reduce energy consumption by 40% by 2050.	**Sample of Disseminated Guidelines** (Ministry of Ecological Transition, 2023, Oct 16; Service Public). • Set the heating temperature to a maximum of 19 degrees at home. • Set the water heater to 55 degrees and stay in the shower for less time. • Air dry the laundry instead of using an electronic dryer. • Turn off all devices when not in use. • Postpone the use of electrical appliances (e.g., washing machine, dryer, dishwasher, etc.) outside the peak hours. • Do not prewash dishes under hot water when you plan to use a dishwasher. • Use the eco-dishwasher program. • Install a programmable thermostat to control the temperature at home • Slow down while driving. • Leave the car and use public transportation, car pooling, or a bike for short trips. • Set the A/C to 26°C. at the office, car, or home. • Install the Ecowatt app. **A sample of other regulatory measures involved:** • Turn off hot water in the toilets of public buildings & order municipalities to reduce water temperatures at public swimming pools by 1°C. (Reuters, 2022, Oct 5). • Asking public-sector workers to travel by train rather than plane for journeys under four hours. (Reuters, 2022, Oct 5). • Enforcing a 19°C. temperature limit in public buildings and lowering that to 18°C on days when the grid is under strain. (Reuters, 2022, Oct 6). • Encouraging work from home. (Reuters, 2022, Oct 6). • Civil servants driving government vehicles will be required to limit their speed to 110 kilometers per hour. (Reuters, 2022, Oct 6). • Limiting air conditioning usage at homes, offices, & public buildings until indoor temperatures exceed 26°C., while upper heating temperature limits are set to an average of 19°C. with some exceptions (e.g., hospitals, medical facilities, establishments accommodating elderly people, etc.). (Service Public, 2024). • Air-conditioned or heated stores and businesses should keep their doors closed and restrict illuminated advertisements between 1 and 6 am. (BBC, 2022). • Marketed the programmable thermostat to help in managing the energy consumption through automatically adjusting the home temperature based on the timing of the day and the occupancy in the room. (Ministry of Ecological Transition, 2023, Oct 16). • Marketed the Ecowatt app: a real-time grid that alerts citizens and other beneficiaries on the times that they need to reduce or shift their electricity consumption to avoid power shortages or potential cuts (Ministry of Ecological Transition, 2023, Oct 16).

Germany	**Sample of Disseminated Guidelines** (Federal Ministry of Economic Affairs & Energy, 2025).
Campaign Slogan: 80 millions working together for the energy shift: *80 millionen gemeinsam für energiewechs-el* Germany makes it efficient: *Deutschland macht's effizient* **Target Plan:** Decrease primary energy consumption by 50% by 2050 compared to 2008.	• Lower the heater by 1°C. • Install smart and programmable thermostats to manage temperatures, • Bleed radiators. • It's better to ventilate intermittently, not continuously. • Seal doors leading to the attic and basement. • Close doors between the rooms. • Heat the rooms that you are actually using. • Change shower head and tap to water saving flow limiters and aerators. • Take shorter showers with low temperature and turn-off the water when soaping. • Wash your hands in cold water. • Use gas-instead of electric fan heaters. • Only heat the rooms that you are using. • Load the washing machine as full as possible and use eco-setting. • Dry clothes on a clothes airer. • Replace old incandescent and halogen light bulbs with new LED bulbs. • Avoid the use of decorative lighting in the house or garden. • Set the fridge temperature at 7°C. and 18 for the freezer. **A sample of other regulatory measures involved:** • Retail stores should close their doors throughout the day to reduce electricity consumption for air conditioning when it is hot / for heating when it is cold outside. • Switching off illuminated advertising after 10 pm, unless they serve traffic safety • Aesthetic lights on monuments & buildings should be turned off at night unless public safety is involved or in the cases of cultural events and festivals. • Halls /corridors in public buildings should not be heated and office temperature is to be limited to 19°C., with some exceptions (e.g., hospitals). • Switching off instantaneous water heaters / hot water tanks for hand washing in public buildings, government offices, including some showers in sports centers. • Heating private pools is prohibited with some exceptions (e.g., rehab centers). • Heating efficiency check-ups will be conducted on buildings (DW, 2022).

Pakistan **Campaign Slogan:** Every Small Switch Adds Up **Target Plan:** Achieve energy savings worth up to $6.4 billion (2022 prices) and a 2050 net-zero transition.	**Sample of Disseminated Guidelines** (NEECA, 2026). • Avoid the operation of high load appliances such as washing machines and irons and switch off unnecessary light during peak hours (6-10 pm). • Set the A/C temperature at 26°C. or above. • Switch off lights, fans, A/Cs when the room is empty. • Keep the fridge 2 to 4 inches away from the wall to maintain a better air flow. • Car pool and combine your errands in smarter trips. • Switch off your car engine while waiting at a signal or a shop. • Limit your highway speed to 100 km/hour. **A sample of other regulatory measures involved:** • Closed schools for two weeks and shifted universities to online class schedules to reduce commuting (Reuters, 2026). • Gov't departments had a 50% cut in fuel allowances for 2 months (Reuters, 2026). • Government offices to operate four days a week and reduction in staff numbers working in offices by 50% with an exception of essential services (Reuters, 2026). • Limiting businesses operating hours to 8 pm in some areas, while bakeries, restaurants, and food and beverage shops, marriage halls and other commercial places to be closed at 10 pm (WION, 2026). • Marketed and incentivised the PM's Fan Replacement Program that aims at swapping old-energy intensive fans with new ones that are energy efficient (NEECA, 2026; ECF). • Launched & imposed energy labelling scheme w/ minimum energy performance standards (MEPS) on appliances such as fridges, A/Cs, & fans (NEECA, 2026; ECF). • Expanded the EV public charging network (NEECA, 2026). • Offered quick home energy checks to provide guidance on how to improve the efficiency of the biggest energy-wasting appliance. (NEECA, 2026).

United Kingdom **Campaign Slogan:** It All Adds Up **Target Plan:** Transition away from fossil fuels and deliver clean power by 2030 and net zero by 2050.	**Sample of Disseminated Guidelines** (Energy Saving Trust, 2026). • Dry laundry using the warm weather or on indoor drying racks, instead of tumble dryer. • Limit the showering time to just four minutes & 4-minutes songs were shared for helping with keeping track of the time. • Unplug or completely turn off appliances instead of operating on standby mode. • Insulate water tanks, pipes, and radiators. • Avoid overfilling the water kettle with extra water and use tap aerators. • Wash clothes on a 30°C. and avoid higher temperatures and reduce the washing machine run to one per week. • Operate the dishwasher when it is fully loaded & limit its usage to one run per week. • Swap a bath for a shorter shower. • Turn the lights off when you are not in the room or when you are not using them. • Seal unwanted gaps in windows & doors to avoid the exchange of air temperatures. **A sample of other regulatory measures involved:** • Manufacturers and suppliers must display energy efficiency class ratings on appliances to help consumers make an informed decision regarding their energy saving attempts. (GOV.UK, 2026). • Providing incentives for home energy efficiency and conservation upgrades and retrofitting such as insulations, low-carbon heating, solar panels, smart thermostats and heating controls, and draught-proofing (Home Energy Guide, 2026).

Table 2: Comparison of different government conservation campaigns and initiatives

Conclusion

Although the study portrayed robust energy conservation campaigns that adopted effective theoretical approaches of successful change management with influencing and persuasion techniques from the management, behavioral sciences, and humanities field, an important question arises: are the associated changes that were motivated by these conservation campaigns considered a temporary shift or alteration in consumer habits and behaviors that were adopted by the public to overcome atypical crises driven shocking times which in turn lead to scarcity in supplied resources, or would that be an embedded and sustainable new norm of how we are likely to consume energy wisely and efficiently on the long-term.

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CO-DESIGNING SCOTLAND'S ELECTRIC HGV CHARGING FUTURE: THE E-FREIGHT PLANNER ONLINE DECISION TOOL

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Abstract

This paper presents the iterative, stakeholder-driven development of the e-Freight Planner, an interactive web-based planning tool for electric heavy goods vehicle (HGV) charging infrastructure across Scotland. Framed as Action Design Research (Sein et al., 2011), the work is distinguished from prior participatory simulation studies in three ways. First, the e-Freight Planner is a web-deployed, sustained-use artefact rather than a workshop-bound model. Second, engagement was with a multi-stakeholder coalition, Transport Scotland, two Distribution Network Operators (DNOs), the National Energy System Operator (NESO), and freight industry representatives, rather than a single client. Third, the headline outcome of iteration was not a set of feature additions but an explicit shift in the tool's primary audience, from haulage fleets and charge point operators to energy system stakeholders responsible for anticipatory grid investment. The e-Freight Planner translates outputs from an agent-based simulation suite (MILES), driven by telematics covering approximately 8 to 10 percent of all HGV-kilometres travelled in Scotland over one year, into an explorable scenario-driven interface. The tool was developed over four documented iteration cycles between November 2025 and January 2026, each producing traceable changes to outputs, spatial conventions, and underlying assumptions. The audience shift reshaped every architectural layer of the tool: output granularity (peak MW and hourly load curves), spatial conventions (5 km radius zones rather than exact sites), and integration formats (CSV exports aligned to Regional Energy Strategic Planning and Distribution Future Energy Scenarios pipelines). We discuss what this reveals for decision-support tool development at the freight-energy interface. The current tool is available at https://efreight-planner-test.onrender.com/. A short tutorial video demonstrating the interface and main functions is available at https://www.youtube.com/watch?v=R2PHIXaQfEY&t=38s.

Keywords: Electric HGV, charging infrastructure, decision-support tool, action design research, stakeholder co-design, agent-based simulation, freight decarbonisation, grid planning

1. Introduction

Scotland has set ambitious targets for transport decarbonisation, with current Scottish Government policy requiring 45% of the national carbon reduction trajectory to come from transport. Heavy Goods Vehicles (HGVs) remain a disproportionate source of road transport emissions, and the transition to battery electric HGVs at fleet scale will require a national charging infrastructure that does not yet exist, designed in coordination with an electricity grid undergoing rapid change under regulatory and investment cycles (ED3, RESP, DFES) that operate on timescales of years rather than months.

Modelling commissioned by Transport Scotland has previously established the technical feasibility of a fleet-scale transition (Utomo et al., 2025), identifying a minimum-viable network of at least 63 en-route charger locations, with the M74 and A9 corridors carrying the heaviest forecast demand. Between technical feasibility and operational investment, however, lies a translation gap: simulation outputs delivered as CSV files or static report figures cannot directly inform the decisions of the network operators, freight operators, and regional planners who must collectively realise the infrastructure. Each stakeholder community has its own modelling pipelines, planning cycles, and data conventions, and a report alone rarely bridges them.

This paper documents the development of the e-Freight Planner, an interactive web-based planning tool designed to close that translation gap. The e-Freight Planner is not a simulation in itself; it is a stakeholder-facing interface to MILES that lets users explore scenarios, view spatialised charging demand against grid capacity, and download data formatted for downstream use. The tool emerged not from a pre-specified requirements document but through an iterative co-design process that ran in parallel with technical development, with each stakeholder iteration reshaping subsequent design choices.

The contribution of this paper is methodological. We frame the work as Action Design Research (ADR; Sein et al., 2011) and identify three features that distinguish the e-Freight Planner from prior participatory simulation studies: a sustained-use web artefact rather than a workshop-bound model; engagement with a multi-stakeholder coalition rather than a single client, introducing audience plurality as a first-order design concern; and a headline outcome that was not a feature set but a fundamental reframing of the tool's primary audience. We argue this audience shift is the central finding of the work, and the kind of emergent design outcome ADR is built to surface.

2. Related Work

Action Design Research (Sein et al., 2011) builds IT artefacts iteratively with organisational stakeholders, drawing on the action research tradition (Susman and Evered, 1978) and sitting within the broader family of design science research (Hevner et al., 2004). ADR is organised around problem formulation; building, intervention, and evaluation (BIE); reflection and learning; and formalisation of learning, with a central premise that what is delivered is an ensemble artefact, a tool together with the organisational arrangements and design principles that make it consumable. Mullarkey and Hevner (2019) elaborate the BIE stage into nested cycles that more closely reflect how iteration proceeds in practice; our four cycles map onto this elaborated process.

ADR shares ground with participatory and facilitated simulation modelling and co-creation approaches in design research, all of which hold that artefacts are more useful when developed with, rather than for, the stakeholders who will use them. The present work extends ADR in two directions relative to established applications such as Tako and Kotiadis's (2015) healthcare-focused participatory simulation framework. First, the artefact is a web-deployed tool for sustained use beyond any single facilitated session, so ongoing iteration replaces facilitated workshops as the dominant engagement mode. Second, the stakeholder community is not a single host organisation but a coalition of distinct communities (energy network operators, freight operators, government, charge point operators) with different planning timescales and data conventions, so audience plurality replaces the single-client structure typical of ADR applications.

Agent-based modelling has emerged as a leading approach for freight decarbonisation transitions, particularly where charging infrastructure decisions interact with route choices and grid constraints (Utomo et al., 2025), sitting within a broader hybrid simulation tradition (Brailsford et al., 2019). International work has examined commodity-level electric truck potential (Liimatainen et al., 2019) and battery/charging requirements against duty cycles (Plötz et al., 2019); UK analyses have addressed minimum-cost long-haul decarbonisation pathways (Ainalis et al., 2020) and electric road systems versus battery-only operation (de Saxe et al., 2023). The WattRoutes project modelled Scottish corridor infrastructure (Hunter et al., 2024). Phase 2 of the Transport Scotland project (Utomo et al., 2025) used telematics from approximately 2 percent of registered Scottish HGVs, identifying 63 charger locations and 11 substations requiring upgrade even at this modest penetration. What distinguishes the present work is its focus on the translation layer between technical simulation and stakeholder decision-making, rather than the simulation itself.

Tools at the transport-energy boundary must bridge different timescales and spatial scales: transport models operate at the level of journeys and depots, energy planning models at the level of grid investment cycles and substations. Recent NESO and DNO guidance emphasises two-way communication between transport demand modellers and energy system planners under the ED3 anticipatory investment framework, with the RESP and DFES pipelines increasingly used as integration points for electrification demand forecasts. Tools producing outputs formatted for these pipelines are more likely to influence investment decisions than tools built only for a transport-side audience.

3. The e-Freight Planner Tool and the MILES Simulation Suite

3.1 The MILES Simulation Suite

The Modelling Infrastructure for Logistics Electrification in Scotland (MILES) simulation suite has been developed across three phases of work commissioned by Transport Scotland. MILES represents individual battery electric HGVs as autonomous agents with rules governing route selection, charging decisions, and energy consumption; collective phenomena, charger utilisation, charge-state distributions, journey time penalties, and substation-level grid power draw, emerge from these interactions. Phase 3, the basis of the work reported here, uses telematics covering approximately 8 to 10

percent of all HGV-kilometres travelled in Scotland over one year, a substantial expansion from the approximately 2 percent of registered HGVs used in Phase 2 (Utomo et al., 2025); synthetic data calibrated to known route networks fills gaps where industry telematics is unavailable. MILES models three charging strategies (depot-only, en-route only, mixed) across vehicle efficiency, battery capacity (500 kWh and 1000 kWh), and charger power (350/500 kW en-route, 150 kW overnight) parameters, and maps simulated demand onto primary substations using DNO open data; full technical detail is reported in Utomo et al. (2025).

3.2 e-Freight Planner: Architecture and Interface

The e-Freight Planner was originally prototyped as a Gradio web application before being rebuilt as a Flask application with a custom HTML and JavaScript front-end, a change driven by the limitations of the prototype framework for stakeholder-facing use around visual design, accessibility, and data pipeline integration. The current architecture comprises three layers. The data layer holds MILES outputs in a Hive-partitioned Parquet structure on Cloudflare R2 object storage; migrating from raw CSV reduced the dataset from approximately 10 GB to 1.15 GB (an 88 percent reduction), essential for a low-cost cloud deployment and rapid scenario loading. The application layer is a Flask backend serving three tabbed analytical views: Routing (proposed and existing charger locations against demand along strategic corridors); Charging (utilisation and grid power draw per location, with a dual-map comparison that emerged directly from Cycle 3 feedback); and Bay Sizing (bay requirements estimated live using Erlang B queueing theory, replacing earlier pre-computed lookup tables, a substantive methodological commitment driven by stakeholder feedback that sizing needed to respond dynamically to scenario choices). The presentation layer is an HTML/JavaScript front-end with season-aware cascading dropdowns and a Leaflet map of Scotland (Figure 1), plus a custom upload feature for external scenario data.

Architectural decisions across these layers are almost all traceable to specific iteration cycles. The 500/350/150 kW parameter values and DNO/NESO CSV formatting were committed in Cycle 1, as was the Gradio-to-Flask rebuild. Live Erlang B bay sizing, the dual-map visualisation, the substation/GSP layer, and the internal/public view distinction emerged from Cycle 3. Hourly load curves, peak MW per location, 5 km spatial zones, the RESP/DFES-compatible export pipeline, and the deprecation of public RAG ratings were specified in Cycle 4. The Parquet migration was an internal performance decision, not stakeholder-driven, but necessary to make the live-calculation moves of Cycles 3 and 4 feasible on a low-cost cloud deployment.

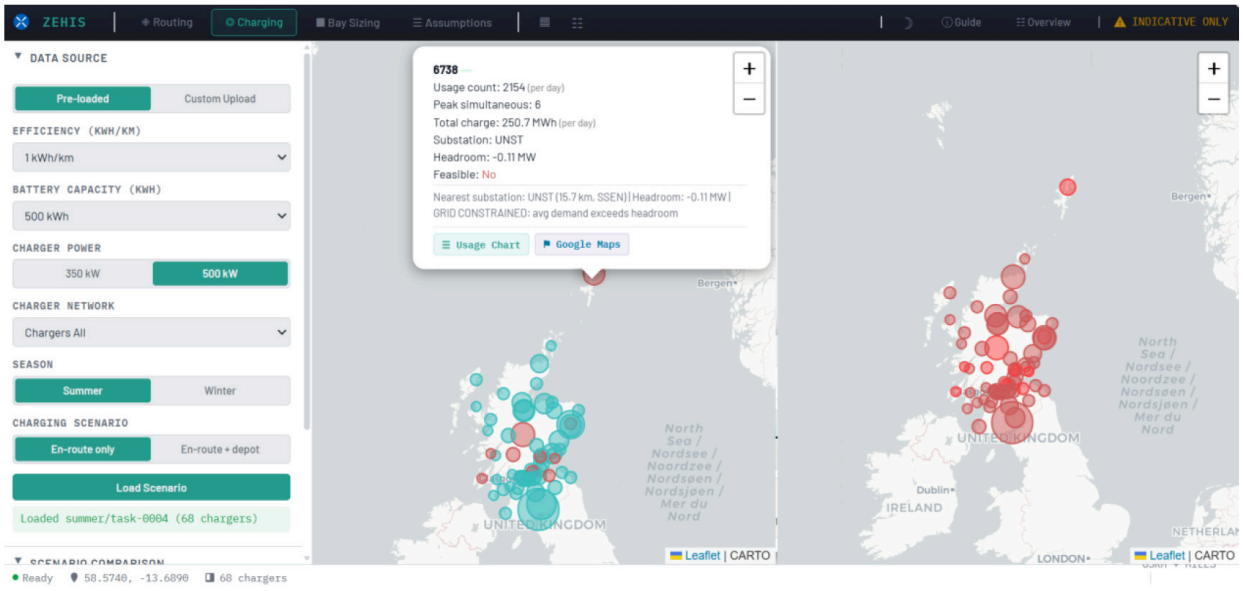

Figure 1. The e-Freight Planner interface (Charging view). Sidebar controls allow selection of season, efficiency, battery, power, network, and scenario; the map renders charger locations and grid impact across Scotland.

The full e-Freight Planner tool is deployed and publicly accessible; a short video walkthrough of the tool is also available:

Tool: https://efreight-planner-test.onrender.com/

Video walkthrough: https://www.youtube.com/watch?v=R2PHIXaQfEY

4. Iterative Stakeholder-Driven Development

The development of the e-Freight Planner was structured around four sequential stakeholder iteration cycles between November 2025 and January 2026 (Table 1). The cycles were not pre-planned as a fixed methodology but emerged as project milestones requiring stakeholder validation; each played a different role, the first established technical alignment with energy stakeholders, the second was a strategic-framing checkpoint, the third tested a working prototype against client priorities, and the fourth produced the most consequential reframing of the tool's audience and purpose. The cycles are reconstructed from primary records, meeting minutes circulated within one week, action lists tracked across cycles, and contemporaneous correspondence, with the audit trail between stakeholder input and tool change established by matching action-list items to development commits where evidenced. This is reconstruction rather than ethnography: decisions reached are captured, not the full deliberative process by which they were reached.

Cycle (Date)	Attendees	Key Stakeholder Inputs	Resulting Tool Changes
C1 – 6 Nov 2025 Energy Stakeholders Meeting	Transport Scotland; NESO (RESP Scotland); SSEN; HWU	Charger sizing to be agreed; coverage upgraded to 8-10% of HGV-km; depot charging flagged as a bigger grid challenge than en-route	500/350/150 kW committed to MILES parameter space; CSV formatting for SSEN/ NESO; depot scenarios prioritised
C2 – 18 Nov 2025 Panmure House Round-Table	Cabinet Secretary for Transport; senior energy and freight representatives	Confidence and clarity established as investment preconditions; nine-figure private capital identified as contingent on demand confidence	Strategic-framing checkpoint (no direct tool change); failure-condition exploration prioritised over central-case display
C3 – 10 Dec 2025 Phase 3 Working Demo	Transport Scotland; HWU project team	DNO outputs prioritised; DfT 75% depot assumption tested live and contradicted (Scotland closer to 60/40); GSP layer, RAG overlay and bay counts requested	Live Erlang B bay sizing; substation/GSP layer; dual-map utilisation-vs-power view; RAG overlay; internal/ public split
C4 – 28 Jan 2026 Co-creation Workshop	Transport Scotland; NESO RESP lead; SSEN; SP Energy Networks; HWU	Audience shift formalised: energy stakeholders as primary end-users; 5 km spatial resolution agreed; RESP/DFES-aligned outputs; RAG deprecated for public use	Hourly load curves and peak MW per location; 5 km zones replace exact sites; RESP/ DFES CSV export; public RAG removed; two-way DNO-CPO communication as design principle

Table 1. Summary of the four stakeholder iteration cycles.

4.1 Cycle 1: Energy Stakeholders Meeting

The first cycle brought together Transport Scotland, NESO's RESP Scotland team, SSEN, and the HWU research team, with the explicit purpose of ensuring the next iteration would support DNO and NESO strategic investment planning against the ED3 cycle (2028-2033). Charger sizing assumptions were formally agreed (500 kW on-route, 350 kW depot, 150 kW overnight) and carried directly into the MILES parameter space; the coverage upgrade from approximately 2 percent of registered HGVs to 8 to 10 percent of HGV-kilometres was confirmed, with HGV-kilometres preferred over vehicle counts for energy-side communication as it better reflects the relationship between fleet activity and charging demand; and the meeting surfaced an emerging recognition that depot charging may pose larger grid challenges than public en-route charging, with medium-sized warehouses potentially requiring 20 to 30 half-megawatt chargers clustered geographically.

4.2 Cycle 2: Panmure House Industry Round-Table (Strategic-Framing Checkpoint)

Not every ADR cycle produces tool features; some reshape the project's framing of its own purpose. This round-table, attended by the Scottish Cabinet Secretary for Transport and senior energy, industry, and freight representatives, produced no direct tool changes but surfaced two contextual frames that propagated forward: that confidence and clarity are preconditions for investment (senior representatives emphasised that nine-figure private capital would not flow without confidence in demand forecasts), which reframed the tool's purpose from showing the optimal network to supporting confidence-building conversations; and that the transition needed to be managed as a gradual realignment rather than a cliff-edge shift, which established that the tool's value would be realised through the conversations it enabled. This cycle reshaped how the project team approached scenario-exploration controls and the deliberate inclusion of failure conditions alongside optimistic central cases.

4.3 Cycle 3: Phase 3 Working Demo

This was the first session at which a working e-Freight Planner prototype was shown rather than described, and stakeholders reacted to what they saw rather than what they imagined. DNO-facing outputs were explicitly prioritised over the public-facing tool, reinforcing the audience-shift trajectory later formalised in Cycle 4. A live test found the DfT planning assumption of 75 percent depot charging was contradicted by Scottish data (closer to 60 percent depot, 40 percent en-route), illustrating how an interactive tool can interrogate planning assumptions in real time. A specific list of requests followed: a substation/GSP map layer, internal versus public tool versions, utilisation-versus-power blob visualisations, a RAG grid-constraints overlay, and bay count per site.

4.4 Cycle 4: Co-creation Workshop with DNOs and NESO

The fourth and most consequential cycle, attended by Transport Scotland, the NESO RESP Scotland lead, and senior SSEN and SP Energy Networks representatives, produced the paper's most significant finding: the explicit reframing of the e-Freight Planner's primary audience from haulage fleets and charge point operators to electricity system stakeholders.

This was not imposed by a single attendee; it emerged from consensus that the actors needing a national-scale charging specification to inform investment ahead of demand are the DNOs (for ED3 anticipatory investment) and NESO (for RESP and DFES), not haulage operators or CPOs, whose decisions are made at depot and commercial-site scale.

The audience shift drove a cascade of design decisions: required outputs were reformulated around peak MW demand, hourly load curves, and seasonal variation; spatial conventions were negotiated to 5 km radius zones rather than exact sites, since actual sites would be chosen commercially by CPOs and higher precision would not be acted upon; output formats were specified for compatibility with RESP, DFES, and Network Development Plan pipelines; and substation RAG ratings were deprecated for public versions, on DNO advice that publicly visible ratings could discourage investment unnecessarily. Two-way communication was established as a design principle: the tool informs DNOs early so capacity can be reserved or upgraded, while DNOs guide CPOs and investors towards site selections aligned with grid capacity, reframing the e-Freight Planner from a one-way decision-support tool into a coordination layer between two mutually dependent planning communities.

5. Findings and Discussion

5.1 The Audience Shift as the Central Finding

The most significant outcome of the four iteration cycles was not any individual feature change but the cumulative reframing of who the tool was for, from helping haulage operators and CPOs visualise feasible charging networks to helping DNOs and NESO conduct anticipatory grid investment. This was not driven by a change in the funding contract's objectives; it emerged from sustained engagement with the actors who would actually act on the tool's outputs. Three observations explain why. Haulage operators, while interested in the technical findings, could not act on a national network specification; their decisions are made at fleet and depot scale, constrained by vehicle prices, electricity prices, payload penalties, and financing rather than by network-level planning. Charge point operators were similarly constrained by commercial site selection based on land availability, planning permission, and grid connection costs rather than a national specification, a constraint the 5 km radius representation directly acknowledges. The actors who genuinely needed a national specification to inform decisions ahead of demand were the DNOs and NESO, whose planning cycles (ED3, RESP, DFES) operate on the timescales at which anticipatory investment must be made.

This connects directly to ADR's notion of the ensemble artefact (Sein et al., 2011): what is delivered is not a tool alone but a tool together with the organisational arrangements that make it consumable. The shift from a CPO-and-operator audience to a DNO-and-NESO audience changed that ensemble, requiring alignment with ED3, RESP, and DFES, and the Cycle 4 design decisions reshaped every architectural layer accordingly (Table 2). That the shift required four iteration cycles to surface, despite the project team's prior knowledge of the energy sector, illustrates the value of structured stakeholder engagement in making such alignments explicit.

Layer	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Data	500/350/150 kW values; 8-10% telematics coverage	—	Substation/GSP map data restored	Hourly load curves; peak MW per location; 5 km radius zones
Application	Three charging strategies parameterised	Failure-condition scenarios prioritised	Live Erlang B bay sizing; dual-map (utilisation vs power)	CSV export pipeline aligned to RESP/DFES formats
Presentation	DNO-suitable output formatting	Scenario exploration controls expanded	Internal vs public views; RAG overlay; blob visualisation	Public RAG ratings deprecated; spatial blobs replace exact sites

Table 2. Design decisions across the four cycles, mapped to the e-Freight Planner's three architectural layers.

5.2 Recurring Patterns and Process Reflections

Beyond the audience shift, four patterns recurred. Failure conditions consistently mattered more to stakeholders than optimistic central cases; across all cycles, stakeholders valued exploring where the network would fail over being shown only the optimal case, shaping the dual-map utilisation-versus-power visualisation. Visual and tabular outputs needed to be integrated rather than separated, stakeholders wanted both a strategic overview and the underlying numbers in a format usable in their own pipelines, and a single integrated interface proved more useful than separate deliverables. Spatial precision was a matter of explicit negotiation rather than a unilateral technical decision; the 5 km radius reflected a practical compromise between what MILES could justify spatially and what stakeholders said they would use. A working prototype surfaced different kinds of input than verbal or document-based engagement; the live contradiction of the DfT 75 percent depot assumption in Cycle 3 illustrates how a queryable tool can test planning assumptions in ways a static report cannot.

Practically, a monthly sprint cadence with incremental releases matched the rate at which stakeholders could absorb change, and written minutes and action lists gave traceability between stakeholder inputs and tool changes, useful both during the project and in reconstructing this account. A low-cost cloud web stack allowed rapid iteration without requiring software distribution to stakeholder machines. Managing scope and balancing disagreeing stakeholder preferences required project-team judgement that was not always easy to defend in retrospect, and engaging energy-sector stakeholders earlier would likely have surfaced the audience shift sooner and reduced rework on de-emphasised transport-side features. The approach should transfer directly to other UK regions or comparable national contexts where DNOs and system operators have analogous planning cycles; where receiving planning processes are less developed, the audience shift may lack an obvious destination, and the iterative process would need to focus on building those processes rather than aligning with them.

6. Conclusion

This paper has documented the iterative, stakeholder-driven development of the e-Freight Planner, framed as Action Design Research and extended to a multi-stakeholder coalition in the freight-energy domain. Through four documented iteration cycles between November 2025 and January 2026, the tool evolved in response to inputs from Transport Scotland, two DNOs, NESO, freight industry representatives, and senior government stakeholders, with each cycle producing traceable design decisions reshaping outputs, spatial conventions, integration formats, and underlying assumptions.

The most significant finding was a fundamental shift in the tool's primary audience, from haulage fleets and charge point operators to energy system stakeholders responsible for anticipatory grid investment. This reframing was not specified at the outset but emerged from sustained engagement with the actors who would act on the tool's outputs, cascading through every subsequent design choice and consistent with ADR's notion of emergent ensemble outcomes.

The contribution is methodological: a documented, evidenced account of how Action Design Research, extended to a multi-stakeholder coalition and a web-deployed sustained-use artefact, can surface audience and scope reframings that would not emerge from a requirements-led specification process. Several limitations apply: the four cycles covered a relatively short period and a single national context, and the reconstruction draws on meeting

minutes and action lists that capture decisions but not the full deliberative process. Phase 4 of the project, currently in scoping, is expected to deepen the DNO co-design relationship and explore tighter integration between e-Freight Planner outputs and DNO/NESO modelling pipelines.

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DIGITAL INFRASTRUCTURE FOR EFFICIENT AND SUSTAINABLE LOGISTICS: UNDERSTANDING RFID ADOPTION IN THE RAILSEAPORT INTERFACE

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Introduction

Rail transport is widely regarded as an important component of more sustainable freight transport. Increasing the share of freight transported by rail is a priority in many national and European transport strategies. However, expanding rail freight volumes does not depend solely on investments in physical infrastructure, such as adding or expanding rail tracks. It also requires more efficient utilization of existing rail capacity.

Seaports (hereafter referred to as 'ports') are often connected by rail to the hinterland, and play an important role in this regard. As interfaces between maritime and inland transport systems, ports depend on the efficient coordination of multiple actors, including terminal operators, rail operators, forwarders, ocean carriers, and infrastructure administrations. Yet managing rail operations in port environments is challenging. Shunting is the activity splittingof are split and reorganizing railcars, and it requires locomotives at the port to handle these operations. Railcars are left and fetched by rail operators that transport the railcars with goods to and from the port. Information about railcar movements is often fragmented across organizations and information systems, limiting operational visibility and reducing actors' ability to plan, coordinate, and optimize freight flows (Gustafsson et al., 2025).

Recent advances in digital technologies have created new opportunities to address such challenges. One technology receiving increasing attention in ports is Radio Frequency Identification (RFID), which enables the automatic identification and tracking of physical assets (Fu and Sun, 2020). By generating real-time information on railcar movements, RFID can provide data to digital infrastructure that supports planning, coordination, and rail capacity management. Although RFID has been widely applied in sectors such as retail and manufacturing (Wang et al., 2010), its potential for supporting rail-port operations remains largely unexplored. Existing research has demonstrated the operational benefits of RFID in supply chains, including improved visibility and resource utilization (Gustafsson et al., 2025; Harris et al., 2015), yet provides a limited understanding of how RFID-generated operational data become operational value in multi-actor rail-port systems and which factors shape organizations to adopt this digital infrastructure.

The operational value of digital infrastructure depends on more than the deployment of technology. Realizing the benefits of RFID-generated data requires integration with existing information systems, alignment with operational workflows, and collaboration among the organizations involved in rail-port operations. These conditions influence both the adoption of RFID-enabled digital infrastructure and its ability to generate operational value through enhanced operational visibility.

This paper examines the adoption and expected operational value of RFID-enabled digital infrastructure in the rail-port interface. The study is situated at a North European port, where the rail-port interface is the unit of analysis. The empirical observations are drawn from stakeholders representing key organizations involved in rail-port operations, including the port authority, rail operators, terminal operators, and forwarders. The paper sheds light on how these stakeholders perceive the operational value of RFID-generated data and the technological, organizational, and environmental factors shaping RFID adoption. The TOE framework provides the analytical lens for examining adoption, while operational visibility explains how RFID-generated data are expected to support rail capacity management.

Literature review and analytical lens Digital technologies increasingly support coordination across freight transport by improving information sharing, operational visibility, and data-driven decision-making (Harris et al., 2015). Within the rail-port interface, RFID-generated data offer opportunities to strengthen rail capacity management by providing timely information on railcar movements. At the same time, realizing this operational value depends on organizations' willingness and ability to adopt RFID-enabled digital infrastructure. This chapter introduces RFID-enabled digital infrastructure as the study's technological context, followed by the TOE framework, which provides the analytical lens for examining the factors that shape its adoption.

RFID-enabled digital infrastructure

Within multimodal freight transport, information and communication technologies provide the foundation for coordinating actors, transport modes, and operational activities through timely information exchange (Harris et al., 2015). Henfridsson and Bygstad (2013) describe digital infrastructure as an evolving combination of technologies, information systems, and organizational arrangements that enables data generation, communication, and coordinated use of information across organizations.

RFID contributes to this digital infrastructure by generating real-time operational data through the automatic identification and tracking of physical assets. In port environments, RFID supports asset tracking, operational planning, and information sharing across logistics activities (Siror et al., 2011). Fu and Sun (2020) further show that RFID creates operational and economic value for ports by improving visibility, operational efficiency, and decisionmaking. Building on this body of research, this study positions RFID as an enabling technology within the digital infrastructure that supports enhanced operational visibility, rail capacity management, and sustainable freight flows at the rail-port interface.

Technology adoption through the TOE framework

The TOE framework (Tornatzky and Fleischer, 1990) is widely used for examining organizational technology adoption. It explains adoption through three types of factors: technological, organizational, and environmental. Technological factors concern the technology itself, including its compatibility with existing information systems. Organizational factors concern how organizations work and their ability to implement and use new technologies. Environmental factors describe the external setting in which adoption occurs, including interorganizational collaboration and developments within the industry. The TOE framework has been applied in studies of RFID adoption (e.g., Wang et al., 2010) and provides the analytical lens for this study. It is used to examine the technological, organizational, and environmental factors that shape stakeholders' adoption of RFID-enabled digital infrastructure at the rail-port interface. The findings then show how these factors relate to the expected operational value of RFID-enabled digital infrastructure.

Research design and process

The empirical study was conducted at a large North European port that initiated the installation of RFID readers to improve visibility of railcar movements and strengthen their rail capacity management. The study focuses on stakeholders expected to be affected by the implementation of RFID-enabled digital infrastructure, including the port authority, rail operators, terminal operators, and freight forwarders. The empirical material originates from the first author's involvement in the RFID implementation project. The study adopts an insider research perspective, where the researcher's organizational position provided access to relevant stakeholders, operational processes, and implementation discussions (Brannick & Coghlan, 2007). To support analytical distance, the empirical material was analyzed after the first author had transitioned from the port organization to a research institute, allowing the findings to be interpreted independently of the implementation project. The empirical material consists of semi-structured interviews with stakeholders representing organizations involved in rail-port operations. The interviews explored stakeholders' expectations regarding the operational value of RFID-enabled digital infrastructure, the perceived conditions for adoption, and anticipated implementation challenges. Interview questions focused on the use cases associated with RFID. Three port members participated in each interview. One led the discussion, one was responsible for detailed note-taking, and one supported follow-up questions and observations. This approach enabled us to reflect continuously immediately after each interview and strengthened the consistency of the empirical documentation. The interviews were not audio-recorded, as the business-tobusiness setting called for a conversational format that encouraged open dialogue among participants. Instead, detailed notes were taken during each interview and consolidated immediately afterward while the discussions were still fresh in our minds. The interviews were designed to explore stakeholders' perceptions of RFID implementation rather than specific theoretical constructs. The TOE framework was subsequently applied as an analytical lens to organize and interpret these stakeholder perspectives in terms of the technological, organizational, and environmental factors influencing adoption.

Findings: Adoption and value creation through RFID-enabled digital infrastructure

The findings are organized according to the technological, organizational, and environmental factors of the TOE framework. These factors explain stakeholders' perspectives on RFID adoption in the rail-port interface. The technological factor focuses on the capabilities required to generate and exchange RFID-generated data. The organizational factor explains how organizations create operational value from these data, while the environmental factor captures the broader conditions encouraging RFID adoption. Table 1 summarizes the stakeholder perspectives identified for each TOE factor, followed by a synthesis that shows how enhanced operational visibility connects RFID adoption to rail capacity management and sustainable freight flows.

TOE factor	Theme	Illustrative stakeholder observations	Relevance for RFID adoption
Technological	Enhanced operational visibility	Real-time information on railcar locations, arrivals, departures and shunting activities provides a shared operational picture across the railport interface.	Creates the operational data foundation supporting planning, coordination and rail capacity management.
	RFIDgenerated operational data	Continuous tracking provides timely information on railcar movements, replacing fragmented information distributed across organizations.	Improves the quality and availability of operational information.
	System integration	RFID-generated data need to integrate with existing systems, before they can support everyday operations.	Enables RFID-generated data to become actionable operational information.
	Interoperability	Common data structures and standardized information exchange are required across organizations.	Supports information exchange and coordinated decision-making.
Organizational	Actor-specific information needs	Different organizations associate RFID-generated information with different operational values, reflecting their responsibilities within the rail-port interface.	Shapes organizational willingness to adopt RFIDenabled digital infrastructure.
	Business value	Value depends on operational improvements, ROI and distribution of implementation costs and benefits.	Creates organizational motivation for implementation.
	Operational workflows	RFID-generated information needs to support existing planning, scheduling and resource allocation activities.	Enables operational value through everyday decisionmaking.
	Interorganizational collaboration	Shared governance, information ownership and coordinated implementation support collaboration across organizational boundaries.	Establishes the organizational conditions required for enhanced operational visibility.
Environmental	Sustainability ambitions	Improved rail capacity utilization supports increased use of rail and contributes to lower-emission freight transport.	Creates external incentives for RFID adoption.
	Digital transformation of rail freight	Stakeholders describe rail freight as lagging behind other transport modes in digitalization while expectations for digital information continue to increase.	Strengthens the strategic importance of RFID-enabled digital infrastructure.
	Industry interoperability	Expectations regarding common standards and information exchange support coordinated digital development.	Facilitates digital collaboration across the rail-port interface.

Table 1: Stakeholder perspectives on RFID adoption organized according to TOE factors.

Technological factors

Four themes related to RFID adoption from a technological perspective were identified: RFIDgenerated operational data, enhanced operational visibility, system integration, and interoperability and data standards.

Stakeholders associated the main value of RFID with enhanced operational visibility, although they emphasized different operational values. Information about railcar locations, arrivals, departures, and shunting activities is currently fragmented across organizations and information systems, making planning and coordination more difficult. RFID-generated operational data were expected to provide timely information that improves planning, scheduling, and coordination. For the forwarder, timely information about railcar locations reduces uncertainty in transport planning and railcar turnaround. For the port authority, the same information provides opportunities to identify bottlenecks and make better use of existing rail infrastructure. The interviews illustrate how a common operational picture creates value in different ways depending on the actor's responsibilities.

The interviews showed that RFID adoption depends on system integration and interoperability. Stakeholders viewed RFID as one component of a broader digital infrastructure, where operational value depends on integrating RFID-generated data with existing planning systems and enabling information exchange across organizations. Common data standards and interoperable information systems were described as important conditions for turning RFIDgenerated data into operational information to support rail capacity management.

Organizational factors

Four themes were identified within the organizational factor: actor-specific information needs, business value, integration into operational workflows, and interorganizational collaboration. RFID-generated data were expected to create value when improving operational workflows. Different actors associated the same RFID-generated data with different operational decisions. The forwarder focused on accurate timestamps to reduce railcar turnaround times and improve customer planning. Rail operators described real-time railcar locations as important for fleet utilization and resource planning. The port authority viewed the information from a network perspective, using railcar movement data to identify bottlenecks, understand rail track utilization, and support future infrastructure planning. These examples illustrate that RFID adoption is shaped by actor-specific information needs and operational priorities.

Stakeholders also differed in how they evaluated the business value of RFID. The port authority viewed RFID as an investment that would support long-term rail capacity management and future growth in rail freight volumes. The terminal operator evaluated RFID from a day-to-day operational perspective, where improved visibility would simplify existing activities but represent a more incremental improvement. These different perspectives show that the expected value of RFID depends on each organization's role at the rail-port interface and on the operational decisions enabled by the technology.

Collaboration formed the final organizational factor shaping RFID adoption. Stakeholders described RFID as part of a shared digital infrastructure where operational value depends on information exchange across organizations. Common information standards, coordinated implementation, and agreement on data ownership and access were viewed as important conditions for enabling shared operational information and coordinated planning across the rail-port interface.

Environmental factors

Three themes were identified within the environmental factor: sustainability ambitions, digital transformation, and industry interoperability. Stakeholders linked RFID adoption to broader developments in the external environment, particularly sustainability ambitions, the digital transformation of rail freight, and increasing expectations for interoperability across the railport interface.

Sustainability ambitions provided an important motivation for RFID adoption. The port authority viewed improved rail capacity management as a way to increase the utilization of existing rail infrastructure and strengthen rail as a freight transport alternative. RFID was expected to contribute by improving planning, reducing delays, and increasing the reliability of rail operations. Rather than directly driving modal shifts, stakeholders described RFID as supporting the conditions that make rail transport a more attractive option for freight.

Stakeholders also described rail freight as lagging behind other transport modes in terms of digitalization and information availability. Increasing expectations for transparency, datadriven decision-making, and digital collaboration were viewed as important drivers for modernizing rail operations. In this context, RFID is an enabling technology that supports the ongoing digital transformation of the rail-port interface.

The interviews further highlighted the importance of interoperability across organizations. Stakeholders emphasized common information standards and industry-wide approaches to information exchange as important conditions for realizing the value of RFID-generated data. These environmental factors position RFID-enabled digital infrastructure as an important component of the ongoing digital and green transitions in freight transport.

Enhanced operational visibility as the enabling mechanism

The findings show that RFID adoption in the rail-port interface is shaped by technological, organizational, and environmental factors. The technological factor concerns the generation and exchange of RFID-generated data. The organizational factor concerns how these data are incorporated into operational workflows and create value for the organizations involved. The environmental factor reflects broader developments that encourage adoption, including sustainability ambitions, digital transformation, and increasing expectations for interoperability. All these factors shape stakeholders' willingness to adopt RFID-enabled digital infrastructure.

The value of RFID was not linked to the RFID readers themselves, but to the data they generate and make available across organizations. Access to timely information on railcar locations, arrivals, departures, and shunting activities gives the organizations involved a common operational picture that supports planning and coordination. Although the organizations use the information for different purposes, they all benefit from having access to the same operational data. For the forwarder, the data improves transport planning and railcar turnaround. Rail operators use it to support fleet utilization and resource planning. The port authority uses the information to identify bottlenecks, monitor track utilization, and support infrastructure planning.

The interviews further showed that RFID-generated data create operational value when they become part of the digital infrastructure supporting everyday operations. Stakeholders repeatedly described the importance of integrating RFID-generated data with existing systems and making information available across the organizations. In this way, RFID-generated data become shared operational information that supports planning, scheduling, and coordination throughout the rail-port interface.

Figure 1 summarizes these relationships. The TOE framework explains the technological, organizational, and environmental factors shaping RFID adoption, while enhanced operational visibility explains how RFID-generated operational data contribute to rail capacity management. Better planning, improved coordination, reduced delays, and more effective use of existing rail infrastructure all strengthen rail as a freight transport alternative and contribute to more sustainable freight flows.

Concluding discussion

This study examined how RFID-enabled digital infrastructure is expected to support rail capacity management and sustainable freight flows, as well as the technological, organizational, and environmental factors shaping its adoption at the rail-port interface.

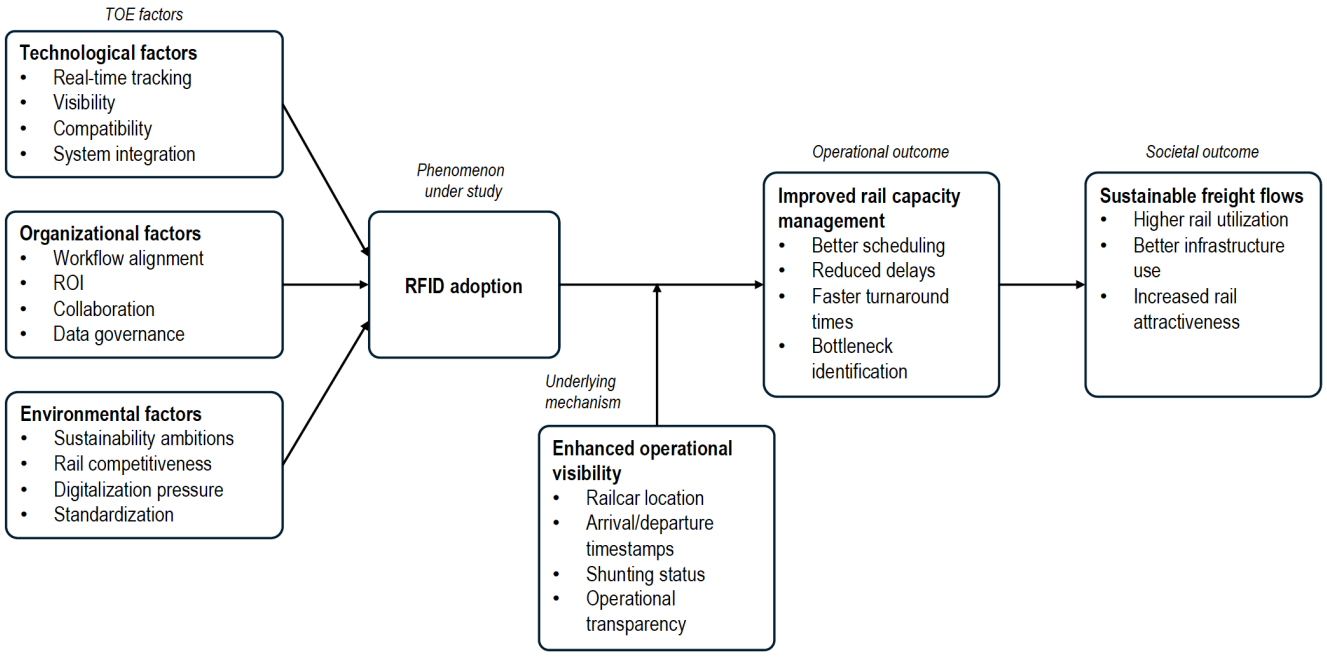

Figure 1: TOE factors shaping RFID adoption and the expected operational value of RFIDenabled digital infrastructure.

The findings position RFID as an enabling technology within digital infrastructure by generatingoperational data that support enhanced operational visibility. Through timely, shared information on railcar movements, enhanced operational visibility enables planning, coordination, and more effective utilization of existing rail infrastructure. The study connects stakeholders' adoption of RFID-enabled digital infrastructure with the operational value they expect it to create.

Contributions

This study contributes to research on technology adoption by demonstrating the applicability of the TOE framework in a multi-actor freight transport setting. The findings show that technological, organizational, and environmental factors are distributed across organizations with different operational responsibilities, information needs, and value expectations. RFID adoption develops through coordinated implementation, information sharing, and collaboration across the rail-port interface. This perspective broadens the application of the TOE framework from organizational technology adoption towards technology adoption in interconnected freight transport systems.

The paper contributes to research on digital infrastructure by illustrating how RFID-generated data create operational value across organizational boundaries. Henfridsson and Bygstad (2013) describe digital infrastructure as an evolving combination of technologies, information systems, and organizational arrangements through which new capabilities come forth. The findings provide an empirical illustration of this process within the rail-port interface. RFID generates operational data that become shared information through the digital infrastructure, while enhanced operational visibility supports planning, coordination, and rail capacity management. This perspective positions enhanced operational visibility as the mechanism, or, to use the words by Henfridsson and Bygstad (2013), the capability that connects RFIDgenerated data to operational value.

The study further contributes to research on value creation in freight systems (e.g., Vural et al., 2019). The findings show that different organizations create value from access to the same operational information. Freight forwarders associated RFID-generated information with transport planning, rail operators with fleet utilization, terminal operators with operational coordination, and the port authority with rail capacity management. Although the organizations expected different operational benefits, they all relied on a shared operational picture enabled by the digital infrastructure. The findings suggest that operational value in freight systems is created through actor-specific use of shared information rather than through identical use across organizations.

Practical and policy implications

The findings suggest that RFID implementation benefits from clearly defined operational use cases that create value across multiple organizations. Stakeholders consistently associated RFID-generated information with improved planning, coordination, and railcar visibility. Implementation strategies then benefit from establishing common information standards, supporting information exchange between systems, and enabling information sharing across organizations. The findings also highlight the importance of digital infrastructure in the ongoing digital and green transitions of freight transport. Investments in rail competitiveness include both physical and digital infrastructure that support more effective utilization of existing rail capacity. Policies encouraging interoperability, common data standards, and digital collaboration across the rail-port interface complement investments in rail infrastructure and strengthen opportunities to increase the share of freight transported by rail.

Future research

This study captures stakeholders' expectations during the implementation of RFID-enabled digital infrastructure at a North European port. Future research can examine how operational value develops following implementation, compare adoption across different rail-port contexts, and investigate how digital infrastructure supports collaboration, rail capacity management, and sustainable freight flows over time. There are also opportunities to do a quantitative study on how the rail tracks are actually used.

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SADC CORRIDOR DEVELOPMENT: INSTITUTIONAL COMPLEXITY AND ECONOMIC REALITIES

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Introduction

The Southern African Development Community (SADC) comprises 16 member states and approximately 360 million people. Six member states are landlocked, while the principal production and consumption centres of several coastal states are located far from their ports. Efficient cross-border corridors are, therefore, not merely transport links: they are the physical and institutional systems through which regional trade, industrialisation, and access to global markets must occur. Yet the continent's transport costs remain among the world's highest and its corridor performance is repeatedly constrained by deteriorating infrastructure, border delays, limited interoperability, and fragmented governance (African Development Bank Group, 2020; Vilakazi & Paelo, 2017). Across Africa, infrastructure deficits are estimated to reduce economic growth and business productivity materially, reinforcing the urgency of delivery (UNECA, 2024).

The region has developed an increasingly sophisticated policy architecture to address these constraints. The SADC Treaty (SADC, 1993) and Protocol on Transport, Communications and Meteorology (SADC, 1996) established regional integration and corridor development as shared objectives. Subsequently, the Regional Infrastructure Development Master Plan (RIDMP) identified strategic infrastructure priorities (SADC, 2012); while the SADC Industrialisation Strategy and Roadmap (SADC, 2015) and the Regional Indicative Strategic Development Plan (RISDP) for 2020-2030 (SADC, 2021) linked corridors more explicitly to value-chain development, trade, and industrial transformation. Implementation has nevertheless remained weak. Of 98 RIDMP Short-Term Action Plan projects scheduled for completion by 2017, only 5% were completed (SADC, 2019). A 2025 Time Release Study on the North-South Corridor further indicated that major border delays persist, with limited improvement from earlier assessments (SADC, 2025).

This gap between strategic ambition and delivery is often framed primarily as a shortage of infrastructure finance. Financing is undoubtedly important, but this explanation is incomplete. SADC must coordinate projects across sovereign states with unequal fiscal and administrative capacity, overlapping regional memberships, multiple continental programmes, and a large group of development partners whose corridor priorities do not always coincide. The result is an institutional ecosystem that can generate extensive planning and stakeholder engagement without consistently producing bankable, sequenced, and regionally optimised projects.

The paper examines how SADC's economic structure and institutional environment shape corridor development outcomes. It first reviews the relationship between corridor infrastructure, regional integration, and industrialisation. It then analyses selected economic and freight-flow evidence, traces the evolution of SADC's corridor strategy, and maps the principal layers of institutional complexity. The contribution is a delivery-oriented interpretation of the implementation gap and a phased framework for aligning corridor investment with SADC's own diversification and industrialisation priorities.

Literature and regional development challenge

Corridors, integration and industrialisation

Transport corridors reduce the economic distance between inland markets, production centres, borders, and maritime gateways. Their development can improve market access, lower inventory and transport costs, facilitate regional production networks, and make consolidation around logistics and industrial nodes more viable. However, a corridor only generates development effects when infrastructure, border administration, operating rules, logistics services, and productive investment are coordinated. A road or railway that accelerates the export of unprocessed resources can increase throughput without necessarily deepening regional value chains.

This distinction is particularly important in resource-dependent economies. Mineral exports can provide the demand base for capital-intensive rail, port, and energy infrastructure, but dependence on extraction can also weaken incentives for diversified investment and expose public finances to commodity cycles (Levin & Makgetla, 2020). Corridor policy must, therefore, connect freight density and commercial viability with deliberate support for beneficiation, agro-processing, and other tradable sectors. The SADC Industrialisation Strategy identifies mineral beneficiation and agro-processing as priority pathways, but translating these ambitions into spatially coherent projects requires stronger links between transport planning, industrial policy, and investment promotion (SADC, 2015).

Trade facilitation remains essential. Delays at borders can represent up to 25% of route charges and cost approximately US$400 per truck per day on affected routes (Vilakazi & Paelo, 2017). Evidence that administrative delays can outweigh physical infrastructure constraints made one-stop border posts, customs modernisation, and harmonised procedures attractive interventions because they require less capital and can yield quicker benefits (Djankov, Freund & Pham, 2006). The risk is that recurring attention to facilitation substitutes for the more difficult task of renewing railways, ports, roads, and energy systems. Effective corridor development requires both: operational improvements that unlock existing capacity and long-term infrastructure that supports structural transformation.

Structural economic and freight-flow context

SADC's current economic structure limits the scale of domestic resources available for corridor development while increasing the urgency of investment. As shown in Table 1, the region accounts for about 8% of global land area and 5% of population, but only around 1% of global gross domestic product (GDP) and electricity generation. Its share of global maritime freight is higher, at approximately 5%, reflecting the importance of bulk commodity exports, while its share of land freight is about 2%. These proportions indicate established links to global markets but relatively weak domestic and regional production networks.

Indicator	SADC	World	SADC share
Land area (million square kilometre)	11	130	8%
Population (billion)	0.4	7.8	5%
GDP (US$ trillion)	0.7	86.8	1%
Employed population (billion)	0.25	3.3	1%
Maritime freight (trillion tonne-kilometre)	4.7	101.5	5%
Land freight (trillion tonne-kilometre)	0.8	42.0	2%
Electricity generation (terawatt-hours)	280	29 925	1%

Table 1: Selected structural indicators for the SADC region in the global context

The information presented in Table 1 stems from the authors' calculations using information from the following sources:

- GDP, land mass, and population data for the SADC region and the World published by the World Bank (2025a; 2025b; and 2025d)

- Employed population data for:
    - the SADC region via individual country national labour statistics and a dataset published by Dierks (2026), and
    - the World based on a dataset published by Galan (2026).

- Land and maritime freight flow data for:
    - the SADC region via the Africa FDM™ (2025), and
    - the World via the International Transport Forum (ITF)'s Transport Outlook 2019 (ITF, 2019).

- Electricity generation data for:

    - SADC countries via their International Energy Agency (IEA) country profile pages, e.g. South Africa (IEA, n.d.), and
    - the World based on information published by Haegel and Kurtz (2025).

Regional trade patterns reinforce this diagnosis. International maritime flows dominate African freight networks, while domestic and intra-regional flows are comparatively thin. In SADC, intra-regional trade accounted for approximately 20% of total trade in 2019, above some other African regional communities but far below mature integrated markets (Makumbirofa, 2022). South Africa is the dominant regional economy and source of many cross-border flows; excluding South Africa, intra-SADC trade has shown a long-term weakening tendency. Corridor networks consequently remain oriented towards ports and external markets rather than dense, mutually reinforcing regional value chains.

Economic concentration and weak investment intensify the challenge. South Africa contributed approximately half of SADC GDP in 2023, while Angola, Tanzania and the Democratic Republic of Congo contributed much of the remainder. Average regional GDP growth of about 2.4% between 1980 and 2023 was below population growth of 2.7%, leaving real GDP per capita broadly stagnant. Gross capital formation is approximately 20% of GDP, compared with the 35-45% maintained by several high-growth Asian economies during their transformation. This implies an indicative annual investment gap of US$40-100 billion. Meanwhile, manufacturing value added remains close to 10% of GDP, while mining contributes substantially to exports and public revenue (World Bank, 2025c). The region's comparatively young and expanding working-age population could become a demographic dividend, but only if infrastructure, skills, and productive employment grow together (United Nations, 2025). The corridor development problem is, therefore, embedded in a wider cycle of low investment, commodity dependence, weak industrial growth, and constrained fiscal capacity.

Research approach

The research applies a qualitative institutional and policy analysis supported by secondary economic and freight-flow evidence. Regional strategies, protocols, implementation reviews, and corridor studies were examined to identify how the purpose and instruments of corridor development have evolved since the establishment of the Southern African Development Coordination Conference in 1980. Particular attention was given to the SADC Treaty; Protocol on Transport, Communications and Meteorology; successive RISDPs; the RIDMP; the Industrialisation Strategy and Roadmap; and recent implementation assessments.

The institutional mapping considered three dimensions: overlapping membership of regional economic communities; the interaction between SADC, African Union, and global infrastructure initiatives; and the corridor priorities of major financing and development partners. This was combined with indicators on GDP, population, investment, manufacturing, trade, and freight flows from sources like the World Bank and Africa Freight Demand Model (Africa FDM™, 2025). The analysis is diagnostic rather than causal: it does not estimate the independent effect of each institution or compare individual corridor project returns. Its purpose is to identify recurrent implementation barriers and derive practical principles for prioritisation and delivery.

Results and analysis

Evolution of SADC corridor strategy

SADC's corridor approach can be interpreted in three broad phases. During the 1970s-1990s, the primary objective was to rehabilitate conflict-damaged links and reduce the region's dependence on apartheid South Africa. Early programmes focused on basic connectivity through Angola, Mozambique, and Tanzania. Political instability, limited maintenance, and weak operating capacity prevented many of these routes from becoming durable alternatives, demonstrating that infrastructure sustainability depends on institutional and political conditions as much as construction.

From the 1990s to the 2010s, the focus shifted towards spatial development, trade facilitation, and public-private partnerships. The 1996 Protocol on Transport, Communications and Meteorology framed corridors as integrated regional networks and encouraged private participation. Spatial Development Initiatives sought to connect transport investment with mining, agriculture, tourism, and industrial nodes; which saw the Maputo Development Corridor become the leading example (Jourdan, 1998). Yet many initiatives remained nationally driven and SADC's ambitious progression from free trade area to customs union, common market, and monetary union largely stalled. The tension between sovereignty and regional optimisation remained unresolved, while overlapping membership of SADC, the Common Market for Eastern and Southern Africa (COMESA), and the East African Community (EAC) created competing obligations and demands on limited capacity (Disenyana, 2009; World Bank, 2018).

Since the 2010s, regional strategy has positioned corridors as platforms for industrialisation and integrated development. The RIDMP introduced a more systematic project pipeline, while the Industrialisation Strategy and Roadmap and RISDP for 2020-2030 linked infrastructure to value chains, digitalisation, and broader economic transformation. Continental initiatives, including the African Union Programme for Infrastructure Development in Africa (PIDA) and the African Continental Free Trade Area (AfCFTA), strengthened the policy case for cross-border connectivity (African Union, 2018; 2020). International interest has also grown around corridors such as Lobito and Dar es Salaam. However, project delivery has not kept pace with the sophistication of the strategy. The shift from connectivity to industrialisation is clear in policy, but less evident in implementation outcomes.

Institutional complexity and implementation barriers

The implementation gap is shaped by complexity at three interconnected levels. Structurally, several member states belong to more than one regional economic community or customs arrangement. The Democratic Republic of Congo, for example, belongs to SADC, COMESA, the EAC, and the Economic Community of Central African States (ECCAS). Multiple memberships can broaden market access, but they also create different tariff, customs, regulatory, and infrastructure commitments. Governments and regional secretariats must allocate scarce technical and political attention across institutions that may advance competing timetables or standards.

Strategically, SADC corridors sit within a dense hierarchy of regional, continental, and global frameworks. SADC's own RIDMP and RISDP interact with the African Union's Agenda 2063, PIDA and AfCFTA, as well as external initiatives such as the European Union's Global Gateway, the G7 Partnership for Global Infrastructure and Investment, China's Belt and Road, and bilateral programmes. These arrangements offer finance and expertise, but each adds project-selection criteria, reporting requirements, and stakeholder processes. Without a clear regional prioritisation mechanism, alignment can become an end in itself and dilute continuity from concept to implementation.

Operationally, development partners prioritise different corridors and often different components within the same corridor. Some interventions focus on one-stop border posts, others on isolated road or rail sections, ports, industrial parks or mineral-export links. This can improve specific bottlenecks, but it does not automatically create an integrated economic corridor. Externally financed rail and port investments may be commercially anchored in mineral exports, while the complementary links, logistics facilities, energy supply, and industrial projects required for broader regional development remain underfunded. The key issue is not the number of partners, but the absence of a binding sequence that relates their interventions to a coherent regional outcome.

Across these layers, four recurrent barriers emerge. First, institutional mandates and accountability are weak: SADC can coordinate and advocate but has limited authority to enforce national commitments. Second, project-preparation capacity is insufficient, resulting in a shortage of investment-ready projects and delays between strategic identification and financial

close. Third, public financing is constrained by low capital formation, rising debt, and reliance on external partners. Fourth, national political priorities frequently outweigh regional benefits, particularly where project costs and gains are distributed unevenly. These barriers reinforce one another; weak preparation discourages finance, fragmented finance produces incomplete corridors, and incomplete results reduce political confidence in regional programmes.

Discussion

From corridor lists to a regional investment sequence

The findings suggest that SADC does not primarily need another broad corridor vision. It needs a disciplined mechanism that converts existing strategies into a limited, continuously updated sequence of projects. Prioritisation should begin with freight demand and the economic functions of each corridor, but should not end with present volumes. Current density identifies where operational improvements and rehabilitation can yield early returns; industrial and agricultural potential indicates where enabling investments could create new regional value chains. A transparent portfolio should, therefore, distinguish between projects that restore existing high-density flows, projects that unlock identified production clusters, and longer-term strategic links whose demand depends on coordinated industrial development.

This approach would also clarify the role of resource exports. Bulk minerals can anchor rail and port investment and improve the bankability of large projects, but concession and financing arrangements should protect capacity for general freight and connect mineral corridors to energy, logistics, and industrial nodes. The objective is not to reject export infrastructure, but to negotiate it as part of a broader development package. The Lobito Corridor illustrates both the opportunity and the risk: substantial geopolitical and financial interest can accelerate infrastructure, yet regional benefits will depend on whether the corridor supports local processing, cross-border supplier networks, and reliable access for a wider set of users.

Trade facilitation and physical investment must be sequenced together. Existing one-stop border posts and digital customs systems should be made fully operational on high-density routes because they can release capacity quickly. These measures should be accompanied by asset-condition programmes, reliable maintenance funding, and targeted removal of rail, road, and port bottlenecks. Border reform without dependable infrastructure shifts queues rather than eliminating logistics costs; infrastructure without coordinated procedures leaves expensive capacity underutilised.

Phased implementation framework

An immediate phase should concentrate on delivery discipline. SADC and participating member states should select a small number of high-density corridors, publish a single sequenced implementation plan for each, assign named institutional owners, and report progress against measurable milestones. Stalled projects with clear economic value should be completed before additional concept pipelines expand. Existing one-stop border posts on routes such as North-South and Maputo should be operationalised fully, supported by joint performance dashboards that track border time, infrastructure availability, rail and port reliability, and total corridor cost.

In the medium term, the project-preparation function should be strengthened and separated from general policy coordination. Multidisciplinary corridor teams require engineering, demand modelling, environmental, legal, financial, and transaction-advisory capability. Projects should enter the regional portfolio only when their economic function, cross-border responsibilities, operating model, and funding path are defined. Blended-finance instruments can then be matched to the risk profile of specific components, with public funds directed towards enabling infrastructure and private capital towards commercially recoverable assets and services.

Long-term transformation requires corridor governance that is accountable for economic outcomes rather than isolated construction outputs. Independent monitoring should assess whether travel times, logistics costs, reliability, modal balance, trade, and industrial activity improve after investment. Successful corridor institutions should have stable technical secretariats, formal participation by freight owners and logistics operators, and escalation mechanisms for unresolved cross-border issues. Regional peer review can strengthen accountability, but it must be based on public evidence and linked to future project support.

The proposed framework does not remove the political economy of regional integration. Member states will continue to weigh national costs against regional benefits, and external partners will pursue their own strategic interests. Its value lies in making these trade-offs explicit. A corridor portfolio grounded in demand, productive potential, delivery readiness, and transparent performance allows SADC to negotiate partnerships from a regional strategy rather than assemble a regional strategy from partner projects.

Conclusions

SADC has moved from rehabilitating basic transport links to promoting corridors as integrated platforms for industrialisation. This strategic progression is appropriate, but it has outpaced implementation capacity. The region remains characterised by weak intra-regional freight density, stagnant per-capita growth, low investment, commodity dependence, and underdeveloped manufacturing. These economic realities increase the importance of corridor development while simultaneously limiting public resources for delivery.

The analysis shows that the implementation gap cannot be understood as a financing shortage alone. It is produced by overlapping regional commitments, proliferating policy frameworks, fragmented partner priorities, weak project preparation, limited accountability, and the recurring dominance of national over regional optimisation. More coordination is not automatically the solution; coordination must be simplified around a small number of sequenced, economically justified and accountable programmes.

Immediate attention should, therefore, be directed towards completing viable high-density corridor projects, fully operationalising existing border investments, and publishing comparable performance evidence. Medium-term effort should establish a specialised project-preparation capability and financing models that allocate risk appropriately between public and private actors. In the long-term, corridors should be governed as economic systems whose success is measured through lower logistics costs, improved reliability, expanded regional trade, and productive diversification. This reorientation would help ensure that SADC's infrastructure partnerships support the region's own industrialisation objectives rather than perpetuating a predominantly extractive connection to global markets.

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SOCIAL SUSTAINABILITY IN ARABIAN GULF PORTS: A COMPARATIVE STUDY OF SAUDI ARABIA AND THE UAE

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Abstract

This study investigates how social sustainability is conceptualised, governed, and advanced in the port sectors of Saudi Arabia and the UAE. A qualitative comparative case study approach was applied using the Multi-Level Perspective (MLP) framework. Primary data were collected from 26 semi-structured interviews with port and maritime stakeholders in both countries, complemented by secondary sustainability reports and regulatory documents. Findings show that while both countries embed social sustainability in policy discourse, the UAE demonstrates a more coherent, institutionally integrated approach, whereas Saudi Arabia's model remains fragmented but innovation-rich. The study concludes that coherent cross-level alignment, transparent reporting, and participatory governance are essential for advancing social sustainability transitions in Gulf ports.

1. Introduction

Social sustainability in port operations encompasses workforce safety, inclusivity, community engagement, and equitable development. Despite growing policy attention, its integration into the maritime industry remains uneven, particularly in the Gulf Cooperation Council (GCC) region. Saudi Arabia and the UAE represent contrasting governance models: the UAE employs a centralised, institutionally integrated approach, while Saudi Arabia relies on a more fragmented, multi-entity structure. This paper applies the Multi-Level Perspective (MLP) to examine how landscape-level visions, regime-level governance, and niche-level innovations interact to shape social sustainability pathways in Gulf ports. Three research questions guide the study: (RQ1) How is social sustainability framed in national strategies and port policies? (RQ2) What structural constraints impede its integration? (RQ3) How do MLP-level interactions create divergent transition pathways?

2. Contextual Background and Literature

Ports are strategically significant nodes of global trade and major urban employers. Social sustainability in ports encompasses health and safety, workforce diversity, community engagement, and localisation (Alamoush et al., 2021). In the Gulf, national development visions — Saudi Vision 2030 and UAE Vision 2050 — provide the normative landscape for sustainability transitions, yet implementation varies considerably across institutional contexts.

The MLP framework (Geels, 2002) conceptualises transitions as emerging from interactions across landscape (macro-level pressures), regime (established practices), and niche (innovative experiments) levels. Applied to Gulf ports, this enables systematic comparison of how governance structures mediate between global sustainability pressures and local operational practices. Prior research has identified fragmented authority and limited cross-sector coordination as key barriers to port sustainability integration in emerging economies (Alamoush et al., 2021; Mudronja et al., 2022), making the Gulf context particularly instructive for understanding how governance architecture shapes social sustainability outcomes.

3. Methodology

This study adopts a qualitative comparative case study design. Twenty-six semi-structured interviews were conducted with port executives, sustainability officers, government officials, and consultants across Saudi Arabia (n=15) and the UAE (n=11) between August and October 2024. Participants were selected through purposive sampling targeting direct involvement in port sustainability planning, regulatory oversight, or operational management. Interview data were complemented by secondary sources including sustainability reports, ESG disclosures, and national policy documents. Data were analysed using NVivo through thematic coding mapped onto MLP levels. Data saturation was reached after approximately 20 interviews, with remaining interviews confirming emerging themes. Ethical approval was granted by Cardiff Business School Social Research Ethics Committee (Reference: 2404).

4. Results

Analysis reveals distinct patterns in how social sustainability is enacted across UAE and Saudi ports. Tables 1 and 2 summarise primary themes by MLP level.

Theme	Evidence	MLP Level
Cultural Accommodation	Prayer rooms; flexible breaks; Ramadan adjustments (11/11 interviewees)	Regime
Employee Safety & Well-being	"Zero Harm" system; injury reporting; PPE routines	Regime
Gender Inclusion	Women Leadership Program; increased participation	Regime
Community Engagement	Youth CSR; mangrove planting; marine awareness	Niche
Education & Localisation	Maritime Academy; Emiratisation pathways	Regime
Reporting & Communication	GRI-aligned sustainability disclosures	Landscape/Regime
Innovation & Partnerships	Coral restoration pilots; circular economy; university collaborations	Niche

Table 1: Social Sustainability Themes in UAE Ports

Theme	Evidence	MLP Level
Cultural Accommodation	Prayer times; Ramadan scheduling (7/15 interviewees)	Regime
Employee Safety & Well-being	PPE; emergency drills; fatigue management	Regime
Gender Inclusion	Non-discrimination rules; NEOM inclusive planning	Regime
Community Engagement	Municipal CSR events; safety/environment weeks	Niche
Education & Localisation	Scholarships; in-house safety certifications	Regime
Reporting & Communication	KPI reporting; GRI-based energy/emissions reporting	Landscape/Regime
Innovation & Partnerships	NEOM pilots; university research; private-sector collaborations	Niche

Table 2: Social Sustainability Themes in Saudi Ports

The UAE demonstrates strong regime-level embedding: cultural accommodation (11/11 interviewees), structured safety systems, gender inclusion programmes, and GRI-aligned reporting are institutionalised across AD Ports Group and DP World. As one interviewee confirmed: "The UAE is a multicultural environment, and we respect diverse cultural practices, including prayer times. There is also a strong emphasis on gender inclusion" (UAE_005). Saudi Arabia shows strong niche-level innovation through university partnerships, NEOM pilots, and private-sector collaborations, but regime-level coordination remains fragmented. As one senior consultant noted: "There is still no unified authority or single reference point" (Saudi_008).

5. Discussion

The findings confirm two divergent social sustainability pathways shaped by governance architecture. In the UAE, centralised governance through AD Ports Group creates consistent cross-level alignment, with landscape visions cascading through institutional frameworks into daily operational routines. In Saudi Arabia, parallel entities (Mawani, Bahri, Red Sea Global) implement initiatives independently, limiting coordination and visibility.

Cultural accommodation practices, including prayer rooms, Ramadan scheduling, and religious holiday adjustments, are the most consistently institutionalised social sustainability dimension across both countries. This finding suggests that culturally

rooted practices achieve regime embedding more rapidly than other social sustainability initiatives, possibly because they align with existing organisational values and face less resistance from operational management. However, the UAE's broader integration of gender inclusion and community engagement demonstrates that governance coherence enables scaling beyond culturally mandated minimums.

These findings align with transition management theory (Köhler et al., 2019), which emphasises that regime-wide reforms require cross-level coordination to scale niche experimentation into systemic change. The contrast between the two countries illustrates how governance centralisation functions as an enabling mechanism for sustainability transitions, not merely an administrative preference, but a structural condition that determines whether niche innovations can be systematically absorbed into regime-level practices.

From a comparative perspective, both systems offer transferable lessons. Saudi Arabia's decentralised model fosters broader niche-level experimentation, including university partnerships and NEOM-linked pilots, that generates innovation potential. The UAE's integrated governance ensures that successful experiments are scaled systematically. A hybrid approach combining Saudi Arabia's innovation breadth with the UAE's institutional coherence may represent the most effective pathway for advancing social sustainability in Gulf ports and could inform wider GCC-level governance frameworks.

6. Limitations

This study focuses on two Gulf states and may not fully represent the diversity of practices across the wider GCC region. The reliance on qualitative interviews and sustainability reports means that some private-sector or community perspectives may remain underrepresented, particularly where public reporting is limited. Differences in data accessibility between the UAE and Saudi Arabia may have influenced the comparative depth of analysis. Future research should expand the geographical scope to include other Gulf and Middle Eastern ports, and longitudinal studies would help assess whether emerging policies translate into lasting institutional change.

7. Conclusion

This study demonstrates that social sustainability transitions in Gulf ports are fundamentally shaped by governance architecture. The UAE's centralised model enables coherent cross-level alignment, while Saudi Arabia's fragmented structure fosters innovation but constrains scaling. Port authorities seeking to advance social sustainability should prioritise unified reporting frameworks, participatory governance, and structured pathways for niche-to-regime transition. This study contributes to the maritime business and CSR literature by providing the first comparative empirical analysis of social sustainability transitions in Gulf port systems using MLP, offering novel insights for port managers and policymakers in the Gulf region and beyond.

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A NEW MEAT QUALITY PARAMETER? QUALITATIVE CONSUMER PERSPECTIVES ON TRACEABILITY TECHNOLOGY IN THE WA SHEEP MEAT SUPPLY CHAIN

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Background

With the 2025 introduction of mandatory electronic identification (eID) for sheep in Australia, the agricultural sector is experiencing a shift toward greater transparency and traceability in livestock production. Historically, traceability has been primarily associated with biosecurity. However, the potential to leverage eID and other traceability tools for consumer-facing purposes, such as supply chain efficiency, branding, quality assurance, and ethical marketing, has received relatively little attention. Australia is a nett exporter of red meat and has a global reputation in terms of high meat-eating quality, consistency of supply and our disease-free status. While Australia is established as a provider of high-quality meat to the world, both domestic and international markets continue to evolve to become more fragmented and values-driven, particularly in high-income segments, consumer expectations around provenance, animal welfare, and environmental impact are rising. In this context, traceability represents not just a regulatory obligation but a commercial opportunity. This study was designed to explore how consumers interpret traceability in relation to sheep meat products, what types of information they find useful or credible, and how this affects their willingness to purchase or pay a premium. The findings will help inform the development of targeted labelling strategies, retailer messaging, and product innovations that can align with the evolving preferences of the Australian meat consumer.

Research Methodology

The study used a qualitative approach based on semi-structured interviews. Interviews were conducted with 10 participants between March and April 2025. Each session lasted 30-45 minutes and explored consumer shopping habits, views on traceable products, and reactions to labelling scenarios. The participants' profile is presented in Table 1. Interviews were transcribed and thematically analysed using Braun and Clarke's[1] (2006) six-phase framework. Coding was undertaken manually and guided by pre-determined themes aligned with the study's research objectives.

Table 1. Participant profiles

ID	Interview date	Gender	Age range (Years)	Role/Background	Residence
P1	4-Apr	Female	35-44	Office-based consumer (UK expat)	Perth metro
P2	1-Apr	Female	25-34	Ag-science student; works in banking	Regional WA
P3	28-Mar	Male	35-44	Animal-welfare researcher	Perth metro
P4	4-Apr	Female	35-44	Health professional & busy mother	Perth metro
P5	10-Feb	Male	35-44	FMCG production manager	Perth metro
P6	24-Feb	Female	35-44	School teacher; time-poor	Perth metro
P7	21-Mar	Male	35-44	Pracademic; dad; nutrient enthusiast	Perth metro
P8	25-Apr	Male	25-34	Sheep-farm family background; agri-business graduate	Regional WA
P9	23-Apr	Male	45-54	International-marketing academic; halal-blockchain advocate	Perth metro
P10	19-Mar	Female	35-44	Administrative officer; parent	Perth suburbs

[1] Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77-101.

Thematic Analysis

Eight major themes emerged from the interviews (Figure 1), each reflecting a distinct but interrelated dimension of how consumers engage with traceable sheep meat products (Appendix 1). These themes capture not only what consumers value, such as quality, ethics, and transparency, but also the tensions they navigate, including trust in labelling, price sensitivity, and information overload. Together, they provide a better understanding of the emotional, ethical, and practical considerations that shape meat purchasing decisions in a traceability-focused marketplace. The themes are summarised below and explored in greater detail in the subsequent sections.

Perceived quality from traceability

One of the most prominent findings from the interviews was the perceived relationship between traceability and meat quality. Participants consistently reported that knowing the origin of their meat made them feel more confident about its freshness, handling, and ethical standards: "If I know where the meat came from, I just feel better about the quality, it feels fresher and more legitimate" (P4). This sentiment was echoed by others, such as "Traceable meat suggests a cleaner process and more care in how it's handled" (P7). The association between traceability and higher standards indicates that for many consumers, quality is not only about taste or appearance, but also about transparency and accountability.

Label trust & understanding

Trust in food labelling emerged as a highly variable but critical factor. Participants differed in their understanding of labels like 'free-range', 'organic', and 'RSPCA-approved'. Some found these designations helpful and reassuring: "I look for RSPCA-approved or grass-fed labels because they actually mean something" (P3). However, there was also significant scepticism: "I don't trust every label, some of them feel like marketing fluff" (P6). This theme focuses on a knowledge gap and credibility issues. While some consumers are label-literate, others are overwhelmed or unconvinced, which affects their trust in traceable systems.

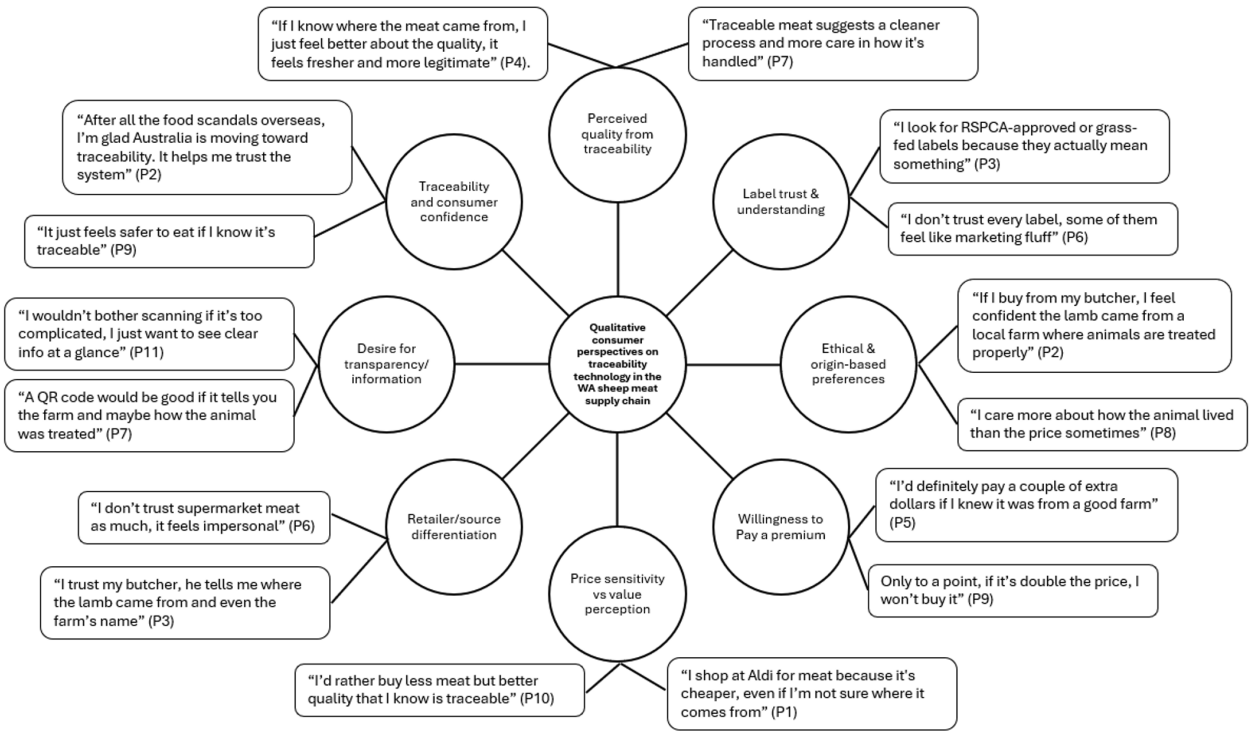

Figure 1: Summary of themes to emerge from interview (n=10) with substantiating data

Ethical & origin-based preferences

Ethical concerns and a preference for locally sourced products strongly influenced participants' choices. The idea that local sourcing implies ethical treatment and better oversight resonated widely: *"If I buy from my butcher, I feel confident the lamb came from a local farm where animals are treated properly"* (P2). This belief was tied not only to geography but also to assumed production values: *"I care more about how the animal lived than the price sometimes"* (P8). Such views suggest that traceability, when tied to ethical origin information, can powerfully influence consumers' preferences beyond price sensitivity.

Willingness to Pay (WTP) premium

A substantial number of participants indicated they were willing to pay more for traceable meat, particularly when it aligns with their values. Price tolerance, however, had limits: *"I'd definitely pay a couple of extra dollars if I knew it was from a good farm"* (P5). This willingness to pay reflects both ethical values and a desire for quality assurance. However, this was tempered by pragmatic concerns: *"Only to a point, if it's double the price, I won't buy it"* (P9). The value consumers place on traceability is real, but it competes with economic realities.

Price sensitivity vs value perception

Price was a decisive factor for many, though not in isolation. Some participants prioritised affordability over traceability, saying *"I shop at Aldi for meat because it's cheaper, even if I'm not sure where it comes from"* (P1). Others tried to balance cost with perceived ethical and quality benefits: *"I'd rather buy less meat but better quality that I know is traceable"* (P10). These comments illustrate how value is interpreted differently, some look for the cheapest option, while others seek moral or qualitative value within a tolerable price range.

Retailer/source differentiation

Consumers made clear distinctions between buying meat from supermarkets versus butchers or specialty stores: *"I don't trust supermarket meat as much, it feels impersonal"* (P6). This sentiment is often related to assumptions about freshness, treatment of animals, and provenance transparency. Conversely, relationships with butchers or local suppliers enhanced trust: *"I trust my butcher, he tells me where the lamb came from and even the farm's name"* (P3). These distinctions affect where and how often consumers choose to shop, especially when seeking high-trust products like traceable meat.

Desire for transparency/information

Participants wanted more accessible and digestible information about the meat they consume. Simplicity was key: *"A QR code would be good if it tells you the farm and maybe how the animal was treated"* (P7). This aligns with growing consumer demand for transparency in food sourcing. However, ease of access was a recurring concern: *"I wouldn't bother scanning if it's too complicated, I just want to see clear info at a glance"* (P11). Consumers support traceability, but the delivery of information must be user-friendly and immediate.

Traceability and consumer confidence

Trust in food safety and quality increased with traceability. Several participants noted that knowing where meat came from offered peace of mind: "It just feels safer to eat if I know it's traceable" (P9). Others connected traceability with national or global food security concerns: "After all the food scandals overseas, I'm glad Australia is moving toward traceability. It helps me trust the system" (P2). In this way, traceability serves as a proxy for broader institutional trust, reinforcing consumer confidence in what they consume.

In sum, consumers generally viewed traceability as a signal of higher quality and safety. However, clarity and credibility of labelling were important. Many participants preferred butcher-sourced meat due to its perceived link to local farms and better animal treatment. Cost remained a significant factor, though a subset of participants indicated a willingness to pay more for traceable, ethically sourced meat. Interest in QR codes and digital traceability tools was mixed: positive when simple and informative, negative when overly complex.

Key Findings

These findings revealed a complex but encouraging picture of consumer perceptions surrounding traceable sheep meat products. One of the most consistent findings across all participant types was a strong preference for locally sourced and traceable meat, with consumers equating local provenance with freshness, ethical treatment, and reduced food miles. Comments such as *"I wouldn't buy any meat that's from anywhere else other than in WA" (P4) and "I would buy meats from my local butcher"* (P8) illustrate the geographic loyalty and desire for transparency in sourcing. This emphasis on origin is closely tied to consumer trust and perceived quality, where traceability was seen as a reassuring signal that the product has been handled safely and ethically. Participants described traceability as a *"cleaner process"* and *"more legitimate,"* associating it with both product integrity and peace of mind.

Differences emerged in motivations between demographic groups. Couples, particularly those in professional or time-pressed contexts, were more likely to be experience-driven and quality-focused, willing to pay more for meat that reflected their values, especially around animal welfare and environmental sustainability. One participant stated, *"As an animal lover, I'd want to know if the animal was kept in a cage or raised free-range"* (P3), underscoring how ethical considerations can outweigh price. Families, on the other hand, were more risk-averse and health-conscious, framing traceability in terms of how it could protect or improve their household's well-being. One participant noted, *"I would be willing to pay more for quality; however, the product needs to show that it clearly benefits family health and safety"* (P10). For these consumers, traceability only added value if it was clearly communicated and did not introduce complexity or cost without justification.

Another important finding was that support for traceability is conditional; consumers must be able to see the added value. Labels and packaging were central to this perception, with several participants expressing scepticism over misleading or vague claims. For instance, a comment such as "You just have to trust what's on the package, sometimes it feels a bit hit or miss" (P6) captures the uncertainty many feel when assessing meat in-store. Thus, the design and clarity of labelling emerged as a vital variable, with interest in QR codes and farm-to-fork storytelling, provided these are presented in a simple and accessible way. Overall, the interviews reveal that traceability has strong latent appeal across diverse buyer types, but success will depend on effective communication, transparent labelling, and price structures that reflect real consumer willingness to pay without deterring budget-sensitive households. These findings not only support the continued rollout of eID systems in WA but also point to opportunities for value-added marketing and labelling innovation across the red meat supply chain.

Taken together, the interviews highlight that while consumers are open, and often enthusiastic, about traceability in sheep meat products, their support is nuanced and shaped by personal values, shopping habits, and trust in the information provided. Local provenance, ethical treatment of animals, and clear, honest labelling emerged as key levers in building consumer confidence and justifying premium pricing. However, this support is not unconditional; traceability must be delivered in a way that is tangible, trustworthy, and aligned with everyday purchasing decisions. As Western Australia moves toward full eID adoption, there is a strategic opportunity to bridge consumer expectations with supply chain transparency, creating not just regulatory compliance but a clear point of differentiation in both domestic and international markets.

Moving Forward

These insights provide the basis of confirmatory work which aims to translate consumer attitudes into concrete, evidence-based strategies for packaging, labelling, and message framing. While interviews revealed strong support for traceability, they also highlighted a need for clarity, credibility, and simplicity in how traceability information is presented. To address this, further research will involve the development of stimulus materials, including varied packaging designs, labelling formats, and messaging strategies, that communicate traceability benefits in ways that resonate with diverse consumer segments. These materials will be created in collaboration with industry partners such as the Dardanup Butchering Company to ensure commercial relevance. The effectiveness of these designs will then be tested through a series of three controlled experiments, each involving 200-300 consumers. Participants will be randomly assigned to different versions of traceability presentations to measure how variations in design affect perceptions of quality, trust, and willingness to pay. These trials will allow the project team to isolate which packaging elements, such as icons, QR codes, or origin badges, have the most impact across consumer types, from budget-aware families to quality-focused couples. Importantly, the experimental phase will also evaluate whether certain messages (e.g. "100% WA sourced" vs. "Farm-to-plate tracked") carry greater persuasive power. Results will be translated into industry-facing guidelines to support producers, processors, and retailers in optimising traceability messaging for both local and export markets. By linking consumer preferences directly to commercial strategies, this approach ensures that investment in traceability technology, particularly mandatory eID, translates into visible market

value. In doing so, it strengthens the business case for adoption across the supply chain and positions WA's sheep industry at the forefront of consumer-aligned, data-driven meat marketing.

Conclusions

This study provides compelling evidence that traceability is more than a compliance mechanism; it is a marketable asset when aligned with consumer values and delivered in a format that fosters trust. Consumers are not merely interested in where meat comes from; they seek reassurance about how it was produced, how animals were treated, and how safe and authentic the end product is. For many, traceability acts as a proxy for ethical quality and institutional integrity. However, the effectiveness of traceability as a value-add depends on clear communication: labelling must be credible, concise, and easily navigable. QR codes and visual cues offer potential, but only if designed with consumer usability in mind. While cost remains a constraint for some consumers, there is a consumer group who are willing to pay more for meat that meets their ethical and quality expectations. For producers, this presents a strategic opening: by aligning traceability systems with transparent, consumer-friendly messaging, they can both meet regulatory requirements and enhance market competitiveness. Future research and testing, as outlined in the next phase of this project, will be vital in refining which messages, labels, and formats resonate most effectively in the real-world retail environment.

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Appendix 1: Thematic analysis codebook

This codebook was developed based on thematic analysis of qualitative interview data. Themes were identified using Braun and Clarke's (2006) six-phase framework, focusing on consumer perceptions of traceable sheep meat. Keywords were derived from recurring phrases in the transcripts, and mention counts reflect the frequency of those terms across the dataset.

Theme	Description	Keywords	Mentions
Perceived quality from traceability	References to how traceability information (e.g., farm of origin, treatment) enhances consumer perceptions of meat quality.	quality, fresh, better meat, good quality	169
Label trust & understanding	Mentions of consumer interpretation and trust in labels such as 'organic', 'free-range', or certifications like 'RSPCA approved'.	organic, label, free-range, grass-fed, RSPCA	65
Ethical & origin-based preferences	Consumer preferences influenced by ethical concerns, locality, known farms, or animal welfare considerations.	local, butcher, origin, farm, animal welfare	342
Willingness to pay (WTP) premium	Statements about paying more for perceived benefits like traceability, origin transparency, or ethical treatment.	pay more, worth paying, expensive but better	19
Price sensitivity vs value perception	Comments reflecting concern about meat prices versus perceived value or quality trade-offs.	too expensive, cost, cheaper, price	162
Retailer/source differentiation	Comparisons between different sources of meat (e.g., supermarkets vs. butchers) and their perceived quality or ethics.	Woolworths, Aldi, butcher, supermarket	83
Desire for transparency/information	Interest in more detailed information about meat products, such as farm origin, QR codes, or production methods.	QR code, information, trace, details	501
Traceability and consumer confidence	Statements linking traceability to greater trust, food safety, or confidence in meat products.	confidence, trust, safe, secure	92

ACCELERATED TRUCK ELECTRIFICATION: ESTIMATING EMISSIONS REDUCTION AND IMPACTS ON CHARGING INFRASTRUCTURE IN THE HELSINKI METROPOLITAN AREA

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Abstract

This conference paper is derived from a master thesis study conducted in collaboration with city of Helsinki under project MADLESS (Meta-Analysis Driven Logistics Emission Solutions through Stakeholder Collaboration) in which four different electrification scenarios for urban logistics were simulated and analyzed. In this paper, one of the scenarios, called accelerated scenario, has been presented. The study investigates the transition towards electrified urban logistics in Helsinki Metropolitan Area for the year 2040. It focuses on estimating emissions and assessing implications for charging infrastructure including identification of new charging infrastructure locations. Moreover, it also aims to utilize the model to evaluate urban logistic measures like Zero Emission Zone (ZEZ) for easing policy decisions.

For this study, empirical truck origin-destination data from Helsinki Region Transport (HSL) has been used with simulation-based approach by combining Simulation of Urban Mobility (SUMO) with python and QGIS to model freight movement, estimating emissions, and to observe charging infrastructural gaps in Helsinki Metropolitan Area under accelerated electrification. Preliminary findings indicate a notable reduction in CO2, NOx, CO, CH, and PMx emissions, alongside an increase in the number of trucks visiting charging stations and a growing need for additional charging infrastructure. The results provide solid insights for policymakers and urban planners in Helsinki Metropolitan Area, supporting evidence-based decisions on charging infrastructure deployment, zoning policies, and electrified urban logistics strategies. Moreover, it contributes to the scientific knowledge by providing a methodological framework to conduct a Metropolitan-scale study for urban logistics electrification scenarios and emission reduction measures.

Keywords: Truck electrification; Charging infrastructure; SUMO simulation; Emission modelling; Urban logistics

Introduction

Climate change is real and so its repercussions – as visible as the broad day light. Carbon emissions are considered as a major contributor in greenhouse gases (IPCC, 2022). According to European Commission (2021) report, urban logistics are significantly contributing to increasing carbon emissions, especially in compact and densely populated European cities where freight vehicles drive up and emit greenhouse gases (GHGs). Although these vehicles take up a small portion of the road transport fleet, they account for a large share of carbon emissions, making them an important target for decarbonizing and achieving carbon neutrality.

To achieve carbon neutrality, European Union (EU) has set some regulatory framework for reducing carbon emissions from transport sector. The Alternative Fuels Infrastructure Regulation (AFIR) and its Regulation (EU 2023/1804) promises scale-up of electric freight operations. For instance, by focusing on accessible charging infrastructure for Trans-European Transport Network (TENT-T) and on urban nodes. In addition to this, the initiative of Sustainable and Smart Mobility Strategy envisions all new cars, vans, heavy duty vehicles, buses to reach the level of zero-emissions by 2050 (European Commission, 2021). It also aims towards deploying numerous public electric charging points.

In Helsinki, the case city examined in this study, the goal is to achieve carbon neutrality by 2030 and carbon-zero status by 2040 (City of Helsinki, 2021). The city has already declared transport as the second largest emission sector after energy (City of Helsinki, 2024). This leads to the need of urban logistic electrification and to our research questions. i.e., 1) To what extent can logistics-related emissions be reduced through accelerated fleet electrification in the Helsinki Metropolitan Area? 2) What are the optimal locations for new charging infrastructure? and 3) how can the effectiveness of Zero-Emission Zones (ZEZs), in combination with accelerated electrification, be evaluated in the Helsinki Metropolitan Area? In a nutshell, this study demonstrates how urban logistics electrification and emission analysis can be carried out at a metropolitan scale, and also helps identify gaps in the existing charging network and provides potential locations for new charging infrastructure.

Theoretical background

Urban logistics engraves the coordinated management and transport of goods within densely populated areas (Savelsbergh & Van Woensel, 2016; Taniguchi et al., 2014; Bekta et al., 2015). This distribution network sustains modern-day cities by supplying utilities to retail hubs, restaurants, and commercial centers, while simultaneously fulfilling e-commerce deliveries to residential doorsteps and automated parcel lockers (Tokta et al., 2024). However, the sector faces immediate sustainability challenges as a significant share of urban freight transport still relies on fossil-fuel-powered delivery vehicles. To achieve sustainability, Fleet electrification is widely considered as a prime mechanism for reducing transport-related carbon emissions (Alarcón et al., 2022), offering a combination of regulatory alignment and long-term economic benefits (ICCT, 2020). However, large-scale deployment will put significant pressure on urban power grids and charging infrastructure. Recent studies highlight the critical need for substantial infrastructural and technological development to support the expanding deployment of electric freight vehicles (Alam & Guo, 2023; Björklund & Forslund, 2023). Another important measure for achieving sustainability in urban transport is the implementation of ZEZs (Zero Emission Zones). Piccoli et al. (2025) reported significant reductions in NO and PM emissions under a ZEZ scenario in Milan. These developments highlight the growing adoption of ZEZs as a strategy for reducing transport-related emissions.

SUMO (Simulator for Urban Mobility) has been extensively used to evaluate fleet electrification and charging infrastructure strategies. Gharbaoui et al. (2014), Moumni et al. (2023), Al-Zuhairi et al. (2025) demonstrated its applicability in modelling Electric Vehicle (EV) operations, charging behavior, and charging infrastructure optimization. Given its ability to simulate vehicle movements, energy consumption, and policy scenarios. SUMO provides a suitable framework for assessing the impacts of fleet electrification and Zero Emission Zones (ZEZs) on carbon emissions in the Helsinki Metropolitan Area. In the following section, the respective methodology employed in this research is presented.

Methodology

This study is based on simulation-based evaluation of urban fleet electrification scenarios, for which, SUMO has been used as the primary tool for simulating urban logistics in the Helsinki Metropolitan Area. The methodology presented in this section mainly carries information about the type of data used, and briefly about how the analysis was carried out. During the study, certain assumptions and limitations have been considered to achieve the research goals. These considerations were mainly related to the size of trucks and trailers, their vehicle classification, and respective battery charge and capacity. In order to maintain uniformity, the size of trucks and trailers were standardized initially with reference to (Logistiikan Maailma, n.d.). Secondly, for logistics classification, Euro VI environmental classification has been adopted. Furthermore, related to the battery charge and capacity, the initial battery charge was set at approximately 50% of the total battery capacity rather than a full charge. As preliminary tests indicated that vehicles initialized with a fully charged battery were able to complete their routes without requiring recharging within the study area, thereby limiting the analysis of charging behavior and infrastructure utilization.

For the analysis mainly four data sets were utilized. Origin-Destination (OD) matrices from Helsinki Regional Transport (HSL), National truck Fleet Electrification Scenarios developed at Transport Research Center Verne by Kercho et al. (n.d.), Charging infrastructure data by Forum Virium Helsinki (2025), and lastly the simulation network data from Geofabrik GmbH (2024) which is an open-source tool for acquiring Open Street Maps (OSM). The OD matrix data was basically collected by HSL via field study in 2012-2013 for Helsinki region which is greater in size on the par with Helsinki Metropolitan Area. It was collected both hourly and every 24 hours. The dataset recorded a total of 29,328 truck trips and 7,504 trailer trips. For the purposes of this research, the 24-hour OD matrix was selected as the primary data source. The dataset was subsequently spatially filtered to include only trips occurring within the Helsinki Metropolitan Area. Following this clipping process, the final dataset was acquired which consisted of 1,948 truck trips and 707 trailer trips respectively.

From the study conducted by Kercho et al. (n.d.), where they used HEETRA (Holistic economic evaluation of emission reduction measures in transport) model for developing National Truck Fleet Electrification Scenarios, four scenarios corresponding to the year 2040 were taken. Out of four scenarios, only accelerated scenario is presented in this paper. It has a 20% share of electric trucks and 27% share of electric trailers in the total truck fleet. In addition to this, the data on charging points was taken from a study conducted by Forum Virium Helsinki (2025), which highlighted the charging stations in the Helsinki Metropolitan Area that could be used by larger vehicles.

Apart from the data sets, three different types of simulations were carried out. First to apply for emissions, then to implement ZEZ, and finally to identify charging infrastructure gaps in the Helsinki Metropolitan Area. Vehicles were defined along with their emission classes, battery attributes and EV physics models; some of the attributes could be seen in Table 1. Moreover, for new charging infrastructure identification, the locations where the EVs either felt the need to charge or the points where their battery exhausted, such points were picked and reflected to as the potential location points for new charging infrastructure. Furthermore, for the implementation of city-wide ZEZ, restrictions were applied to the network which allowed only EVs to travel inside the zone.

	Attribute	Truck value	Trailer value
Basic	ID	ICE_truck/EV_truck	ICE_trailer/EV_trailer
	Length	16.5 m	25.25m
	Acceleration	1.0 m/s2	0.9 m/s2
	Deceleration	3.0 m/s2	2.5 m/s2
	Emission Class	HBEFA3/HDV_D_EU6	HBEFA3/HDV_D_EU6
	Mass	26,000 kg	60,000 kg
Battery	Battery capacity (Wh)	300000	500000
	Battery charge level (Wh)	150000	200000
	Maximum charge rate	150000	150000
Charging intelligence	Station finder probability	1	1
	Station finder radius (m)	100000	100000
	Need to charge	0.4	0.4
	Charging strategy	balanced	balanced

Table 1: Vehicle attributes for simulations

Results

After embedding the data sets and percentage share of trucks and trailers for accelerated electrification into the SUMO's framework, simulations were carried out. In Figure 1 the network of the Helsinki Metropolitan Area, which is used in simulations, is presented.

Figure 1: Simulation network of Helsinki Metropolitan Area

Initially a base scenario was simulated, which had zero percentage share of electric trucks and trailers. The idea behind running this scenario was to fetch emission outcomes without electrification so that a comparison can be drawn with the emission outcomes acquired from accelerated electrification. In base scenario, 1948 trips were recorded for trucks and 707 for trailers. The recorded Vehicle Kilometers Travelled (VKT) were 25,718km for trucks and 12,023 km for trailers. In addition, 44,514 kg of CO2 were accounted for a day-long simulation, followed by NOx, CO, HC, and PMx. Figure 2 presents VKT and total pollutant emissions from base scenario.

Afterwards, the accelerated scenario was simulated which have a percentage share of 20% and 27% of electric trucks and trailers. This resulted in 1,582 trips for ICE trucks, 503 trips for ICE trailers, 366 trips for EV trucks and 204 for EV trailers respectively. Similarly, the recorded VKTs were 20,979km for ICE trucks, 8,581 km for ICE trailers, 4,738 km for EV truck, and 3,647 km for EV trailer. It was also observed that with accelerated electrification, a prominent decrease of 17.7% in CO2 emission related to ICE trucks and 31.7% decrease in CO2 emissions related to ICE trailers can be achieved which is quite pertinent to meet the carbon neutrality goals. Figure 3 can be observed for visualization.

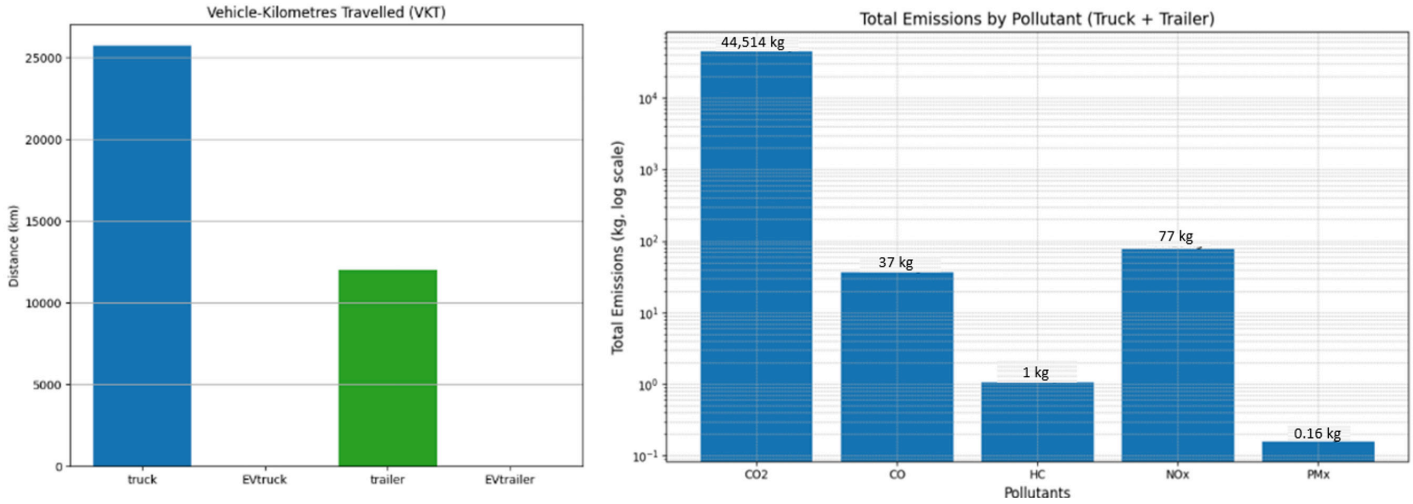

Figure 2: VKT and total pollutant emissions from Base Scenario

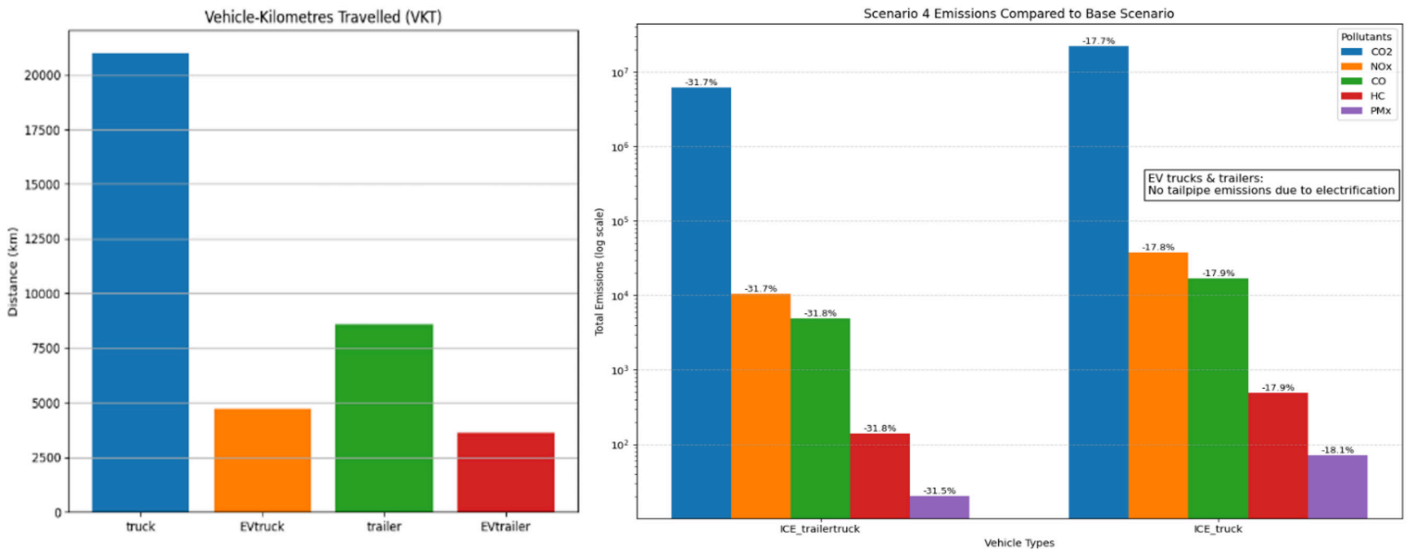

Figure 3: VKT from accelerated scenario and percentage change recorded in emissions in comparison to the Base Scenario

After acquiring results from accelerated electrification, ZEZ was also introduced, as an urban logistics measure. The idea was to study the extent of reduction that can be achieved with ZEZ implementation, and to utilize the model to evaluate an urban logistic measure. In Figure 4, an illustration of the build ZEZ can be seen. It covers the city-wide road network and allows only EV trucks and EV trailers to move inside. Moreover, in figure 4, the corresponding percentage change in emissions in comparison to the Base Scenario can be seen. It was observed that a reduction of 44.8% in CO2 emissions from ICE truck and 55% from ICE trailers was accounted with the implementation of city-wide ZEZ.

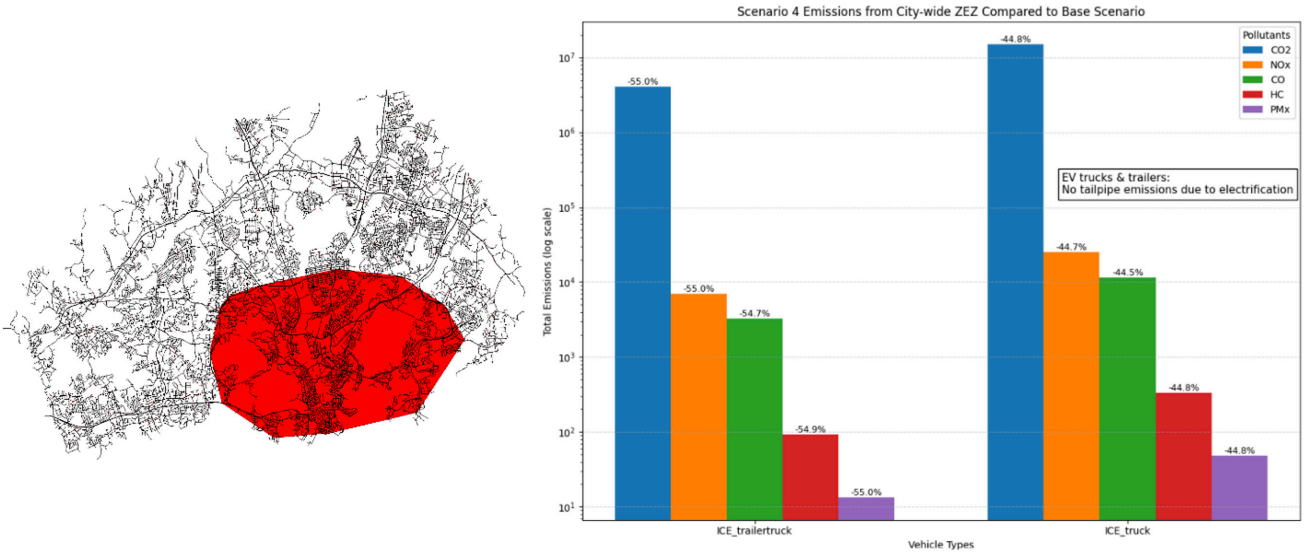

Figure 4: Simulation network with city-wide ZEZ and percentage change recorded in emissions in comparison to the Base Scenario

With the accelerated electrification, the effects on the charging infrastructure are expected, which will eventually lead to the need for new charging stations. This led the study to its final simulation, during which the accelerated electrified fleet was simulated (with no ZEZ) with an aim to identify locations where there is a need for a new charging infrastructure. The idea was to pick the points where the vehicles either felt the need to charge or their battery exhausted. Such points were picked up and presented as the potential location for the new charging station that could be seen in Figure 5.

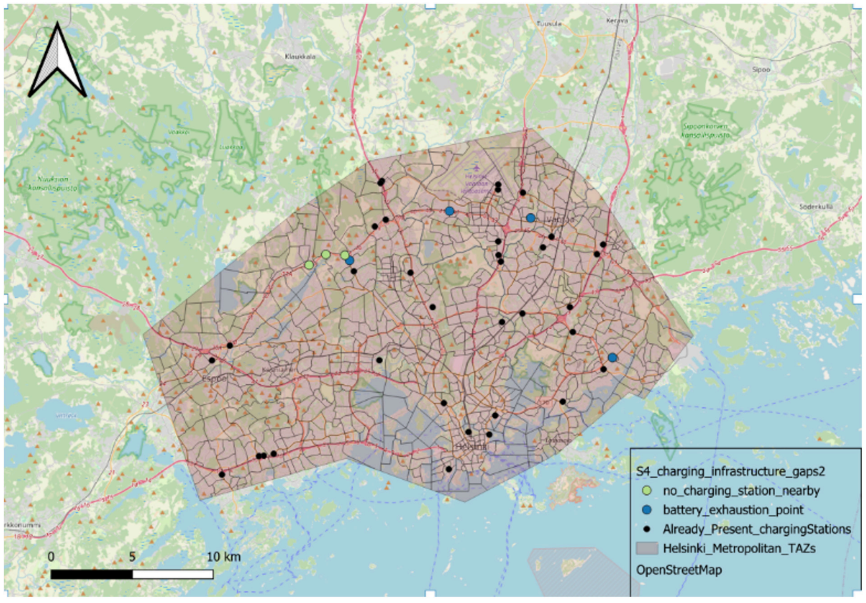

Figure 5: Existing charging stations and identified infrastructure gaps in the accelerated scenario and "pre-existing charging stations" data by (Forum Virium Helsinki, 2025)

Conclusion

This paper presents the potential of using SUMO simulations to evaluate accelerated fleet electrification, charging infrastructure development, and ZEZs for reducing logistics-related emissions in the Helsinki Metropolitan Area. The results showed that accelerated electrification, with 20% electric trucks and 27% electric trailers, reduced CO emissions from ICE trucks and trailers by 17.7% and 31.7%, respectively. The implementation of a city-wide ZEZ further enhanced these benefits, resulting in emission reductions of 44.8% for ICE trucks and 55% for ICE trailers compared to the base scenario. In addition, potential locations for new charging stations were also identified to support the increasing demand associated with freight electrification.

These findings offer a solid empirical foundation for local policymakers, and scientific community that are ambitious like the City of Helsinki towards their carbon neutrality targets. Instead of speculative forecasting and predictions, the study provides empirical data via model to back climate policies, and urban measures. Specifically, the findings show the level of carbon reduction that could be achieved with varying percentage of electric fleet, and with the implementation of city-wide ZEZ. It also highlights when existing infrastructure falls short and shows where new charging stations should be. Ultimately, these insights bridge the gap between research and implementation, and also contribute to the scientific knowledge. Overall, the findings indicate that fleet electrification and ZEZs can substantially reduce emissions from urban logistics, while adequate charging infrastructure remains essential for supporting this transition. The study also demonstrates the applicability of SUMO as a tool for assessing transport decarbonization strategies and infrastructure needs at a Metropolitan scale.

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WHAT SHAPES THE GOVERNANCE OF SUSTAINABLE SUPPLY CHAIN FINANCE? EMPIRICAL INSIGHTS FROM MULTIPLE CASE STUDIES

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1. Introduction

Sustainable supply chain finance (SSCF) has emerged as a promising mechanism to align financial incentives with sustainability improvements in supply chains. Extending traditional supply chain finance (SCF), SSCF links suppliers' access to financing support to their sustainability performance. In doing so, it aims to simultaneously enhance supply chain efficiency and incentivise more sustainable production practices (He et al., 2025; Wang et al., 2025). As firms face increasing regulatory pressure and stakeholder expectations regarding sustainability, SSCF has gained attention as a practical tool for embedding sustainability into core supply chain operations rather than a peripheral compliance activity.

Despite this potential, SSCF remains difficult to implement and sustain in practice. While early research highlights its conceptual benefits (Jia et al., 2020; Tseng et al., 2018), more recent empirical work suggests that many SSCF initiatives struggle to move beyond pilot stages or fail to achieve broad supplier participation (Guo et al., 2022; Ma et al., 2023; Medina et al.,2023a). SSCF requires firms to connect financial decisions with sustainability performance across organisational boundaries, which introduces dependencies on external data, third-party assessments, and inter-organisational coordination (Soni et al., 2022; Sun et al., 2024). Unlike traditional buyer–supplier relationships, SSCF programmes typically involve a broader ecosystem including financial institutions, technology providers, and third-party sustainability assessors (Chakuu et al., 2019; Liao et al., 2025). Research on supply chain integration suggests that coordination depends not only on data availability but also on governance mechanisms that support alignment and trust (Cao and Lumineau, 2015; Flynn et al., 2010). Empirical evidence increasingly suggests that the effectiveness of SSCF depends less on its formal design and more on how it is organised and governed across a network of actors (Medina et al., 2023b). Nevertheless, current SSCF research provides limited empirical insight into how responsibilities are distributed among participating actors, how decision rights and accountability are structured, or how these arrangements evolve as programmes scale.

Taken together, these observations indicate that SSCF should be understood not only as a financial innovation but as a governance problem. While prior research has focused on designing SSCF mechanisms, less attention has been paid to how these mechanisms are governed in practice, in terms of how responsibilities are allocated, how coordination is achieved, and how performance is evaluated across multiple actors. Without addressing these issues, it remains difficult to explain why some SSCF programmes are sustained and expanded, while others remain fragmented or fail to deliver intended outcomes. Therefore, this study seeks to sharpen the understanding of SSCF through the following research question:

RQ: Why do SSCF schemes/programmes have different governance structures?

To address this question, this study adopts a contingency theory perspective as its primary analytical lens and employs a multiple case study design to examine SSCF programmes in practice. Contingency theory posits that organisational effectiveness depends on the "fit" between structural arrangements and the conditions under which they operate, rather than the existence of a universally optimal form of organisation (Thompson, 2003). In operations and supply chain management, this perspective has been widely used to explain why the performance implications of practices such as integration, governance mechanisms, and coordination structures vary across contexts (Flynn et al., 2010; Sousa and Voss, 2008). In SSCF, governance configurations are unlikely to perform uniformly across programmes. Instead, their effectiveness is contingent upon structural features such as the complexity of actor networks, the reliability of sustainability data, and the degree of interdependence among participating actors.

This perspective aligns closely with the research question. SSCF programmes are inherently heterogeneous and involve multiple actors, and prior research suggests that such supply network settings exhibit varying governance and coordination challenges depending on their structural characteristics (Medina et al., 2023b). A contingency approach therefore provides a theoretically grounded way to move beyond identifying governance patterns toward explaining why certain configurations are more effective under certain conditions (Cao et al., 2015; Parast, 2022). To capture this variation and enable systematic comparison, this study adopts a multiple case study design, which is well-suited for examining complex, context-dependent phenomena and identifying patterns of similarity and difference across cases (Yin, 2018). By analysing multiple SSCF programmes with differing governance configurations and structural features, the study uncovers how different governance elements and conditions align to produce distinct outcomes. In doing so, it develops a configurational understanding of SSCF governance, showing that effectiveness arises not from any single governance model, but from the alignment between governance arrangements and the structural characteristics of the programme.

2. Literature Review

SSCF can be understood as a governance problem because it connects financial liquidity, supplier relationships, and sustainability performance. While SCF research shows that financial arrangements improve working capital and distribute financial risk across supply chains (Gelsomino et al., 2016; Wuttke et al., 2013), SSCF extends this logic by linking financing terms to sustainability criteria (Jia et al., 2020; Liao et al., 2025). This extension changes coordination, as effectiveness depends not only on financial availability, but also on actors' ability to define sustainability metrics, verify performance, and convert information into financing decisions.

Relevant literature highlights three governance challenges. First, financial flows are triadic and networked. Supply chain financial stability depends on focal firms, suppliers, customers, platforms, and distributed resources, including capital, data, supplier access, and digital infrastructure (Reza-Gharehbagh et al., 2022; Wang et al., 2025). Second, sustainability governance requires control and collaboration. Supplier assessment and collaboration can improve environmental performance, while contractual and relational governance jointly reduce opportunism and support performance (Cao and Lumineau, 2015; Gimenez and Sierra, 2013). However, close relationships may create dependence and rigidity, requiring adaptability (Villena et al., 2021). Third, authority extends beyond dyads. Governance depends on transaction complexity, information codifiability, and supplier capabilities, and buyers may control or delegate governance over lower-tier suppliers (Chae et al., 2017; Gereffi et al., 2005).

3. Data collection

Data were collected through a combination of semi-structured interviews, follow-up interactions, and archival materials, enabling a rich and triangulated understanding of SSCF governance in practice. The primary data source consists of semi-structured interviews conducted with key stakeholders involved in each SSCF programme. For each case, interviewees were purposefully selected to represent the main actors participating in the programme, including internal functions within buying firms (e.g., treasury, procurement, and sustainability teams) as well as external partners such as financial institutions, sustainability rating agencies, and technology providers. This multi-stakeholder approach allows the study to capture governance as an inter-organisational process shaped by interactions across organisational boundaries.

In total, 26 interviews were conducted with 18 individuals across the four cases, as shown in Table 1. Interviews followed a semi-structured format, enabling consistency across cases while allowing flexibility to explore case-specific dynamics and emerging themes (Rashid et al., 2019). To enhance reliability and reduce potential researcher bias, each interview was conducted by a team of two to four researchers. This approach facilitated real-time probing from different perspectives and supported a more robust interpretation of the data (Hancock et al., 2021). Interviews focused on key aspects of SSCF governance, including the allocation of responsibilities, coordination mechanisms, decision-making processes, and approaches to evaluating financial and sustainability performance.

Case	Organisation type	Organisation	Interviewee code	Functional area
A	Buyer	Company A	A1	Working capital, finance, and investor relations
			A2	
			A3	
	Technology Provider	Technology Provider A	A4	Technology support
B	Buyer	Company B	B1	Procurement, purchasing and sustainability
			B2	
			B3	
	Bank	Bank B	B4	Business andstakeholder relationship management
			B5	
	Technology Provider	Technology Provider B	B6	Technology support
			B7	
	Rating Agency	Rating Agency B	B8	ESG assessing
C	Buyer	Company C	C1	Working capital and finance
			C2	
	Bank	Bank C	C3	Sustainable finance
D	Buyer	Company D	D1	Working Capital and finance
	Technology and Finance Provider	Technology and Finance Provider D	D2	Technology support
Shared across Case ABCD	Rating Agency	Rating Agency A	R1	ESG assessing

Table 1. Interview overview

To deepen understanding and ensure accuracy, interviews were complemented by ongoing engagement with participating organisations. Follow-up discussions were conducted where necessary to clarify emerging findings and capture developments in SSCF initiatives over time. In addition, the study incorporates both publicly available and internal documents, such as programme descriptions, sustainability reports, and operational materials, which were used to triangulate interview data and provide additional context on programme design and implementation. The use of multiple data sources strengthens construct validity and helps mitigate potential biases associated with single-source data (Yin, 2018).

Furthermore, workshops were organised with participating organisations to present preliminary findings and obtain feedback from informants. These workshops served as an additional validation mechanism, allowing researchers to refine interpretations, resolve inconsistencies, and ensure that the findings accurately reflect the practices and experiences of the actors involved. Such iterative engagement with informants is consistent with qualitative research approaches that emphasise the co-development and validation of insights (Dubois & Gadde, 2002).

4. Preliminary findings

Preliminary analysis is expected to show that SSCF governance authority is not fixed at programme launch, but is continuously redistributed according to which actor controls the resource that is most critical at a given stage. In cases where the buyer controls supplier access, commercial legitimacy, and programme objectives, governance is likely to remain buyer-centred. The buyer defines the strategic purpose of SSCF, selects target supplier groups, and determines how sustainability is connected to financing eligibility. However, even in buyer-led arrangements, execution authority may be delegated to banks, technology providers, or rating/data providers when they possess specialist capabilities that the buyer lacks.

A potential finding is that digital platforms and sustainability assessment providers become governance actors rather than neutral service providers. Their role may extend beyond data processing to shaping what counts as acceptable evidence of sustainability performance, how suppliers are segmented, and how information flows between buyers, financiers, and suppliers. This can improve scalability and transparency when sustainability information is codified and trusted, but it may also create new accountability questions when suppliers or buyers do not fully understand how assessments are produced.

We also observed that governance configurations vary with the type of coordination problem. Where SSCF is used mainly to reward already compliant suppliers, monitoring-based governance may be sufficient. Where the aim is to improve supplier sustainability capabilities, relational and collaborative governance becomes more important. The findings may therefore reveal multiple SSCF governance configurations, ranging from buyer-orchestrated control to platform-enabled delegation and collaborative co-governance.

5. Discussion and expected contribution

This study is expected to contribute to SSCF literature by shifting attention from mechanism design to governance configuration. Rather than treating SSCF as a financial product that can be implemented once incentives and metrics are specified, the study conceptualises SSCF as a multi-actor governance arrangement in which authority follows the distribution of critical resources. This perspective helps explain why similar SSCF mechanisms may unfold differently across contexts and why programmes may struggle when formal responsibility does not match the actor that controls data, finance, supplier relationships, or sustainability expertise.

The study also contributes to contingency research in supply chain management by showing how governance fit is produced in a setting where financial and sustainability objectives intersect. The expected contribution is a framework that links resource control, data codifiability, actor capability, and coordination complexity to different SSCF governance configurations. For managers, the study suggests that successful SSCF implementation requires explicit decisions about decision rights, accountability, and delegation, rather than assuming that buyers, financiers, platforms, and sustainability specialists will naturally align once a programme is launched.

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UK PORT PERFORMANCE: A LONGITUDINAL STUDY 1969 – 2024

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Introduction

In a highly maritime-dependent economy such as the United Kingdom (UK), port throughput has served as a critical proxy for understanding key trends in trade flows and economic activity. Several UK port studies have used port-tonnage throughput to address gaps in economic analysis, although recent periods have been unexplored. This paper provides an up-to-date analysis of key regional trends in trade flows and aims to improve understanding of whether location continues to determine cargo volumes through ports at a macro level. A longitudinal analysis using the most recent regional groupings in UK Department for Transport port traffic data, analysed on a decadal basis, identifies regional trends and changes in cargo tonnage throughput. It offers a reinterpretation of recent developments and by examining regional differences over more than five decades, provides a more comprehensive understanding of the cumulative effects of long-standing trends and the underlying structural factors at play. This paper thus analyses trends in port traffic in GB across the two full decades of the 2000s and 2010s, and additionally the early 2020s for which data was available. The paper builds on the earlier studies which discussed port performance from the 1970s to the 2000s. This allows for a view to be taken on how the UK has been influenced by commercial and political pressures, and structural changes in the port sector over a period of around 55 years. Previous studies were based around nine regions (Pettit and Beresford, 2008) covering the UK mainland (Great Britain (GB)) and excluded Northern Ireland, reducing complexity associated with incorporating cross Irish Sea traffic. In order to ensure that this analysis is based on the current situation, the most recent regional groupings in published UK government data are used, there now being 12 GB regions (Table 1) although the broad patterns of change are largely unaffected by changes in the dataset.

Pettit and Beresford, 2008	Current Analysis
North Scotland	-
West Scotland	West Scotland
East Scotland	East Scotland
Northeast	Northeast
	Humber
Northwest	Lancashire and Cumbria
	West & North Wales
East Anglia	Wash & Northeast Anglia
	Haven
South	Sussex & Hampshire
Southeast	Thames & Kent
Southwest	West Country
	Bristol Channel

Table 1: Great Britain Regional Port Groupings

Historically, studies of regional economic disparities (e.g. Hensher and Brewer, 2001) did not specifically consider the port sector but did provide a platform for researchers to take an analytical approach using officially collected data on port traffic. While issues exist in relation to the quantification of the economic value of the port sector, as a variety of indicators could be used including commodity values, employment or trade volumes, earlier studies (see, for example, Pettit and Beresford, 2008) used port-tonnage throughput as the key measure. As with these earlier studies, port performance is evaluated

through the context of annual changes in cargo tonnage throughputs in relation to port location. The broad-scale cargo forms considered are dry bulk, container, semi-bulk and conventional, as these categorisations are consistent with UK government statistical analysis. While liquid bulks were excluded in earlier studies, in this analysis they are included as they are relevant to structural changes to UK economic activity. The port data are recorded in official UK government statistics and provide the longitudinal dataset covering the period of the analysis (DfT, 2026).

Pre-2000 Developments in UK Port Traffic

A wide range of challenges confronted the UK port sector in the years immediately after world-war II (Rochdale, 1962). These problems continued into the 1970s which were a period of significant flux in the UK port sector where a part nationalised port system, operating alongside privately operated ports, as well as those retained as municipal ports run by local government created a mix of ownership that did not allow for forward planning at a UK scale. The nationalised port sector was riven with underfunding, poor management and a heavily unionised port-labour system which was in constant competition with the management to improve working conditions, but which created a toxic interface between them which was never effectively bridged. This allowed those ports which remained in the private sector to develop more efficiently and attract private funding, but the scale of infrastructure required to service the UK economy as a whole did not exist in that portion of the port sector (Pettit, 2008). The UK's economic focus in the early part of the 1970s was west facing as the economy was still heavily influenced by trans-Atlantic trade, and west coast ports were in some cases better connected to inland transport infrastructure though increasingly hampered by lock dimension constraints, water-depth and tidal windows, for example at Liverpool and the Severn Estuary ports. The second half of the 1970s saw the beginning of fundamental changes in the UK economy driven by the UK's accession to the European Union (EU) in 1974. Trade through west coast ports started to decline significantly and by the beginning of the 1980s they had lost between 40 and 70 percent of their cargo volumes (Pettit and Beresford, 2008). The swing to trade moving through east coast ports driven by EU accession was compounded by the now rapidly developing unitised cargo handling systems following the containerisation of cargo in the late 1960s and early 1970s. Felixstowe, sitting outside the public sector system, was well placed to accommodate the rapid increase in trade during that period.

The 1980s move by the government to a market-based economy led to the privatisation of public sector ports, through a series of public auctions of shares of the companies created by the government, Associated British Ports and Stena Ports (Beresford et al, 2004). Improving transport infrastructure and the shift of UK trade to the European continent both improved the fortunes of south and east coast facing ports such as Southampton, Dover and Felixstowe, while at the same time west coast ports suffered relative declines in trade (Pettit and Beresford, 2008). Ports with access to deeper water also benefited as the size of vessels accessing UK ports increased, which continued to impact UK ports to as recently as the 2010s when London Gateway port was developed to take advantage of deep-water access in the Thames Estuary.

The 1990s were a relatively stable period for UK ports with a continuation of government policies through the first half of the decade although there were some legislative changes allowing further privatisation. Efficiency and asset utilisation were markedly improved with both target setting and benchmarking playing a greater role. While UK port cargo volumes grew slowly, by the late 1990s record tonnage of around 565 million tonnes had been reached. Of note during the 1990s was the growth in container traffic in all regions, prompting several proposals for new container terminals and a major review of overall national need in the sector (Dawe, 2001). It was not until 1997 that political change occurred and a more detailed focus on ports began, however consistency in allowing the market to determine success or failure with some intervention around planning policies continued (Pettit and Beresford, 2008).

Post-2000 Developments in UK Port Traffic

The first part of this analysis covers the full period of the years between 2000 and 2024 as there have been significant structural changes to the UK economy which would not necessarily be identifiable in addressing decadal changes. An overview of the full period highlights some clear trends which are then disaggregated by decade.

Tonnage shows a significant change over the 25-year period and the major port tonnages are shown in Table 2. In 2000 total UK tonnage stood at 551.6 million tonnes but by 2024 this had declined to 401.3 million tonnes. This represents an overall decline of 27.5%, at a compound annual rate of -0.985%. In the intervening period tonnage peaked at 584.5 million tonnes in 2005 with a relatively steady decline since then. A substantial decline of 58.5 million tonnes (8.9%) occurred following the 2007/2008 financial crisis with a small recovery to 2010, but this did little to impact the overall decline. Within the overall national 27.5% decline in tonnage there were substantial variations. The largest regional decline was in East Scotland (-72%) driven largely by the contraction of the North Sea oil and gas sector. The western regions 'West and North Wales', and 'Lancashire and Cumbria'; and 'Thames and Kent' all remained relatively stable with only low single percentage declines. The largest percentage increase in tonnage was in Scotland West, although relatively small in tonnage terms. Other more significant structural factors came into play during the later years such as the changing energy mix which significantly impacted tonnages. The largest percentage decline of 9% occurred between 2019 and 2020 although this was smaller than 2009 at 43.3 million tonnes (DfT, 2026).

Port	2000	2004	2009	2014	2019	2024
Felixstowe	29,686	23,413	24,267	28,127	25,344	23,101
Forth	41,143	34,892	36,690	24,608	25,221	17,184
Grimsby & Immingham	52,501	57,616	54,708	59,370	51,245	43,718
Liverpool	30,421	32,233	29,936	30,996	34,315	31,284
London	47,892	53,289	45,442	44,489	54,035	51,869
Milford Haven	33,768	38,452	39,293	34,309	34,951	32,875
Orkney	22,798	17,934	3,241	1,151	3,050	1,686
Southampton	34,773	38,431	37,228	36,688	33,151	33,259
Sullom Voe	38,204	23,939	11,217	7,185	7,371	4,504
Tees & Hartlepool	51,473	53,819	39,163	39,537	28,156	24,242
Dover	-	-	25,087	27,605	23,433	19,402
Hull and Humber	-	-	-	-	10,699	10,480
Bristol	-	-	-	11,421	8,190	8,608
Total Tonnage	**382,659**	**374,018**	**317,944**	**337,150**	**320,550**	**287,414**

Table 2: Tonnages at Top Ten Major GB Ports (000 tonnes) (DfT, 2026)

During the 25-year period it is also important to note that there has been relatively little change in the port sectors concentration structure. In 2000 the top 10 UK ports accounted for around 70% of all tonnage, increasing to 73% in 2024. Within the top ten ports, eight have remained consistent, with the major change being the decline in tonnage at Sullom Voe and Orkney (Flotta) as the North Sea oil sector declined. These ports were generally replaced by Dover and the Humber ports apart from a short period in the mid 2010s when Bristol's tonnages exceeded those of the Humber. A key aspect to understand in this analysis is that tonnage, while providing a proxy for UK trade has become less relevant over this period. While UK trade was heavily influenced by bulk trades up until 2010, from that time structural shifts in UK economic development have shifted trade from lower value bulk cargoes to higher value commodities transported in unitised form. This has been particularly important in terms of the UKs energy mix, with significant reductions in the use of coal and wet bulks. Thus, overall goods trade values have increased from £413 billion in 2000 to £989 billion in 2024 (Table 3) even though cargo volumes reduced over the same period (DfT, 2026).

Year	Exports	Imports	Total
2000	186.6	226.6	413.2
2004	190.9	258.4	449.3
2009	228.1	317.1	545.2
2014	291.5	419.2	710.7
2019	379.2	514.3	893.5
2024	391.5	597.4	988.9

Table 3: UK Trade Values (£ billion) (Note: Values not seasonally adjusted; Source: DfBT, 2026)

The 2000s: The early 2000s saw rapid globalisation and strong international trade expansion, leading to peak tonnages at several major ports. A further significant factor during this period was the growing impact of the Chinese economy and the shift of manufacturing to south-east Asia. This was particularly important for those ports that handled containers such as Felixstowe and Southampton, as containerisation accelerated so they solidified their role as the primary gateways for Lo-Lo Cargo. Conversely, this also led to reductions in cargo at smaller ports where shallower drafts and ageing infrastructure compromised their ability to compete effectively for market share.

Total tonnage throughput for major GB ports fell from 382.7 million tonnes to 317.9 million tonnes, a reduction of 64.8 million tonnes (Table 2). Total UK port tonnage increased steadily during the early 2000s, reaching its highest level of the entire 2000-2024 study period in 2005 and 2006 at 560.5 million tonnes. These peak years were heavily driven by energy-and industry-related cargo flows concentrated in a few ports such as Grimsby and Immingham, Tees and Hartlepool, and Milford Haven (Table 4). However, the 2008 Global Financial Crisis brought this growth to a halt, impacting on economic activity in the UK which led to a decline in tonnages. The impact of crisis varied across ports depending on their dominant functional characteristics, reflecting their sensitivity level to the crisis. Bulk and energy-export-oriented ports such as Grimsby and Immingham (-16%) and Sullom Voe (-23%) experienced the most severe declines between 2008 and 2009, while container hubs such as Felixstowe exhibited relative stability, with only a slight decline of 2.9%. In contrast, ports primarily providing connectivity functions in short-distance trade, such as Dover (+3%), or those oriented towards energy imports, such as Milford Haven (+9.5%), demonstrated the highest levels of growth, as they are less dependent on fluctuations in industrial demand and more closely linked to essential trade and energy flows. Overall, most regions experienced contraction, although the scale varied widely. The Scottish east coast port tonnages contracted by around 45 percent. The period was the first clear divergence between energy and bulk dependent regions, versus those supported by short-sea (Dover), deep sea Lo-Lo (Felixstowe), and Ireland facing trades (DfT, 2026). This is illustrated in Table 4, where changes in tonnage at the top ten ports are shown.

Port	Main Cargo Type	Overall Change (2000 - 2009)	Financial Crisis Impact (2008 - 2009)
Felixstowe	Container	Decrease (-18%)	Relatively stable (-3%)
Forth	Bulk (Mixed energy / dry bulk)	Decrease (-11%)	Decrease (-6%)
Grimsby and Immingham	Industrial Bulk & Ro-Ro	Increase (+4%)	Decrease (-16%)
Liverpool	Mixed	Decrease (-2%)	Decrease (-7%)
London	Mixed (Container + bulk+ ro-ro)	Decrease (-5%)	Decrease (-14%)
Milford Haven	Liquid bulk	Increase (+16%)	Increase (+10%)
Southampton	Container / Ro-Ro	Increase (+7%)	Decrease (-9%)
Sullom Voe	Liquid bulk	Decrease (-71%)	Decrease (-23%)
Tees and Hartlepool	Bulk (Energy-chemical)	Decrease (-24%)	Decrease (-14%)
Dover	Ro-Ro / short-sea	Increase (+44%)	Increase (+3%)

Table 4: Total Change in tonnage at Top 10 GB ports in 2000s (Note: % rounded)

The 2010s: Between 2010 and 2019, UK port traffic experienced an overall decline in total freight tonnage, alongside significant changes in the types of cargo handled and the structure of UK trade. At the beginning of this period UK ports handled approximately 512 million tonnes of freight but by 2019, this had declined to around 486 million tonnes, a decrease of around 5% over the decade. Within these totals mainland GB ports handled 489 million tonnes in 2010 declining to 455 million tonnes in 2019, a reduction of around 7%. While there were annual fluctuations the general trend after 2011 was downward. Total mainland traffic remained around 480 million tonnes for much of the decade before declining further in the latter half. Much of this decline was influenced by the beginning of the transition to a low carbon economy. While the UK had already been shifting away from coal as a main input into energy production its decline of during this period became significant. This had an impact on ports used for coal imports such as Grimsby and Immingham. A further significant issue was the UKs decision to leave the EU, known colloquially as Brexit. In the latter half of the decade the impact of this decision began to be felt, and by 2019 there were spikes in volumes as preparations for Brexit began, with stockpiling taking place. However, the EU remained the UK's most important maritime trading partner throughout the period. In 2019, 41% of all major-port freight traffic was between the UK and EU countries, accounting for around 197 million tonnes. Overall, imports consistently exceeded exports, reflecting the UK's broader trade patterns. In 2019, major ports handled about 256 million tonnes of imports compared to 127 million tonnes of exports. Liquid bulk cargo (oil, petroleum products, liquefied gases) accounted for about 46% of all traffic in 2010 but by 2019 this had reduced to 41%. Dry bulk cargoes (coal, ores, agricultural products) also declined, particularly due to the reduction in coal imports. By 2019, while bulk cargoes still represented around 60% of major-port traffic, the sector only recorded a first increase since 2011, largely because of the growth in liquefied gas and biomass imports.

Containerised freight showed strong growth, increasing steadily throughout the decade. This was reflected in Lo-Lo container traffic at UK major ports, which increased from 4.9 million units in 2010 to a record 6.0 million units by 2019 (22% increase) (DfT, 2011). This trend highlights the growing importance of container shipping in global trade and the wider use of standardised freight transport. London Gateway port became a significant disruptor to the established order during the 2010s. The port began operations in 2013 and both its proximity to the economically important south-east region and London, as well as its state-of-the-art automation, allowing it to increase volumes quickly. Ro-Ro traffic (lorries and trailers driven directly onto ferries) also became more volatile and remained vital for trade with continental Europe and Ireland. Ro-Ro freight volumes declined in the late 2010s but remained higher than at the beginning of the decade. In 2010 Ro-Ro traffic stood at around 96 million tonnes, increasing to 107 million tonnes by 2017. The final year of the decade saw a significant reduction, declining to 104 million tonnes, a 3% decrease compared with the previous year.

In summary, several factors explain the observed trends. The UKs energy transition led to declines in coal imports and changes in oil demand leading to reduced bulk freight volumes overall. Economic conditions continued to impinge on economic growth with the aftermath of the 2008 financial crisis still being felt, and slower economic growth in the 2010s limiting freight growth. Uncertainty around the impact of Brexit meant that by 2018–2019, concerns over future UK–EU trade arrangements were affecting freight patterns and port cargo volumes. Overall, therefore, the decade saw a decline in total port freight volumes, driven mainly by reductions in bulk commodities, while container traffic grew strongly, reflecting changes in the UK's economy, energy sector, and international trade patterns (Table 5).

Port	Main Cargo Type	Overall Change (2010 - 2019)
Felixstowe	Container	Decrease (-2%)
Forth	Bulk (Mixed energy / dry bulk)	Decrease (-27%)
Grimsby and Immingham	Industrial Bulk & Ro-Ro	Decrease (-5%)
Liverpool	Mixed	Increase (+14%)
London	Mixed (Container + bulk+ ro-ro)	Increase (+12%)
Milford Haven	Liquid bulk	Decrease (-18%)
Southampton	Container / Ro-Ro	Decrease (-16%)
Sullom Voe	Liquid bulk	Decrease (-35%)
Tees and Hartlepool	Bulk (Energy-chemical)	Decrease (-21%)
Dover	Ro-Ro / short-sea	Decrease (-3%)

Table 5: Total Change in tonnage at Top 10 GB ports in 2010s (Note: % rounded)

The 2020s: The early 2020s saw a polycrisis where several major economic shocks occurred within a short period of time.

Brexit was followed swiftly by the COVID 19 pandemic and several energy shocks. Further, in 2023 Russia began an illegal occupation of western Ukraine, which had repercussions for global trade, with the impact still being felt.

The economic separation of the UK from Europe was a major change in the UK's trading arrangements. Despite the pro-Brexit political arguments, it was clear that the reality was a decline in volumes, with total GB tonnage falling from about 455 million tonnes in 2019 to about 411 million tonnes in 2020, a fall of about 9.7%. This structural change was not a single impact of the pro-Brexit, as coincided with the outbreak of COVID-19 pandemic, making it difficult to disentangle the effects of Brexit from those of the pandemic. Temporary shutdowns and reduced economic activity across multiple sectors contributed to a significant reduction in overall port throughput during this period.

Following the initial contraction, a partial recovery was observed in 2022, with total tonnage rebounding to 431 million tonnes. However, this looked like a transitional spike during an adjustment process, rather than evidence of a sustained recovery as tonnage levels remain weak over the rest of the period. This temporary increase can be partly explained by post-pandemic reopening of the economy, which led to the clearance of backlogged or deferred cargo that had accumulated during the peak lockdown period. This rebound was further amplified by exceptional energy-import demand in 2022, as the European energy shock caused by the Russia-Ukraine conflict increased the urgency of securing alternative energy supplies, including higher LNG imports through energy-oriented port. This is reflected in the significant surge observed at Milford Haven (+28%) compared to 2021 (Table 6). Towards the mid 2020s, tonnages then settled down at a lower level, reaching around 429 million tonnages in 2024, which remained below the levels seen in previous decades. This suggests a process of normalisation after the temporary rebound, as the effects of post-pandemic reopening and exceptional energy import demand gradually dissipated, leading throughput levels to revert towards its underlying trend.

This period can be understood as a phase in which long-term structural trends, developed over previous decades, have become more visible and intensified. Notably, all major container-oriented ports recorded growth during this period, whereas a widespread decline was observed among ports handling bulk cargo. This clear divergence highlights a cumulative configuration of the UK port system, in which changes in trade structure and energy demand have progressively reoriented port activity towards containerised flows.

Port	Main Cargo Type	COVID Recovery Phase (2021 – 2022)	Overall Change (2020 – 2024)
Felixstowe	Container	Increase (+3%)	Stable (+0.1%)
Forth	Bulk (Mixed energy / dry bulk)	Increase (+4%)	Decrease (-25%)
Grimsby and Immingham	Industrial Bulk & Ro-Ro	Stable (+0.3%)	Decrease (-4%)
Liverpool	Mixed	Decrease (-2%)	Increase (+1%)
London	Mixed (Container + bulk+ ro-ro)	Increase (+6%)	Increase (+10%)
Milford Haven	Liquid bulk	Increase (+28%)	Decrease (-2%)
Southampton	Container / Ro-Ro	Increase (+13%)	Increase (+21%)
Sullom Voe	Liquid bulk	Decrease (-9%)	Decrease (-34%)
Tees and Hartlepool	Bulk (Energy-chemical)	Decrease (-5%)	Decrease (-17%)
Dover	Ro-Ro / short sea	Decrease (-8%)	Decrease (-11%)

Table 6: Total Change in tonnage at Top 10 GB ports in 2020s (Note: % rounded)

Conclusions and Future Analysis

All UK ports in the data set are included in the analysis, thus providing a comprehensive overview of changes in trade through UK ports. Clear structural changes are identified across the regions, with overall declines in tonnage in East Scotland and western regions, although the latter experienced only marginal declines. Scotland West recorded the largest increase. The 2000s had high volumes driven by globalisation and economic development, followed by a decline after the global financial crisis, leading to a transitionary phase in the 2010s. In the 2020s, increased supply chain risk and fragility have led to greater focus on resilience, and in particular how best to enhance the robustness of supply chains. UK government policy has historically been based on UK manufacturing and until the turn of the century this was reflected in the type of goods and their flows. Historically this was reflected in analyses of port data, where it could be shown that trade and port volumes were inextricably linked. However, in the two and a half decades of the twenty-first century there has been a fundamental shift in the manufacturing base, energy usage, and the UK's relationships with key trading partners. The results of the study show that, historically, while port clearly reflected economic flows, this may no longer be the case. While trade volumes are much lower than they were before 2000, the economic value of trade has significantly increased. The relationship between port cargo volumes and the value of trade has become disengaged.

In summary, the 2000s were a period of high cargo volumes as globalisation and economic development enhanced global trade. However, the global financial crisis of the second half of the 2000s knocked the volumes back, leading to a transitionary phase during the 2010s. Overall the 2020s while still not returning to the volumes of the 2000s have seen increased efficiency in port activity. Global trade in the 2000s followed a conventional pattern with steady economic growth leading to increased tonnages. However political decisions have led to a reshaping of regional trade through Brexit, and the exposure of global supply chains to greater risk and fragility has led to greater consideration of how best to enhance the robustness of supply chains. A further political shift followed the returning of a republican government in the 2020 USA election. The USA-centric policies of the government have led to a variety of trading shocks, not least the imposition of significant tariffs on many countries and the subsequent beginnings of the reshaping of global trade. While these impacts are still working through the global economic system, they will undoubtedly have an impact on tonnages and thus the volumes moving through UK ports.

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PUBLIC ATTITUDES, STRUCTURAL BARRIERS, AND POLICY SUPPORT IN THE TRANSITION TO SUSTAINABLE AGRICULTURE

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Introduction

Under the multiple pressures of global warming, frequent extreme weather and ecological degradation, the agricultural system faces unprecedented challenges (IPCC, 2022). As the core of food security and ecological balance, sustainable agricultural transformation not only involves technology selection, but also the interactive game between institutional arrangements and social acceptance (Loos et al., 2014). Although organizations such as FAO advocate the use of technological innovation to promote "green transformation" and propose CSA as a guiding framework (Lipper et al., 2014), there are significant differences in cognition, resources and institutional adaptability among different countries, regions and groups, resulting in highly fragmented practices (Makate et al., 2019).

In this context, the public's cognitive structure of agricultural environmental issues, acceptance of policy tools and feedback perception of technical paths (such as CSA) constitute the basic conditions for the enforceability of agricultural policies (Bell et al., 2021). However, existing research focuses on institutional design and technology evaluation, and rarely explores cognitive structures and social stratification mechanisms in the acceptance path. In particular, there is a lack of systematic analysis of the threshold-structure-institutional interaction of adaptation paths such as CSA in the early promotion stage (Gebre and Haile, 2018). In response to the above research gaps, this study uses a structured questionnaire to identify public attitude characteristics from three dimensions: climate cognition, policy preference, and technology acceptance.

Literature Review

As the industry most vulnerable to climate change, agriculture is systematically reshaping its production model and institutional adaptability (IPCC, 2022). On the one hand, ecological constraints such as soil degradation, water shortage and extreme climate have weakened the production capacity of high-intensity agriculture, pushing the policy system to evolve in a more resilient and equitable direction (Loos et al., 2014). Although technical paths such as precision agriculture and CSA are seen as solutions, the uncertainty caused by their high technological dependence, participation threshold and unequal access to resources has triggered continuous reflection on their social justice (Taylor, 2018).

In this process, the public's cognitive attitudes, institutional feedback and behavioural expectations have become important variables affecting the choice of transformation paths. Especially in the context of policies emphasizing

"public participation" and "pluralistic governance", understanding the public's perceived ranking of agricultural environmental risks, trust in policy tools, and willingness to accept technical paths has become a core premise for measuring the feasibility, fairness, and legitimacy of agricultural policies (Bell et al., 2021).

Although international research on sustainable agriculture and climate adaptation paths is increasingly abundant, existing literature focuses on macro- policy design and ecological performance evaluation, and pays less attention to cognitive structures and group attitude differences at the public level (Tomich et al., 2019). Especially in the context of China and the global South, there is still a lack of systematic, comparative, and institutionalized empirical research on the acceptance conditions, structural barriers, and institutional biases of different social groups in the green transformation of agriculture (Taylor, 2018).

Therefore, this study focuses on the public cognitive structure and social mechanisms behind the acceptance of sustainable agricultural paths through questionnaires and statistical modelling, aiming to provide more context- adaptive institutional feedback for policy making, promote transition research from "program effectiveness" to "social acceptability", and expand theoretical discussions on the relationship between development justice and environmental governance. The purpose of this research is to investigate the public's perception, acceptance, and policy preferences regarding the sustainable transformation of agriculture and animal husbandry in the context of climate change. This study seeks to provide a comprehensive understanding of how different stakeholders—including farmers, policymakers, and consumers—respond to sustainable agricultural models. Furthermore, it aims to identify critical barriers to transformation and develop policy recommendations that emphasize fairness, accessibility to technology, and public participation.

On the basis of clarifying the research purpose, further refining the problem setting is the premise for promoting empirical verification. Especially in the real situation where technical path disputes and institutional feedback are highly intertwined, it is necessary to start from the public's experience and clarify the inherent relationship between their risk judgment, policy trust and technology attitude.

To fulfil the research purpose, the objectives of this study are to:

1. Assess public awareness of the environmental impact and climate adaptability of traditional agricultural and animal husbandry practices.
2. Investigate public attitudes and acceptance levels towards sustainable agricultural models.
3. Evaluate the level of public support for various policy interventions aimed at promoting sustainable agriculture.
4. Identify major barriers to the implementation of sustainable agricultural transformation.
5. Provide policy recommendations that enhance fairness, technological accessibility, and stakeholder participation in sustainable agriculture.

To achieve these objectives, this study will address the following research questions:

1. What is the public's level of awareness regarding the environmental issues and climate adaptability of traditional agriculture and animal husbandry?
2. How do different groups perceive and accept sustainable agricultural models, including organic farming, circular agriculture, and climate-smart agriculture?
3. What policy measures do the public support most in facilitating sustainable agricultural transformation?
4. What are the primary obstacles hindering sustainable agricultural transformation?
5. How can different stakeholders contribute effectively to agricultural sustainability?

Research Problem

Current research on sustainable agricultural transformation focuses on macro- policy design, ecological benefit assessment or technical path optimisation (Lipper et al., 2014), while the public's cognitive structure, acceptance mechanism and the relationship between social identity in the transformation process are still relatively weak. Although technical paths such as climate-smart agriculture, organic agriculture and circular agriculture have been widely discussed, their social acceptance process is still often regarded as "non-core variables", and related studies often ignore how individual cognitive differences are transformed into institutional constraints on technology adoption.

In existing studies, the public is usually simplified as "consumers", and their role is mainly reflected in market preferences and sustainable consumption tendencies (Györene Kis et al., 2023). However, there is a lack of systematic research on the

behavioural logic and acceptance threshold of multiple subjects such as farmers, researchers, and policy implementers. In particular, the impact of social structural factors such as occupation, education, and region on environmental attitudes and policy support tendencies has not yet formed a unified analytical framework (Taylor, 2014).

In addition, existing studies rarely reveal the "practicability" of the public in agricultural transformation from the perspective of institutional feedback. Some literature points out that low-income groups and marginal communities are excluded by technical barriers or information barriers in the transformation (Makate et al., 2019), but there is a lack of empirical data to classify and verify the types of obstacles and structural logic, which makes it difficult for policymakers to accurately identify the "social fault lines" in actual implementation.

This study responds to the above shortcomings from the perspective of the public, combined with structured questionnaires and stratified statistical analysis, it systematically identifies their risk perception, policy preferences and resistance to acceptance of agricultural environmental issues, and uses occupation, education, region and other variables as entry points to explore structural differences and institutional accessibility issues in agricultural transformation. By constructing a cognitive-structural-institutional analytical framework, the study will provide a micro-foundation for understanding the social acceptance conditions of agricultural transformation and provide structured empirical support for future policy optimisation.

Methodology

The study is based on the pragmatic paradigm, emphasizing the adaptability between methods and goals, and advocating that knowledge serves real problems (Morgan, 2007). Given the complexity of the CSA system, although it is mainly quantitative, subjective feedback from respondents is still included to enhance explanatory power (Johnson and Onwuegbuzie, 2004).

In terms of logic, deductive reasoning is used to test theoretical hypotheses through cross-sectional surveys to depict a horizontal map of differences in CSA cognition (Blaikie and Priest, 2019). The questionnaire covers five modules: problem cognition, demographic characteristics, policy preferences, technical attitudes, and subjective opinions. The structured items are based on the Likert five-point scale (Boone and Boone, 2012), and open questions are set to obtain subjective interpretations of CSA implementation barriers (Plano Clark and Ivankova, 2016). This study aims to construct the reasoning path of "cognition-attitude-support- resistance" to provide a structural basis for CSA policy formulation and institutional adaptation.

Research Design -This study adopts a quantitative research design, with a structured questionnaire survey as the main tool, to collect data through standardized questions and scales to identify structural differences in the acceptance of CSA (climate-smart agriculture) among different population groups. This design form helps to identify trends and infer relationships between variables in a larger sample size, and is particularly suitable for testing specific research hypotheses such as "whether occupation type affects CSA support" and "whether educational background affects policy preferences".

The research questions (RQ1–RQ5) involve CSA cognition, policy support, technology attitudes and institutional barriers. To this end, the research team divided the questionnaire into five structural modules based on the logic of the questions:

1. *Problem cognition (RQ1): measure the respondents' subjective judgment on agricultural environmental issues;*
2. *Demographic characteristics: collect variables such as age, gender, education, occupation, and region to serve subsequent group analysis;*
3. *Policy preferences (RQ2, RQ3): assess the respondents' acceptance of CSA-related incentive policies;*
4. *Technology adoption attitude (RQ4): identify the respondents' subjective evaluation of resistance factors such as technology costs and information acquisition;*
5. *Open opinions (RQ5): capture institutional factors or individual experiences not covered by the structured questionnaire through subjective fill-in-the-blank questions.*

Each closed-ended question is based on a five-point Likert scale design (1=completely disagree, 5=completely agree), which is convenient for reflecting the distribution characteristics of attitudes through descriptive statistics and inferential tests. The entire research process strictly follows the logic of deductive reasoning, proposes hypotheses based on theory, and tests and explains them through quantitative data.

Data Collection -The data collection for this study was conducted through an online questionnaire survey. The questionnaire was prepared by the research team using the Jisc questionnaire platform and was publicly released through social media channels (including WeChat, Red note, Instagram, Twitter and Discord) from March to April 2025.

The research team did not use probability sampling, but adopted the convenience sampling method in non-probability sampling, that is, invitations were issued through social networks, and individuals willing to participate voluntarily filled in the questionnaire. Although this method limits the representativeness of the sample in a statistical sense, considering the exploratory goals of this study and the need to identify structural variables, this strategy is still realistic and feasible.

Sample Size - In the end, a total of 220 questionnaires were received, of which 205 were valid questionnaires, with an efficiency of 93.18%. All data collection followed the principle of anonymity, no personal identity information was recorded, and all respondents had read the consent statement before answering the questions, and clearly understood that the data was only used for academic research.

Data Analysis Strategy -This study uses Statistical Package for the Social Sciences (SPSS) as the main data analysis tool because it is highly stable and practical in processing large-scale questionnaire data, cross-variable analysis, and group difference tests (Pallant, 2020). Given that this study focuses on the impact of social structural variables such as education and occupation on CSA acceptance, the variance analysis and multivariate regression models provided by SPSS just meet the research needs (Field, 2018). The analysis strategy is mainly based on descriptive statistics and inferential analysis, supplemented by the theme induction method of open-ended questions to enhance the integrity and authenticity of data interpretation.

Results

Respondent demographics - 205 valid questionnaires collected, ages of respondents

were mainly between 18 and 35 years old, of which 18-25 years old accounted for 40.98%, and 26-35 years old accounted for 37.07%, The gender ratio was basically balanced, with males accounting for 48.78% and females accounting for 51.22%, with 69.27% were undergraduates and 23.9% were masters or above.

Urban and rural areas each accounted for 39.51%, and suburban areas accounted for 20.98%. For occupational composition, consumers accounted for 50.24%, researchers/educators accounted for 21.46%, and policymakers/managers accounted for 20%. It is worth noting that 72.2% of respondents said they were “very concerned” or continuously concerned about climate change, and 36.1% expressed both concerns. This shows that climate issues have formed a broad consensus among the public and strengthened the social foundation for sustainable agricultural development.

For RQ1 - The results show that ‘declining soil fertility’ is considered the most serious problem (n=96), The second most serious problem is ‘excessive consumption of water resources’ (n=82). In water- stressed areas, biodiversity decline (n=82) and insufficient climate adaptability (n=86) are also widely concerned, those that indiscted that ‘pesticides and fertilizers pollute the environment’ is (n=75), it still reflects the public’s continued concern agricultural pollution and consequences.

RQ2: the differences in acceptance of sustainable agricultural models (including organic agriculture, circular agriculture and CSA) among different gender groups (Test, 2025). The results show that the mean values of acceptance of organic agriculture for men and women are 2.29 and 2.3, respectively, with standard deviations of 0.56 and 0.54, $t = -0.191$, $p = 0.849$; in circular agriculture, the mean values are 3.58 and 3.74, with standard deviations of 1.23 and 1.14, $t = -0.985$, $p = 0.326$; in CSA, the mean values are 3.51 and 3.65, with standard deviations of 1.18 and 1.07, $t = -0.879$, $p = 0.381$. The above p values are all greater than 0.05, indicating that there are no significant gender differences in the acceptance of the three sustainable agricultural models. Overall, gender has little impact on the acceptance of sustainable agriculture.

A variance analysis on the acceptance of sustainable agricultural models by residents in different regions. In terms of organic agriculture, the mean scores of urban, suburban and rural areas were 2.31, 2.21 and 2.33 respectively, with standard deviations of 0.52, 0.62 and 0.55 respectively,ll three p values were greater than 0.05, supporting hypothesis H3, indicating that there were no significant differences in the acceptance of sustainable agriculture between different region.

RQ3:shows the respondents’ policy preferences for promoting sustainable agricultural development (Despotovi et al., 2021). The results show that ‘strengthening financial subsidies for sustainable agriculture and promoting

low-carbon agricultural technologies' was supported by 84 people, and 'strengthening agricultural education and technical training' was supported by 82 people, reflecting that the respondents generally recognized that the government promoted green transformation through financial and technical means. 'Providing special support for small farmers' was supported by 79 people, which is relatively low, but highlights its key position in the transformation. The highest support rates were 'enhancing sustainable consumption awareness' and 'strengthening environmental supervision of industrialized agriculture' (both 85 people), indicating that the public attaches great importance to the synergy between consumer behavior and production governance in agricultural sustainability.

RQ4: With the response of (n=97), Its shows that "lack of market demand" is the biggest challenge facing agricultural transformationreflecting that if the new agricultural model cannot connect with the market, it will be difficult to achieve sustainable growth. At the same time, "lack of technical support" is also widely recognized as a key obstacle, indicating that technological innovation and popularization capabilities have a decisive impact on the effectiveness of agricultural transformation.

RQ5: Table 1.0 shows the results of regression analysis of sustainable agricultural development by different stakeholders. This analysis takes sustainable agricultural development as the dependent variable and 'agriculture-related occupations' as the independent variable, covering agricultural practitioners, policy makers, researchers and consumers. The constant term is 2.544, indicating that the baseline level is already high when the occupational influence is not considered (Montgomery et al., 2021). The independent variable regression coefficient is 0.078, the standard error is 0.038, the standardized coefficient is 0.143, $t = 2.064$, $p = 0.040$, indicating that occupation has a significant positive impact on sustainable agricultural development (Seber & Lee, 2003; Uyanık & Güler, 2013).

Table 1.0 Regression analysis of the impact of different stakeholders on agricultural sustainable development

	Unstandardized coefficients		Standardized coefficient			Collinearity diagnostics	
				t	*p*		
	B	Standard error	Beta	VIF		Tolerance	
constant	2.544	0.1251	-	20.31	-		
The relationship between your profession and agriculture	0.078	0.038	0.143	2.064	1		
R 2		0.021					
Adjust R 2		0.016					
F		F (1,203) = 4.259 , p = 0.040					
DW value		2.042					

Dependent variable = Sustainable agriculture *p<0.05 **p<0.01 ***p<0.001

This study focuses on five core research questions (RQ1–RQ5). Through structured questionnaires and basic statistical analysis, it explores the differences in public perception of agricultural environmental issues, policy preferences and technology acceptance, and reveals multiple challenges in the sustainable transformation of agriculture.The results show that "soil degradation" in RQ1 is considered the most serious problem, which is consistent with its association with food security as described by Lal (2020). RQ2 shows that there are no significant differences in gender, age and regional variables, which may be due to the convergence of cognition within the highly educated group, but it also suggests that structural inequality may be more hidden. As for RQ3, the public is more supportive of low-threshold measures such as fiscal subsidies and technical training, while lacking awareness of market mechanism tools, reflecting the general recognition of capacity building orientation. RQ4 points out that "high technology cost" and "lack of information" are the main obstacles, highlighting the tension between institutional design and resource accessibility. The results of RQ5 show that the "occupation" variable is weakly significant, and agricultural practitioners have a higher acceptance of CSA, indicating that practical experience has a positive impact on technology adoption. In summary, although the CSA concept has been widely recognized, technical and institutional barriers still limit its fair popularization. Future policies need to seek a balance between effectiveness and fairness.

In summary, future research needs to be expanded on multiple levels: on the one hand, field interviews, participatory observation and other methods can be used to supplement the experience feedback omitted by structured questionnaires, especially the practical perspectives of farmers and grassroots policy implementers; on the other hand, a more explanatory behavioural path model should be constructed to systematically integrate cognitive, resource, institutional and environmental variables, and deeply analyse the internal logic of the public's transition from attitude recognition to behavioural adoption; at the same time, mature theoretical tools such as TAM model and social practice theory should be introduced to enhance the systematic Ness and predictive power of the analysis dimension

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EVALUATING MACHINE LEARNING AND DISCRETE CHOICE MODELS FOR TRAVEL MODE CHOICE IN AIR–RAIL INTEGRATION

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Abstract: This paper compares the Multinomial Logit (MNL) model with five machine learning (ML) approaches, Random Forest (RF), ExtraTrees, Histogram Gradient Boosting (HistGB), Deep Neural Networks (DNN), and XGBoost, for travel mode choice within air–rail integrated journeys under service disruption. Its novelty is a controlled experimental comparison under systematically varied disruption intensities using a 3×2×4 factorial design and 24 synthetic datasets generated from a known Data Generating Process. It also provides the first joint evaluation of discrete choice and ML models on four dimensions: predictive accuracy, probabilistic calibration, xbehavioural validity, and aggregate market-share forecasting. Results show that MNL achieves the highest predictive accuracy (79.69%, Macro-F1 = 0.761, GMPCA = 0.624) but produces increasingly biased aggregate forecasts as disruption severity grows (Normal-mode market-bias rising from 0.039 to 0.302). Among machine learning models, DNN uniquely achieves 100% behavioural validity across all disruption levels while maintaining competitive calibration. Importantly, disruption magnitude systematically changes model rankings and suitability, so no single model dominates across all scenarios. These findings underscore that model selection should depend on evaluation criteria and disruption intensity and calls for real-world validation in future work.

Keywords: Air–rail integration, Travel mode choice, Machine learning, Deep learning, Behavioural modelling, Multimodal transport

1. Introduction

1.1 Background and Motivation

Air–rail integrated journeys are structurally more exposed to disruption than single-mode journeys because the two legs are operated, monitored, and recovered by organisations that share neither passenger information nor a common recovery protocol. Airlines hold passenger manifests and can identify and rebook travellers on a disrupted connection; rail operators typically cannot, since most rail tickets are unassigned and boarding is unsupervised, so a delayed train cannot easily be matched to the flights its passengers are trying to catch (Toet et al., 2025). This gap is compounded by tight connection buffers: rail-to-air transfers rarely benefit from through-check arrangements, so a short rail delay can be enough to miss a connecting flight, while a flight delay can strand a passenger needing onward rail service with no seat guarantee or interline agreement between operators (Xia and Zhang, 2017). Airports, rail providers, and journey planners therefore face a shared but poorly coordinated problem: how much contingency capacity to hold, whether to reallocate rail capacity for passengers who may not show up, and what to tell travellers, correctly and in real time, about whether to wait, rebook, or reroute. Each decision depends on an accurate, real-time estimate of how passengers will choose between the disrupted and alternative modes.

The MNL model has been the standard framework for travel mode choice modelling for decades, valued for its theoretical grounding in random utility maximisation and its interpretable parameter estimates. In recent years, ML classifiers have been proposed as alternatives, with several studies reporting accuracy gains of up to 35 percentage points over MNL (Hagenauer and Helbich, 2017). A systematic review of 70 peer-reviewed articles demonstrates that many of these gains are artefacts of methodological problems, specifically data leakage caused by trip-wise sampling in panel datasets and class balancing applied to both training and test sets (Hillel et al., 2021). When these problems are corrected, discrete choice models trail top ML classifiers by only 3-4% on accuracy in large-scale benchmarks (Wang et al., 2024). The central question, therefore, is not whether ML beats MNL on accuracy the evidence suggests only a marginal edge but whether ML models are reliable enough to support transport policy decisions requiring calibrated probabilities, economically consistent behaviour, and accurate aggregate demand forecasts. These dimensions are rarely evaluated together in existing studies (Martín-Baos et al., 2023), leaving practitioners without clear guidance on which model to use and when.

This study uses a controlled framework to prevent data leakage, apply class balancing techniques, and evaluate models with multiple metrics and significance tests. By emphasizing interpretability, computational feasibility, and contextual robustness, it addresses methodological shortcomings to yield more reliable assessments of ML-based mode choice predictive performance and to support responsible, policy-relevant transportation modelling. Behavioural validity matters more here than in single-mode contexts because no other actor in an air–rail journey can cross-check a demand forecast against ground truth in real time: if a model predicts rising demand for a disrupted leg as delay worsens, a pattern this paper treats as a monotonicity violation, an airport or rail provider acting on that forecast would misallocate contingency capacity precisely when passengers need it most, with no equivalent single-mode failsafe to catch the error.

This study has three objectives: (1) compare MNL with five ML classifiers (RF, Extra Trees, HistGB,DNN,and XGBoost) across classification accuracy, probabilistic calibration/behavioural validity, and aggregate market-share forecasting; (2) evaluate how relative performance varies with disruption magnitude, utility structure, and error distribution using a controlled factorial design with a known Data Generating Process (DGP); (3) determine which model type suits prediction, probability estimation, or policy counterfactuals under different disruption conditions.

We use synthetic data from a known DGP to enable exact ground-truth comparisons (Martín-Baos et al., 2023). The factorial design spans three disruption levels, two utility structures, and four error distributions (24 datasets). MNL uses standard linear utilities.

2. Related works

2.1 ML vs. MNL on Predictive Performance

Early comparisons report large ML gains over MNL. RF achieves 92% accuracy vs 57% for MNL on the Dutch NTS dataset (Hagenauer and Helbich, 2017), and RF ranks top across data sets more broadly, spurring early ML interest (Zhao et al., 2020). A key flaw is trip-wise splitting of panel data, which allows the same individuals in both train and test sets, leaking preference information; correcting this largely erases the advantage (Hillel et al., 2021). In a large benchmark of hundreds of classifiers, discrete choice models (DCM) fall within 3-4% of the best ML methods under rigorous validation (Wang et al., 2024). Similar findings are reported when accounting for response heterogeneity (Salas et al., 2022). The consensus from methodologically sound studies is that ML's accuracy advantage over MNL is modest and context dependent.

2.2 Behavioural Validity of ML Models

Predictive accuracy is only part of model evaluation. RF, despite higher accuracy, yields small marginal effects and poor extrapolation beyond training ranges, limiting its use for policy counterfactuals (Zhao et al., 2020). XGBoost and RF suffer numerical issues in derivative calculation and fail to produce monotone probability responses to service attributes (Martín-Baos et al., 2023). DNNs can, in principle, extract interpretable economic information comparable to DCMs but face three practical challenges: high hyperparameter sensitivity, model non-identification, and local irregularity that produces unreliable estimates at small sample sizes (Wang et al., 2020). Hybrid approaches attempt to combine DCM interpretability with ML flexibility. The Theory-Based Residual Network (TB-ResNet) combines DCM utility structure with DNN flexibility to improve interpretation and robustness (Wang et al., 2021), while ResLogit models utility as a linear logit term plus a DNN residual, reducing sensitivity to cross-effects (Wong and Farooq, 2021). These advances blur the boundary between DCM and ML, yet purely data-driven tree-based methods remain problematic for behavioural applications. Existing air–rail integration research has concentrated on network design and scheduling problems, such as minimising connecting time to raise social welfare (Xia and Zhang, 2017), and on stakeholder-level accounts of why disruption recovery across the two modes is difficult in practice (Toet et al., 2025). None of this work quantitatively models how passengers themselves choose between a disrupted and an alternative mode, nor whether the models used to forecast that choice remain trustworthy as disruption severity increases. No existing study has evaluated these differences under systematically varying disruption magnitude, which is the gap this paper addresses.

3. Study Design

3.1 Synthetic Data Generation

Twenty-four synthetic datasets are generated from a known DGP for a three-alternative mode-choice problem: Normal (undisrupted baseline service), Enhanced (improved substitute), and Disrupted (degraded under disruption). This setup represents passenger decisions during service disruption, where utility shifts asymmetrically across alternatives as service conditions worsen. In an air–rail context, Normal corresponds to an on-time connecting service, Enhanced to a substitute such as a rebooked flight or an alternative rail departure, and Disrupted to the traveller's own delayed leg, for example a rail delay that jeopardises a connecting flight, a flight delay stranding a passenger needing onward rail travel, or a cancelled service requiring rerouting through another hub. The fully crossed $3 \times 2 \times 4$ factorial design varies disruption magnitude ($\beta D \in \{0.5,1.0,2.0\}$), utility form (linear vs. nonlinear), and error distribution (Gumbel, Normal, Exponential, Uniform), yielding 8 datasets per disruption level. The nonlinear specification is implemented through interaction, quadratic, and threshold-style terms (rather than a Cobb-Douglas form), creating controlled misspecification conditions for MNL. Each dataset has 5,000 training and 1,000 test observations. Alternative attributes and stochastic components are generated via Monte Carlo from predefined ranges/distributions. This design enables reproducible, controlled comparison of model behaviour across disruption regimes.

3.2 Models Compared

Six model classes were compared: Multinomial logit (MNL), Random Forest (RF), ExtraTrees, Histogram Gradient Boosting (HistGB), a feed-forward neural network (DNN), and XGBoost. MNL was implemented as multinomial logistic regression with standardized inputs. RF and ExtraTrees are ensemble trees, with ExtraTrees using more split randomization. HistGB used gradient-boosted trees on histogram-binned features for multiclass prediction. DNN was a fully connected multilayer perceptron with ReLU hidden units and softmax outputs. XGBoost used the multiclass softprob objective. ML hyperparameters were tuned via Bayesian optimization (Optuna TPE) with 30 trials per model and 5-fold stratified cross-validation, and a multi-metric criterion prioritizing predictive accuracy while accounting for macro-F1 and GMPCA; the Dummy baseline was not tuned.

3.3 Experiments

Three experiments evaluate models across complementary dimensions, motivated by the argument that probability-based indices are essential alongside accuracy (Hillel et al., 2021), and the finding that market-share forecasting and behavioural indicators require separate assessment (Martín-Baos et al., 2023).

Experiment 1 - Classification: measures test-set accuracy, macro-F1, and Geometric Mean Predicted Choice Probability (GMPCA). GMPCA rewards correct labels that are also assigned high predicted probability, penalizing models that predict the right class with low confidence.

Experiment 2 - Calibration and Behavioural Validity: evaluates the multiclass Brier score (quality of the full three-class probability vector), expected calibration error (ECE) for P(Normal), ProbCorr (correlation between predicted and DGP P(Normal) over a 41-point delay grid from 0 to 70 min), and strict monotonicity of P(Normal) with increasing delay. Monotonicity is the central behavioural validity test: an increasing Normal-mode share as delay worsens is implausible here and, because probabilities sum to one, would imply compensating errors in Enhanced and Disrupted shares.

Experiment 3 - Market-Share Response: compares predicted Normal-mode share trajectories over delays 0-70 min to the DGP ground truth. Measures include mean absolute bias at delay = 0 (initial-share error), and trajectory monotonicity (does predicted Normal share decline consistently with increasing disruption).

Friedman omnibus tests ($n = 24$ paired datasets) assess overall inter-model differences (Friedman, 1937), followed by pairwise Wilcoxon signed-rank tests with Holm–Bonferroni correction ($\alpha = 0.05$) and rank-biserial effect sizes (Wilcoxon, 1945; Holm, 1979). Binary monotonicity comparisons are evaluated using McNemar tests.

4. Results & Discussion

4.1 Classification Performance (Experiment 1)

Figure 1 shows the performance measures averaged across all 24 datasets. MNL leads on all three measures: highest accuracy (79.69%), highest Macro-F1 (0.761), and highest GMPCA (0.624). GMPCA separates the models more sharply than accuracy alone. RF drops to 0.562 and ExtraTrees to 0.546, revealing that these models assign lower probability mass to the correct class even when they occasionally predict the right label. XGBoost and DNN are effectively tied on accuracy ($p = 0.175$ after Holm–Bonferroni correction, $r = 0.32$) but DNN shows slightly lower GMPCA (0.610 vs 0.616), indicating marginally less confident correct-class probabilities.

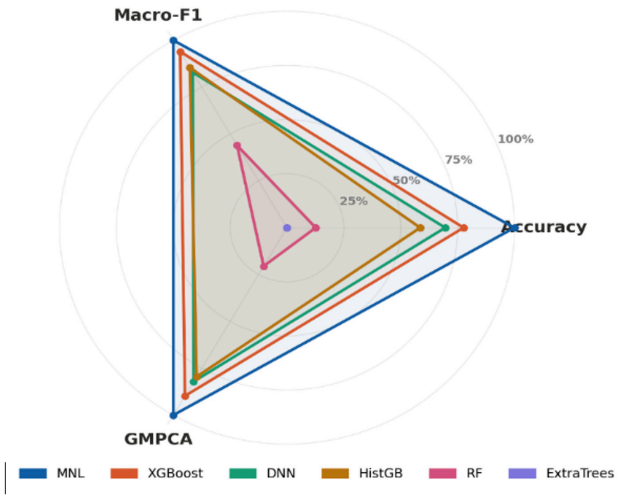

Figure 1: Radar plot comparing models on three normalized axes: Accuracy, macro-F1 and GMPCA. Scores are averaged across all 24 datasets.

4.2 Probabilistic Calibration (Experiment 2)

Table 1 shows Experiment 2 results, the mean probabilistic measures across disruption levels. Calibration was assessed with the multiclass Brier score and ECE for P(normal). Despite leading in accuracy, MNL has the worst overall Brier score (0.318), reflecting miscalibration across all three alternatives; its ECE for P(normal) (0.084) is substantially higher than for ML models (0.027 – 0.053). XGBoost achieves the best Brier (0.290) and DNN the second-best (0.294). Critically, MNL's ProbCorr is only 0.852, far below all ML models (0.97–0.99), showing that its delay-response shape poorly matches the DGP. XGBoost and ExtraTrees achieve the highest ProbCorr (0.985–0.986) but Table 3 shows they often violate monotonicity at low disruption, demonstrating that high correlation does not ensure behaviourally valid delay trajectories.

Model	Brier ↓	βD=0.5	βD=1.0	βD=2.0	ECE ↓	ProbCorr ↑
MNL	0.318	0.370	0.336	0.248	0.084	0.852
DNN	0.294	0.350	0.298	0.234	0.027	0.984
XGBoost	0.290	0.350	0.296	0.225	0.027	0.985
ExtraTrees	0.302	0.360	0.309	0.237	0.028	0.986
RF	0.311	0.370	0.319	0.245	0.029	0.973
HistGB	0.310	0.375	0.318	0.239	0.053	0.984

Table 1: Results for Experiment 2 – mean probabilistic measures.

Figure 2 shows P(Normal) against the DGP ground truth for four conditions: βD = 1.0 and 2.0, linear and nonlinear utility, Gumbel error. The range is restricted to 0-70 min (the training domain) to provide a clean in-sample comparison. Only the Gumbel specification is shown due to page size restrictions, with similar patterns observed across all 24 datasets. The key finding is that MNL (blue) consistently declines too slowly, remaining well above the ground truth through the mid-delay range across all panels. At βD = 2.0, MNL also starts below the ground truth at zero delay before overshooting, reflecting structural underestimation of the disruption coefficient. All ML models track the ground truth more closely, with some early-delay divergence visible under nonlinear utility.

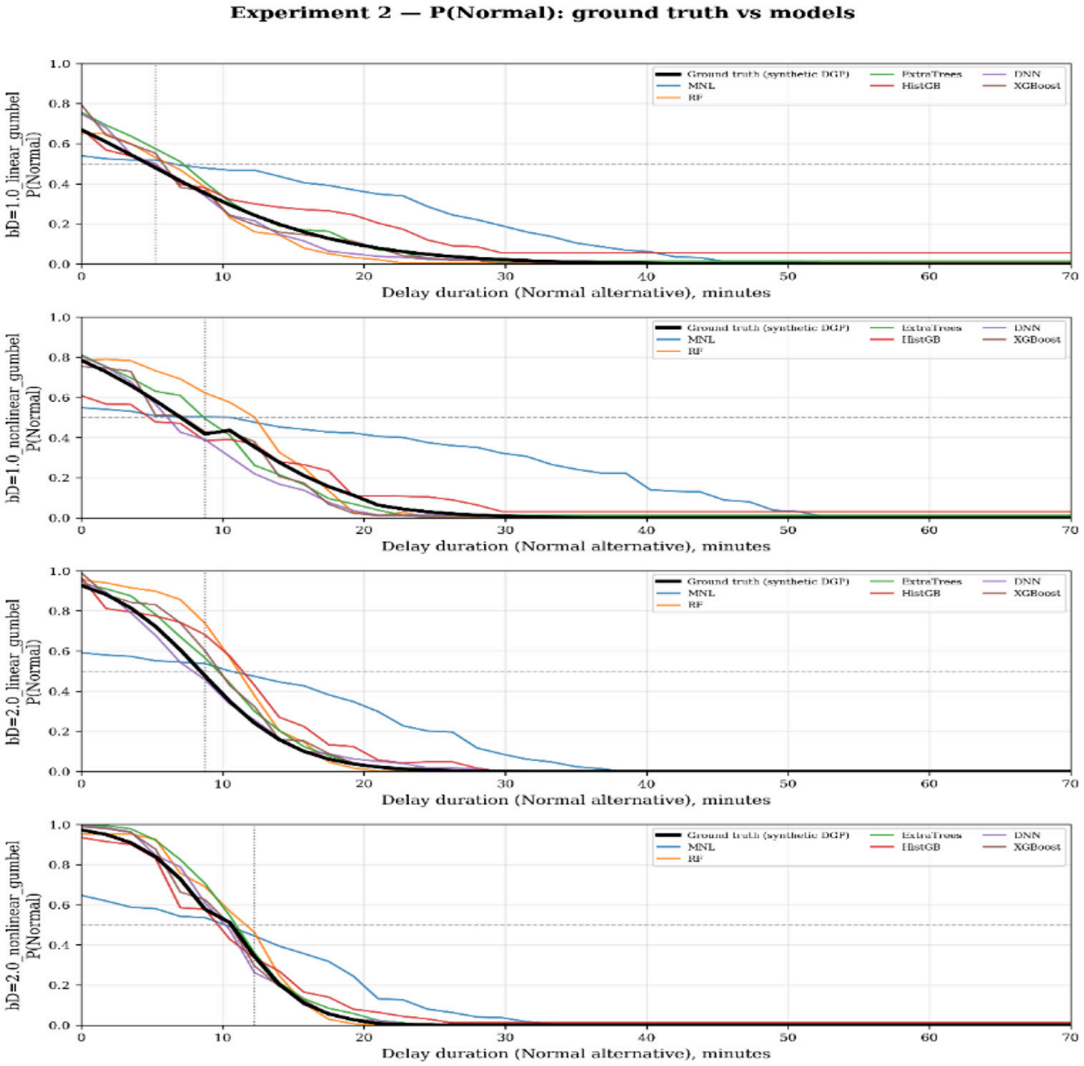

Figure 2: Experiment 2 P(Normal) ground truth vs. model predictions within the observed delay range (0–70 min)

4.3 Behavioural Validity by Disruption Level

Across all 24 datasets, MNL achieves 100% behavioural validity, strictly monotone P(Normal) with increasing delay at every disruption level by construction, since its logistic utility is monotone regardless of signal strength. DNN is the only ML model to match this, also achieving 100% validity across all 24 datasets for $\beta D = 0.5$, 1.0, and 2.0.

Tree-based methods fail substantially at low disruption (weak delay signal). At $\beta D = 0.5$, ExtraTrees records 0% valid datasets, meaning monotonicity is violated in all eight low-disruption cases. HistGB achieves only 25%; XGBoost 38%; and RF 50%. These low-disruption scenarios are precisely where planners require reliable sensitivity analysis, as choice responses to modest delays are subtle. McNemar tests (McNemar, 1947) confirm significant superiority of MNL and DNN over RF, HistGB, and ExtraTrees at every disruption level. Pairwise comparisons produce discordant counts favouring MNL or DNN (e.g., MNL vs. HistGB: 11 discordant pairs, $p < 0.001$; MNL vs. RF: 10 pairs, $p < 0.002$). The difference between MNL and DNN is not statistically significant, supporting the conclusion that MNL and DNN are jointly the only models consistently valid for behavioural applications across disruption regimes.

4.4 Market-Share Forecasting (Experiment 3)

Table 2 reports mean absolute bias in predicted Normal-mode share at delay = 0 against DGP, and trajectory monotonicity across the 15 delay steps, a distinct criterion from Experiment 2 since aggregation can smooth individual-level non-monotonicity's. MNL's initial-share bias grows from 0.039 at $\beta D = 0.5$ to 0.202 at $\beta D = 1.0$ and 0.302 at $\beta D = 2.0$. At severe disruption, MNL predicts approximately 0.65 while the true share is near 0.95, underestimating by 0.30 and misallocating mass to Enhanced and Disrupted shares since all three must sum to one. All ML models show substantially lower bias, with DNN (0.023 at $\beta D = 2.0$) providing the best combination of low bias and full trajectory monotonicity. A notable nuance emerges in Table 2: HistGB, which achieved only 54% validity in Experiment 2, reaches 100% trajectory validity here across all disruption levels, confirming that a model unreliable at the individual probability level can still produce aggregate trajectories that decline consistently. These results highlight that aggregate market share behaviour can mask individual level irregularities, so both granular probabilistic validity and aggregate trajectory assessments are necessary for reliable policy forecasting. RF remains the worst performer on trajectory monotonicity (38% at $\beta D = 0.5$) and does not fully recover even at $\beta D = 2.0$ (88%).

Model	βD=0.5		βD=1.0		βD=2.0	
MNL	0.039	100%	0.202	100%	0.302	100%
DNN	0.052	100%	0.057	100%	0.023	100%
ExtraTrees	0.080	100%	0.088	100%	0.019	100%
RF	0.092	88%	0.079	100%	0.015	100%
HistGB	0.052	88%	0.088	100%	0.083	100%
XGBoost	0.141	38%	0.074	88%	0.023	88%

Table 2: Experiment 3 Mean absolute bias in predicted Normal-mode and Market-share monotonicity (in %) by disruption level.

Figure 3 shows predicted Normal-mode market-share against delay for three representative conditions $\beta D = 0.5$, 1.0, and 2.0 under linear utility, Gumbel error. Due to page size constraints, only one error specification and utility form is included; the remaining 21 datasets covering Exponential, Normal, and Uniform error distributions under both linear and nonlinear utility are not shown, but they follow the same directional pattern. Across all three panels, MNL (blue dashed) declines too slowly relative to the ground truth (black), with the gap widening as disruption increases. At $\beta D = 0.5$, HistGB shows a pronounced floor effect while MNL lags moderately. At $\beta D = 1.0$, MNL's slow decline becomes more prominent. At $\beta D = 2.0$, the contrast is sharpest MNL starts ~0.34 below the ground truth at zero delay and remains well above it through the mid-range, while all ML models track the ground truth closely and converge near zero by delay 30. This confirms that MNL's market-share forecasting error grows systematically with disruption magnitude, as quantified in Table 2.

4.5 Statistical Summary

Table 3 confirms all inter-model differences are systematic across the 24 datasets. All six metrics yield highly significant Friedman statistics (all $p < 10^{-11}$ before correction). The largest statistic is for GMPCA ($\chi^2 = 107.8$), confirming that probability quality on the true class is where models diverge most sharply. ProbCorr yields the smallest statistic (62.90) but remains far beyond any conventional significance threshold, confirming that MNL's weak delay-response tracking is a consistent phenomenon across all 24 conditions.

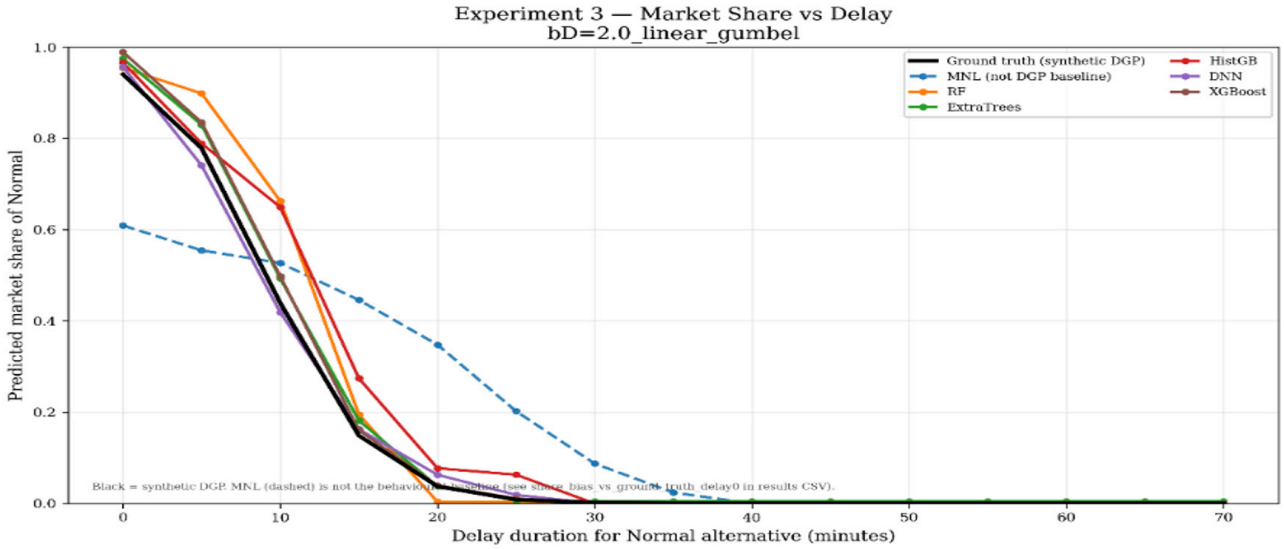

Figure 3: Predicted Normal-mode market share vs. delay at $\beta D = 0.5$, 1.0 and 2.0

Metric	Experiments	Friedman χ^2	p-value
Test Accuracy (%)	Exp 1 Classification	96.84	2.45×10^{-19}
Test F1 (macro)	Exp 1 Classification	92.86	1.69×10^{-18}
Test GMPCA	Exp 1Classification	107.8	1.19×10^{-21}
Brier (multiclass)	Exp 2 Probabilistic	81.31	4.47×10^{-16}
ECE - P(Normal)	Exp 2 Probabilistic	70.02	1.01×10^{-13}
ProbCorr (delaygrid)	Exp 2Probabilistic	62.90	3.05×10^{-12}

Table 3: Friedman test statistics (n = 24 paired datasets). Post-hoc: pairwise Wilcoxon signed-rank with Holm–Bonferroni correction at $\alpha = 0.05$.

5. Limitations and Future Work

This study uses synthetic data for exact ground-truth evaluation but cannot fully replicate real-world attribute correlations, unobserved heterogeneity, or panel effects, so observed rankings and behavioural-validity patterns must be validated on air–rail survey data before generalisation. The scope is limited to MNL and five ML classifiers, excluding Mixed Logit, Nested Logit, and hybrid neural-logit models. Future work will validate these results on real-world air–rail data and extend the framework to multimodal settings with KPI-driven operational metrics.

6. Conclusion

This study presents the first controlled comparison of MNL and five ML classifiers across prediction, calibration, behavioural validity, and market share forecasting under systematically varied disruption. Key finding: no single model dominates. MNL achieves highest predictive accuracy, but its aggregate forecasts grow increasingly biased with disruption (Normal mode

bias up to 0.302). DNN uniquely matches MNL on behavioural validity while delivering superior calibration and forecasting across disruption levels. Tree based methods fail at low disruption, the regime where sensitivity analysis matters most. Practical implication: model choice must depend on the evaluation objective and expected disruption intensity. For policy counterfactuals and demand forecasting under disruption, DNN is preferred. While MNL remains competitive for routine prediction, DNN is the only model that combines high behavioural validity with strong calibration and forecasting accuracy across all disruption levels, making it the more defensible choice for disruption-management systems such as passenger information displays, capacity-allocation algorithms, and contingency-capacity decisions. The results caution against choosing models on accuracy alone and advocate adopting the paper's multi criterion evaluation framework as standard practice for disruption sensitive air–rail and multimodal transport modelling.

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BUILDING TRANSPORT INFRASTRUCTURE RESILIENCE THROUGH TRANSITION CAPABILITY

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1. Introduction

Transport systems depend on physical assets that often remain operational far beyond their original design assumptions. Bridges, tunnels, ports, ferry terminals and movable access systems face ageing, corrosion, climate stress, cost pressure and tighter expectations for safety, continuity and environmental stewardship. Owners must keep services safe and reliable while condition information is often partial, periodic and difficult to translate into timely intervention. Resilience is therefore not only the ability to restore services after disruption; it is also the organisational, technical and institutional capability to detect deterioration early, interpret condition evidence, prioritise action and justify investment before failure occurs.

Recent research links resilience, sustainability and decision support. Kopiika et al. (2025) develop sustainability- and resilience-driven prioritisation for restoring critical infrastructure, while digital twin research is moving from general modelling to asset-level decision support (Wu et al., 2025) and into port and maritime contexts (Zhu et al., 2025). Emerging work argues that data-driven monitoring strengthens resilience only when it enables early warning, predictive maintenance and adaptive governance rather than remaining a disconnected technology layer (Ajayi et al., 2025; Afolabi et al., 2025; Leong, 2026). Yet little attention is given to the transition through which an organisation moves from evidence-poor maintenance to evidence-rich predictive assurance. A sensor platform generates data, but data becomes resilience capability only when it is trusted, interpreted, routinised, accepted by practitioners, aligned with statutory assurance and supported by institutional linkages. This paper argues that resilience in ageing transport infrastructure should be understood as a process of transition.

The empirical setting is RELIQ (REliability Of LInkspans Through Quantum Sensing), a Phase 1 feasibility study of a hybrid monitoring architecture – quantum sensing, fixed sensors, AI analytics and a lightweight digital twin – for ageing linkspans. A linkspan is a movable ramp connecting shore and vessel for roll-on/roll-off ferries; in island settings it is lifeline infrastructure whose failure disrupts mobility, freight, emergency access and local economies. Anchored in XY Harbour Authority (XYZHA) at the ferry terminal, and validated with SP (technology provider company) , NHA, O Marine (marine infrastructure inspection company) and WB (technology integrator company), the case is interpreted as an institutional transition rather than a purely technical exercise. The paper asks how evidence gaps constrain resilience-building, how quantum-enabled monitoring can create transition capacity and capability, and what institutional pathways enable willingness to transition. It contributes a process framework, empirical NHA evidence from a real asset-owner context, and practical guidance for embedding advanced monitoring in sustainable asset management.

2. Literature review and conceptual framework

2.1 Resilience, evidence gaps and digital twins

Resilience has engineering, ecological and organisational definitions. Bruneau et al. (2003) emphasise robustness, redundancy, resourcefulness and rapidity, but resilience is increasingly understood as more than recovery: it includes anticipating, monitoring, learning and adapting (Hollnagel et al., 2011; Woods, 2015). This process view matters for ageing infrastructure because deterioration accumulates before disruption is visible – a system can appear operational while latent risk rises. Asset owners decide under uncertainty, constrained by incomplete information about hidden deterioration, limited access, budgets, regulation and the social cost of disruption. Resilience is therefore partly created through routines that improve the quality and timeliness of information (Kopiika et al., 2025).

Evidence is frequently incomplete: hidden weld fatigue, sub-coating corrosion, inaccessible bearings, underwater scour and hydraulic deterioration may remain poorly observed. Acting too late raises safety and continuity risk; acting too early wastes resources and embodied carbon. Evidence gaps are therefore not merely technical weaknesses but resilience bottlenecks that restrict the range and quality of organisational action. This is acute for lifeline infrastructure, where a single linkspan defect can threaten continuity that a redundant road network would absorb.

Digital twins promise to connect physical assets with models, sensor streams, analytics and decision interfaces (Wu et al., 2025; Afolabi et al., 2025), including port and maritime resilience and sustainability assessment (Zhu et al., 2025). However, a digital twin can remain a passive model if detached from maintenance governance; it builds resilience only when it creates a feedback loop between condition, interpretation and action. The relevant concept is predictive assurance – broader than predictive maintenance – providing credible, auditable, decision-ready evidence for compliance, certification, prioritisation and investment. In conservative public contexts, decision-makers need evidence they can defend, so the digital twin must function as a socio-technical assurance mechanism, not a purely technical replica (Leong, 2026).

2.2 A transition framework: capacity, capability, willingness and institutional pathways

To explain the move from reactive inspection to predictive assurance, the paper develops three constructs. Transition capacity is the resources and enabling conditions that make transition possible: sensing architecture, data infrastructure, funding logic, access, supplier availability and commercial feasibility. Transition capability is the routines and competences that convert capacity into prioritised maintenance, risk interpretation, assurance documentation and learning, connecting to dynamic capabilities theory's sensing, seizing and reconfiguring (Teece, 2007) and including human capabilities such as data literacy and engineering interpretation. Willingness to transition is stakeholder readiness to adopt evidence-based practice, shaped by perceived usefulness, trust, legitimacy, risk appetite and compatibility with existing inspection (Ajayi et al., 2025). Institutional pathways are the formal and informal cross-actor linkages that legitimise and coordinate change; following North (1991), institutions reduce uncertainty and structure cooperation among asset owners, providers, inspectors, regulators and funders. Table 1 defines the constructs and their indicators.

Construct	Definition	Empirical indicators
Evidence gap	A risk that cannot be observed with sufficient confidence through existing inspection or monitoring.	Hidden weld fatigue; corrosion under coatings; hydraulic anomalies; hinge/bearing deterioration; subsurface scour.
Transition capacity	Resources, architecture, data and economic conditions enabling movement to predictive assurance.	Quantum campaign sensing; fixed monitoring; AI/digital twin platform; fleet economics; technical and cost-benefit feasibility.
Transition capability	Routines and competences that convert capacity into maintenance, compliance, investment and learning decisions.	Anomaly interpretation; maintenance prioritisation; evidence packs; integration with engineering judgement; inspection targeting.
Willingness to transition	Stakeholder readiness to adopt predictive assurance alongside familiar periodic inspection.	XYZHA pilot interest; inspection practitioner acceptance; integrator interest; NHA validation; modular route.
Institutional pathways	Formal and informal cross-actor linkages that legitimise, coordinate and scale the transition.	Owner-provider-university-inspector-integrator-funder-regulator linkages; certification and fleet pathways.

Table 1. Core constructs and empirical indicators

The framework treats evidence gaps as a pre-disruption resilience deficit. Resilience-building requires translating gaps into a problem specification, creating capacity, developing capability, building willingness and connecting actors through institutional pathways, yielding outcomes such as earlier detection, better prioritisation, reduced closure risk, stronger statutory assurance and extended asset life. Digital twins and sensors are mechanisms, not outcomes: a twin increases resilience only when it changes what stakeholders can know, how they decide and how they coordinate. The process model is shown in Figure 1.

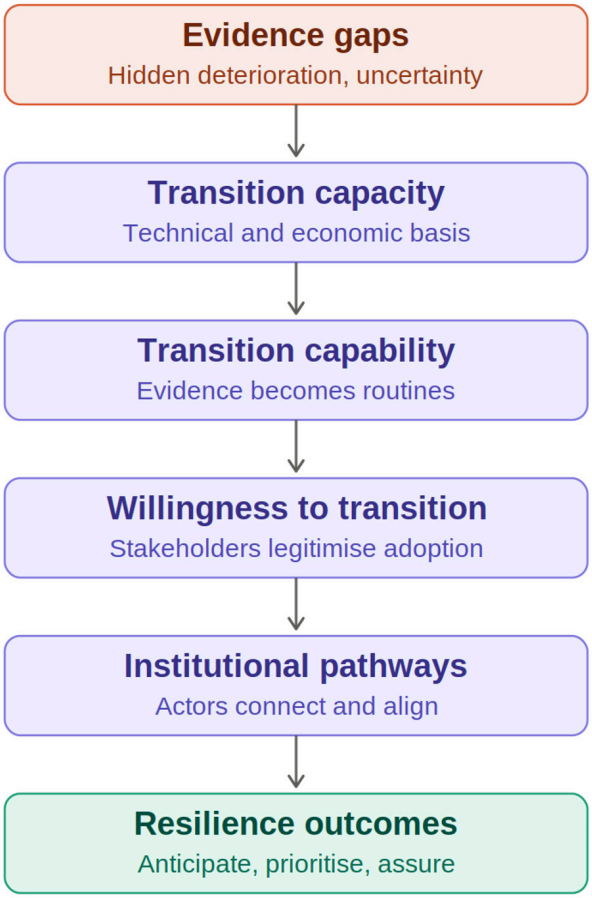

Figure 1. Process model of resilience-building through transition capability

3. Research design and case context

The study uses an engaged qualitative case study with design-science elements: empirical material came from an applied feasibility project with a real asset owner, and the project specified and evaluated a proposed architecture rather than only observing practice. Case study research suits questions about how and why processes unfold where phenomenon and context are inseparable (Yin, 2018); RELIQ is a single but critical and revelatory case, enabling analytical generalisation to other evidence-constrained transport assets.

RELIQ was led by Heriot-Watt University with XYZHA , using the Kirkwall ferry terminal linkspan as the primary context. The business case describes the asset as essential to community connectivity, operating in a highly corrosive marine environment, and dependent on periodic inspection that cannot detect early-stage hidden deterioration with sufficient confidence. Data sources included XYZHA engagement, site observation, documentary review, technology mapping, cost-benefit analysis, and external validation with SP, NHA, O Marine and WB. Analysis was iterative: identify the problem and evidence gaps; map the architecture to those gaps to locate transition capacity; analyse validation evidence for capability, willingness and institutional pathways; and interpret through the resilience-as-process framework. Because RELIQ is a feasibility study, the paper theorises transition conditions rather than reporting measured reductions in emissions, failures or downtime, and specifies the empirical tests required at pilot stage.

4. Findings

4.1 Evidence gaps as the starting point of transition

The resilience problem begins with evidence gaps, not absent technology. XYZHA 's linkspans are operational assets with existing inspection, but Phase 1 confirmed five gap categories: hidden weld fatigue, corrosion under coatings, hydraulic anomalies, hinge and bearing deterioration, and subsurface scour. These are concealed or intermittent conditions that periodic inspection cannot capture with continuous, georeferenced evidence. They are pre-disruption vulnerabilities that reduce resilience before any closure, because they limit the owner's ability to anticipate and adapt. The finding reframes evidence gaps as resilience bottlenecks; predictive assurance adds the option of generating richer condition intelligence that changes the decision space.

4.2 Transition capacity

Capacity is created through a modular three-layer architecture and fleet-based economics. Campaign quantum sensing – NV-diamond magnetometry for hidden weld fatigue, optically pumped magnetometry for corrosion mapping, and quantum gravity gradiometry for scour – provides periodic high-resolution diagnostics; fixed sensors (strain, tilt, accelerometers, hydraulic diagnostics) give continuous visibility; and an AI/digital twin layer fuses both into anomaly alerts, maintenance priorities and evidence packs. Modularity matters: an owner can begin with a baseline survey, add fixed monitoring, adopt the full platform, or design it into replacement infrastructure, reducing adoption friction. Commercial viability emerges at fleet scale, where shared quantum instruments lower per-asset cost; the business case uses conservative 30–50% maintenance-saving assumptions (not the original 80% headline) and an indicative payback of about 5.6 years across ten linkspans. Affordability is thus an architecture and deployment-model problem, not only a device-cost one.

4.3 Transition capability

Resilience capability emerges when evidence is converted into routines. The digital twin is positioned as a lightweight assurance and decision-support platform – dashboards, configurable thresholds, anomaly detection, maintenance prioritisation, georeferenced baselines and evidence packs for certifiers, insurers and regulators. A signal still needs interpretation: is it a true anomaly; does it require inspection, repair or no action; which component takes priority; how is it recorded for compliance? Capability therefore includes human and organisational routines – staff who read dashboards, engineers who relate anomalies to structural behaviour and managers who fold alerts into work planning. A three-stage cycle (baseline campaign, continuous monitoring, analytics) shifts maintenance from calendar- or access-driven to risk- and evidence-driven, and repeated cycles build a traceable condition history supporting renewal and investment decisions (Wu et al., 2025; Afolabi et al., 2025).

4.4 Willingness to transition

Willingness depends on framing and validation. XYZHA validated the baseline and the five gaps and indicated interest as a beachhead pilot, turning a technology proposition into a problem-driven case. External validation reinforced this: SP confirmed feasibility while acknowledging limits for hidden weld detection; NHA judged the combined fixed-plus-campaign architecture realistic and broadly relevant; O Marine saw it as complementary to inspection rather than a replacement; and WB confirmed integration feasibility while challenging sensor fusion, repeatable positioning and supplier maturity. Willingness grows when technology addresses a recognised problem, supports professional judgement, fits accountability needs, is modular and is honest about uncertainty and false positives. Assessor feedback – low false-positive tolerance, clarity on the quantum advantage, and caution on both the 80% claim and retrofit versus design-in – was answered through conservative assumptions and a tiered adoption pathway, itself evidence of learning in the transition.

4.5 Institutional pathways

Pathways are the connective tissue of transition. RELIQ linked XYZHA (problem owner and pilot), Heriot-Watt University (integrator and architect), quantum and sensor firms (capability), O Marine (professional validation), WB (integration and commercialisation), NHA (transferability) and Innovate UK (early-stage funding), with certifiers, insurers and regulators as future actors. Transitions scale when these roles align: owners gain confidence the system supports their responsibilities, inspectors see complementarity, integrators make components deployable, regulators obtain trustworthy assurance evidence and funders see public value. The pathway is incomplete pending Phase 2 field validation, after which certification and regulatory bodies must engage more directly, because predictive assurance is credible only when accepted within the formal accountability environment. Table 2 maps each evidence gap to the RELIQ response and the resilience mechanism.

Evidence gap	RELIQ response	Resilience-building mechanism
Hidden weld fatigue and stress anomalies	NV-diamond magnetometry and targeted NDT in campaign surveys.	Earlier detection of concealed deterioration; targeted inspection before visible failure.
Corrosion under coatings and section loss	Optically pumped magnetometry with thickness/laser scanning.	Improved visibility of sub-coating degradation; better maintenance prioritisation.
Hydraulic anomalies and abnormal loading	Hydraulic diagnostics, event-triggered logging and fixed monitoring.	Early warning of intermittent operational stress and abnormal behaviour.
Hinge/bearing deterioration and support integrity	Tilt/inclinometer arrays, strain gauges and accelerometers.	Continuous monitoring of movement; earlier intervention planning.
Subsurface scour and voids	Quantum gravity gradiometry and campaign condition surveys.	Non-invasive evidence of beneath-structure risk; less intrusive access.
Weak decision evidence	AI/digital twin dashboard, condition baseline and evidence packs.	Predictive assurance for compliance, maintenance, renewal and stakeholder confidence.

Table 2. Evidence gaps, RELIQ response and resilience mechanism

5. Discussion

The findings support treating transport resilience as a transition process. RELIQ demonstrates resilience not because it combines quantum sensing, fixed sensors, AI and a digital twin, but because it shows a pathway from evidence-poor inspection to evidence-rich predictive assurance. This matters for the fast-growing digital twin literature (Wu et al., 2025; Zhu et al., 2025; Ajayi et al., 2025; Afolabi et al., 2025; Leong, 2026): technology potential is insufficient, and twins build resilience only when embedded in maintenance routines, assurance processes, professional judgement and institutional accountability – otherwise they become sophisticated dashboards with little organisational consequence. The process view also extends resilience theory beyond robustness, redundancy and recovery to a pre-disruption problem, hidden deterioration and evidence uncertainty, that may be invisible in network performance until failure.

A theoretical contribution is the framing of evidence gaps as pre-disruption resilience bottlenecks, distinguishing apparent reliability (the asset works today) from actual resilience (the organisation can detect, interpret and respond to emerging risk). This has sustainability consequences: unnecessary replacement raises embodied carbon, while deferred intervention raises emergency works, closures and safety risk, so better-timed, better-targeted interventions support sustainable asset management – extending the resilience-sustainability integration of Kopiika et al. (2025) into ongoing maintenance. The claim is kept proportionate: RELIQ has not measured emission or maintenance savings, so the contribution is a decision-mechanism one pending lifecycle quantification.

A second contribution separates transition capacity (enabling infrastructure) from transition capability (the ability to use it in decisions), preventing the common error of treating deployment as adoption and data as capability. This foregrounds the human challenge – data literacy, systems thinking and cross-functional communication – without which a sound system fails to change decisions (Ajayi et al., 2025; Afolabi et al., 2025). Future studies should measure both: capacity indicators (coverage, latency, supplier readiness, fleet cost) and capability indicators (alert-to-inspection conversion, decision quality, evidence acceptance, governance). Finally, willingness and institutional pathways show technology adoption as an institutional process (North, 1991): a technically elegant system will not scale without pathways through procurement, safety culture, professional norms, certification and funding.

6. Implications and conclusion

For policy, transport resilience planning should treat evidence gaps as a distinct risk category alongside hazards and recovery; funding should support capacity and capability together, requiring applicants to show how data becomes decisions and how false positives and assurance are handled; and regulators, certifiers and insurers should engage early so digital evidence packs can support statutory assurance. For asset owners, the case suggests starting with the evidence gap, not the technology, and using modular adoption pathways – baseline survey, fixed monitoring, full platform, or design-in for replacement assets. For practitioners, predictive assurance should be positioned as a complement to engineering judgement that targets inspection and strengthens evidence. For technology providers, the lesson is to avoid technology-push: owners buy evidence, safety, continuity and compliance, so providers must show how each modality closes a specific gap, behaves in harsh environments and integrates into a deployable system.

This paper reframed the RELIQ Phase 1 feasibility study as a transport resilience contribution by treating resilience as a transition process. Ageing critical infrastructure can remain operational while evidence deficits restrict anticipatory action. The proposed architecture addressed these through campaign quantum sensing, fixed monitoring and AI-enabled digital twin decision support, and the main theoretical contribution is the framework linking evidence gaps, transition capacity, transition capability, willingness to transition and institutional pathways. Together these explain how advanced monitoring becomes a resilience capability rather than a demonstrator.

The practical message is that digital twins and quantum sensing do not make infrastructure resilient by themselves; they matter when they close decision-relevant evidence gaps, support professional judgement, produce auditable assurance and fit institutional accountability. The study is limited to a single Phase 1 case, with inferred rather than measured environmental benefits and willingness assessed through validation rather than longitudinal adoption. Future research should follow the Phase 2 pilot, measure maintenance and downtime outcomes, test false-positive performance, quantify lifecycle carbon, and compare transitions across bridges, ports, airbridges and other dynamic transport assets.

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WHAT DEFENCE LOGISTICIANS CHOOSE TO RESEARCH: A THEMATIC MAPPING OF PRACTITIONER-MANAGER DISSERTATION TITLES WITHIN THE UK DEFENCE LOGISTICS ENTERPRISE

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Introduction

Defence logistics has reemerged as a critical field of study as armed forces confront increasingly complex operational, technological, and organisational challenges. From contested supply chains and expeditionary sustainment to digital transformation and the pursuit of Support Advantage. The modern defence environment demands a logistics enterprise that is agile, data driven, resilient, and culturally adaptive. As these pressures intensify, academic research, particularly undertaken by practicing military logisticians at postgraduate level, plays a growing role in shaping how defence organisations understand, diagnose, and respond to emerging issues. Student dissertations, often situated at the intersection of theory, practice, and lived professional experience, provide a unique lens through which to observe evolving priorities within the defence logistics community.

This paper explores the dominant themes emerging from student dissertations on defence logistics. By analysing patterns across these works, the review identifies how students conceptualise contemporary logistics challenges and sets this within an external context. This paper contributes a bottom-up, practitioner-derived map of Defence logistics research priorities at a time when the field remains underrepresented in peer-reviewed scholarship. Understanding these thematic trends is valuable, highlighting where academic attention is currently concentrated, revealing the issues that practitioners and scholars perceive as most urgent. In doing so, this review contributes to a broader understanding of how defence logistics knowledge is being generated, where gaps remain, and how academic inquiry can better support the transformation ambitions of organisations such as the UK Ministry of Defence.

Literature Review

Literature reviews occupy a central position within logistics scholarship because they synthesise a fragmented and multidisciplinary evidence base, clarify conceptual boundaries, and integrate diverse empirical findings. In doing so, they contribute to theory development, refinement, and the identification of boundary conditions (Seuring & Müller, 2008). Systematic review methodologies further enhance rigour and transparency, reducing bias and strengthening the reliability of cumulative knowledge (Durach et al., 2017). Moreover, literature reviews expose unresolved questions and methodological limitations, thereby shaping coherent future research agendas in areas such as sustainability, resilience, and digitalisation (Tukamuhabwa et al., 2015). They also play an important translational role by converting academic insights into evidence based guidance for managerial and policy decision making.

The imbalance between strategic studies and defence logistics scholarship, captured in the observation that “for every book on defence logistics there are a thousand books on strategy” (Kane, 2001, p.1) illustrates the longstanding marginalisation of this field. Existing assessments of military logistics literature reviews confirm a persistent and well documented gap. Rutner et al. (2012) demonstrate a marked decline in military logistics scholarship after the 1960s and acknowledge that their own analysis is heavily skewed toward U.S. practitioner outlets, with 28 of their 43 “key papers” drawn from Army Sustainment. Yoho et al. (2013), employing a broader ABI/INFORM database search, identify 276 relevant articles between 1952 and 2010—an average of only five academic papers per year, yet still find that 64% of publications appear in specialist practitioner journals. Further evidence from Tatham (2010) reinforces this disparity: of the 1,150 articles evaluated in major logistics research indices (Gibson et al., 2004; Menachof, 2009), only nine relate to defence. Collectively, these studies demonstrate a clear and enduring lack of peer reviewed research in military logistics.

Recognising both the value of literature reviews and the significant deficit in military logistics scholarship, this paper draws upon a focused body of knowledge, defence logistics student dissertations, to identify the themes emerging practitioners and scholars consider most salient. This paper addresses the first stage of this research identifying trends and key words within dissertation titles. This approach provides an alternative empirical foundation that contributes to addressing the longstanding gap in academic research on defence logistics.

The Opportunity

Using student dissertations as the foundation for this work offers a uniquely valuable perspective on defence logistics research. Unlike traditional academic publications, dissertations are written by serving military personnel, defence civil servants, and defence industry practitioners who operate within the logistics enterprise daily. Their work is therefore grounded in lived experience, organisational realities, and first hand exposure to the challenges facing defence. This practitioner proximity enables dissertations to surface issues that may be under represented in formal academic literature but are central to operational effectiveness.

Dissertations also respond rapidly to emerging events and policy shifts. Themes such as support advantage, digital transformation, sustainability, and lessons from COVID 19 or Ukraine appear in student work far earlier than in peer reviewed journals. As a result, analysing dissertations provides an early indicator of evolving priorities within defence logistics thinking. By analysing dissertations collectively, this paper contributes by revealing practitioner driven insights, highlighting emerging research trajectories, and offering a contemporaneous snapshot of how defence logisticians conceptualise and investigate the challenges facing the modern support enterprise.

Research Approach

This study forms part of an ongoing research project, and the findings presented here represent the first iteration of results. Subsequent phases will expand the sample size and incorporate a longitudinal dimension to examine how practitioner identified themes evolve over time.

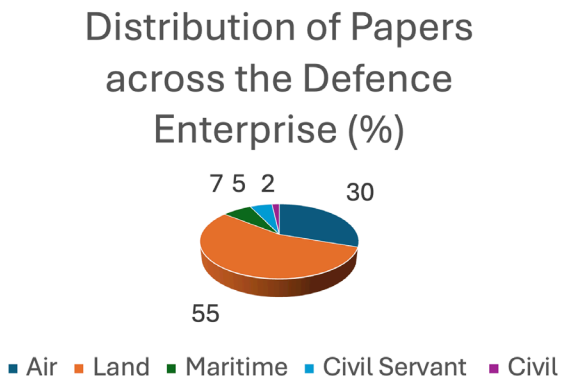
The present paper undertakes a focused review of final project dissertations submitted to the University of Lincoln as part of the MSc in Logistics Management, delivered under contract to the UK Ministry of Defence. A total of 56 dissertations, submitted between 2021 and 2026, were analysed using thematic analysis to identify the areas of enquiry prioritised by defence logistics practitioners. Typical students are serving defence logistics managers selected for academic development and employed within the wider Defence logistics enterprise, providing a practitioner centred perspective on contemporary issues.

Responding to calls within the supply chain literature for qualitative investigations that explore the underlying “why” of supply chain phenomena (Mangan et al., 2004; Burgess et al., 2006), this study adopts an exploratory, qualitatively oriented research design grounded in a focused literature review approach. This paradigm is well suited to eliciting the realities embedded in practitioner experience and aligns with a subjectivist research philosophy that emphasises the interpretive role of individuals within the military supply chain (Attride Stirling, 2001; Mangan et al., 2004; Braun & Clarke, 2006; Howitt, 2010).

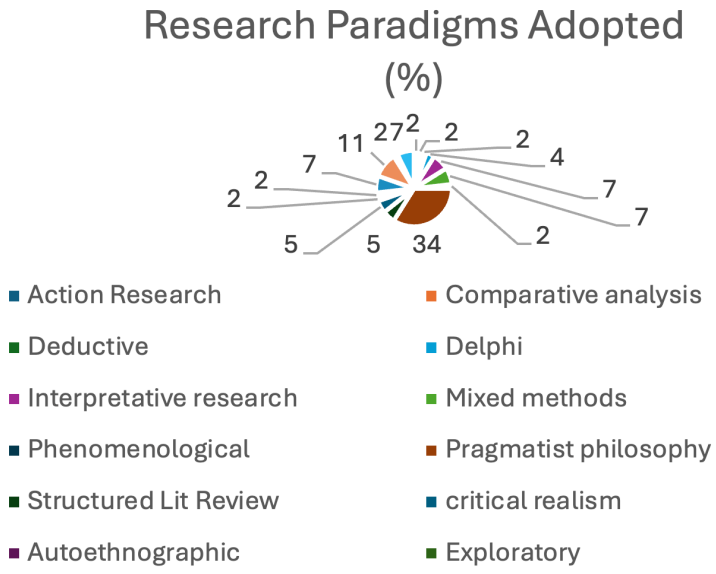
Data for this study was collected via the Turnitin online submission platform, with each dissertation comprising approximately 18,000 words of practitioner generated analysis. The corpus was imported into NVivo, where data were coded and organised into themes derived inductively from patterns emerging within the texts. This grounded, iterative approach enabled the identification of practitioner defined priorities and concerns, providing an empirically informed foundation for understanding contemporary defence logistics discourse.

Findings and Analysis

This paper explored 56 submissions delivered by students based with the Defence Enterprise. Their location within the enterprise is shown in Figure 1:



This echoes of the distribution of peoples across MOD with a noticeable exception in the under representation of the maritime domain. Consequently it is argued that although Land dominated this sample it offers a reliable and valid sample nevertheless. The sample also reflected a range of research approaches. Figure 2 articulates the paradigms adopted.



Pragmatism at 34% is the most significant paradigms. Pragmatism is widely adopted by vocational and practitioner based students because it aligns closely with the applied, problem solving nature of their professional environments. For students working in Defence logistics, the priority is generating insights that improve real world practice rather than contributing to abstract theory. The research flexibility enabled by pragmatists mirrors the decision making demands of military and organisational contexts, making pragmatism an attractive philosophy for students seeking actionable, context specific findings grounded in lived professional experience. Therefore while interesting the large number of students choosing a pragmatist approach is unsurprising.

Table 1 details the results of the thematic analysis. Initial coding created 148 individual themes. Revised secondary co-coding refined the thematic analysis into 34 named themes as shown below. The % score reflects number of occurrences within the data.

Theme	%	Theme	%	Theme	%
Culture	6	Contract Management	3	Relationship Management	2
Inventory Management	6	Collaboration	3	Inventory Control	2
Change Management	6	Reverse SC	2	SC Data	2
Support Advantage	4	HADR	2	Resilience	2
MIS	4	Additive Manufacturing	2	Agility	2
Sustainability	4	Leadership	2	Outsourcing	2
Decision Making	4	AI	2	Relationship Management	2
People	4	Retention	2	Inventory Control	2
Procurement	3	JIT	2	SC Data	2
CSR	3	MIS Integration	2	Resilience	2
SCM	3	Agility	2		
Expeditionary SC	3	Outsourcing	2		

Analysis

Culture and Change

The prominence of change management and organisational culture has significant implications. These two factors share 12% of the results. This links well to external lenses driving Defence Logistics. The 2025 Strategic Defence Review (SDR) urges transformation and reform leading to flux in the daily operations. The ongoing Defence reform, controversy over the Defence Investment plan and a changing military climate all necessitate change. This position aligns with established theoretical perspectives that help explain why these themes are so influential in the Defence context, suggesting the importance of people is greater than frameworks.

Kotter's (1996) model of organisational change provides a useful lens for interpreting the challenges faced within the Defence supply chain. Kotter argues that transformation requires a compelling sense of urgency, strong guiding coalitions, and the institutionalisation of new behaviours. Defence's ongoing reform agenda, driven by the SDR (2025), contested operating environments, and technological disruption creates urgency, but the persistence of cultural resistance and fragmented ownership often inhibits the later stages of Kotter's model, particularly embedding change into organisational norms. Complementing this, Schein's (2010) theory of organisational culture highlights how deeply embedded assumptions shape behaviour within complex institutions. Defence logistics is characterised by hierarchical structures, risk aversion, and strong professional identities. These cultural attributes can stabilise operations but also impede innovation, cross boundary collaboration, and the adoption of new digital or data driven practices. Schein's (2010) framework helps explain why cultural factors appear so frequently in practitioner led research: they are often the hidden constraints that shape supply chain performance.

With resource constraints, change management and organisational culture become important coping mechanisms for practitioners to achieve their goals. this reflects the framework of the Conservation of Resources (COR) model (Hobfoll, 1989;2001) a resource centred motivational theory developed to explain human behaviour in a range of settings. This concern regarding coping with actual or potential loss of resources forms the second principle of COR theory. According to this second principle, "...people must invest resources in order to protect against resource loss, recover from losses, and gain resources" (Hobfoll, 1998, 63). Similarly, Latack and Havlovic (1992, 483) argue that coping entails "...constantly changing cognitive and behavioural efforts to manage the internal and external demands of transactions that tax or exceed a person's resources". This suggests practitioners are undertaking research to strength their use of resource within a continuously constrained environment. Finally, socio technical systems theory positions defence logistics as an integrated system in which technology, processes, people, and organisational structures must be aligned. Transformation efforts such as digitalisation, support advantage, or new procurement models often focus on technical solutions without addressing the social and cultural subsystems that determine whether change is adopted or resisted. This theoretical perspective reinforces the finding that the ability to manage change is not a peripheral skill but a core enabler of logistics effectiveness.

Inventory Management

The status of inventory related themes within the dataset indicates that stock availability, optimisation, and supply chain responsiveness remain central concerns in defence logistics research. This cluster reflects both the operational realities of the UK Armed Forces and wider debates in the logistics literature regarding efficiency, resilience, and supply chain design. Initial codes such as "inventory management", "inventory control" and "vehicle spares" argue the need of the supply chain (SC) to balance effective delivery within the constraints of doctrine and cost. The defence operating environments amplify these tensions due to platform complexity, historic demand patterns and the operational consequences of stock failure. The recurrence of these terms suggests that practitioners view inventory governance as a persistent capability gap.

Similar to post Covid SC literature and the growth of resilience in SCM (Supply Chain Management) The presence of "JIT" and "JIT in contested environments" (Just in time) reflects a growing recognition that traditional lean paradigms optimised for efficiency and predictability are increasingly misaligned with the realities of modern, contested logistics emerging from the wars in Ukraine and the Middle East. This aligns with emerging scholarship arguing for a shift from lean to resilient, multi strategy, and redundancy based models in military supply chains.

Attenuating the implications of JIT themes such as "demand management" and "capacity management" point to the analytical and forecasting challenges inherent in defence supply chains. Uncertain demand profiles, volatile operational tempos, and ageing platforms complicate the ability to match supply with requirement. These issues are widely recognised in defence logistics literature as barriers to readiness and cost control.

Data, MIS and Decision Making

Emerging from the need to control inventory and develop evidence-based decision making visibility across the defence SC has risen as an important lens to delivery military effect.The review identified a significant thematic cluster in the dataset concerning "data quality", "logistic management information systems", "integration", and "decision making". This reflects a growing recognition across defence logistics scholarship that information flows, digital systems, and analytical capability are now as critical to operational effectiveness as physical inventory and material availability. Echoing established practice in commercial SCM. Codes such as "impact of poor data" and "SC data user requirements" highlight persistent concerns regarding the accuracy, completeness, and reliability of supply chain information. Defence supply chain information systems are characterised by complex multi tier networks, and legacy systems, making them particularly vulnerable to data degradation. Poor data quality undermines forecasting, readiness reporting, and asset visibility—issues repeatedly identified in both practitioner literature and MOD audit findings. Themes including "MIS integration", "data visibility", and "MIS/Share" build on this point to argue the structural fragmentation of defence information systems. Despite ongoing investment in the Digital Backbone, defence continues to operate multiple, siloed platforms with limited interoperability. This misalignment constrains end to end visibility and inhibits the development of a coherent, data enabled Defence Support Enterprise. The recurrence of these codes suggests that practitioners view digital integration as a foundational requirement for transformation.

The role of the information systems is articulated within the position of decision making. The appearance of "decision making" and "risk appetites" reflects the human and organisational dimensions of supply chain performance. Defence operates in environments characterised by uncertainty, contested logistics, and rapidly shifting operational demands. Effective decision making therefore depends not only on data availability but also on organisational risk tolerance, cognitive biases, and the ability to interpret information under pressure. This aligns with wider literature emphasising the socio cognitive aspects of military logistics decision making. Like the commercial view codes such as "AI in defence", "automation", and "technology" indicate growing interest in the potential of advanced analytics, machine learning, and automation to enhance supply chain performance and decision making. These technologies promise improvements in predictive maintenance, demand forecasting, and anomaly detection. However, their effectiveness is contingent on the very data quality and MIS integration issues identified above, reinforcing the interdependence of technical and organisational factors.

The value of data and logistics information systems integration is not merely administrative; it is operational. It enables the Armed Forces to sustain forces in the deployed space, regenerate combat power, and maintain tempo core components of military effect. A data enabled Defence Support Enterprise therefore becomes a critical enabler of Support Advantage, ensuring that logistics moves from a constraint to a force multiplier and genuine deterrent.

Implications

Despite the need for effective and standardised X-Defence logistics information systems the Defence SC cannot transform through technology or process redesign alone. Without cultural alignment; shared risk appetite, empowered decision making, and acceptance of new ways of working, reform efforts will stall. Culture becomes a strategic constraint on logistics performance. Cultural resistance and fragmented ownership will continue to undermine reform unless addressed alongside digital and process change.

Despite complex and challenging financial conditions, the Defence SC must shift from lean optimisation to resilient, multi strategy inventory models that incorporate redundancy, surge capacity, stronger industrial relationships and more sophisticated demand forecasting. This has become a "truism" across defence practitioners. However historic practice such as entryism in defence procurement which focuses on the platform rather that delivering a logistics supported capability may return as managers are constrained by future integrated force decisions. Mental distance may resonate across defence as it looks to deliver modern, fast changing technology to deliver military effect while knowing investment in the SC is also essential. To redress this mental distance and subsequent cognitive impairment (Schaufeli et al., (2019) digital integration may be foundational to achieving support advantage. Without reliable data and interoperable systems, defence cannot exploit AI, automation, or predictive analytics. Decision making remains slow, risk averse, and vulnerable to error. A data enabled Defence Support Enterprise becomes essential for accelerating decision cycles and improving operational agility. However technology as a panacea to fix all defence needs is questionable. The balance of people, process and technology tools to deliver a support advantage through the SC will become an important element of delivering defence reform.

Conclusions

This paper has examined the research priorities articulated by Defence logistics practitioner-managers through a thematic mapping of postgraduate dissertation submissions. In doing so, it responds to the continuing under-representation of military and Defence logistics within the wider logistics literature and offers an alternative route into understanding the concerns, assumptions and priorities emerging from within the Defence Logistics Enterprise itself.

The findings suggest that practitioner research is clustering around three interdependent areas. First, culture and change management appear as recurring concerns, indicating that Defence logistics transformation cannot be understood as a purely technical or procedural challenge. Reform depends on organisational behaviours, risk appetite, leadership, and the ability to embed new ways of working across complex Defence structures. Second, inventory management, resilience and the limits of lean supply chain models remain central to practitioner thinking. The recurrence of these themes reflects the operational consequences of stock failure, contested environments, ageing platforms and volatile demand signals. Third, data, management information systems and decision-making emerge as enabling conditions for Support Advantage. Without reliable data, interoperable systems and decision-making cultures able to use information effectively, the Defence Support Enterprise will struggle to exploit AI, automation or predictive analytics in a meaningful way.

The paper therefore argues that Defence logistics transformation is best understood as a socio-technical challenge. Technology, inventory policy, data integration and process redesign matter, but their value is constrained if cultural alignment, professional practice and organisational learning are not addressed simultaneously. The practitioner-manager perspective is particularly valuable because it highlights the issues experienced within the enterprise before they are fully visible in formal academic publication or doctrine. As a first iteration of a wider research project, this study has limitations. The current analysis is based on a defined sample of submissions and provides a thematic snapshot rather than a longitudinal account of change over time. Future work will expand the dataset, examine variation by service, rank and practitioner characteristics, and compare practitioner-generated themes against Defence policy, doctrine and wider academic literature. This will support the development of a more complete evidence base for Defence logistics scholarship and provide a foundation for knowledge exchange between practitioners, educators, policy-makers and professional bodies.

Overall, the study demonstrates that Defence logisticians are not only responding to operational and organisational change; they are actively conceptualising the future of their discipline. Their research choices reveal a profession concerned with resilience, data-enabled decision-making, cultural adaptation and the practical delivery of military effect. Capturing and analysing these choices provides a valuable foundation for strengthening Defence logistics research, education and practice.

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NAVIGATING COMPLIANCE AND EMBRACING OPPORTUNITIES: AN IRISH PERSPECTIVE ON MARINE DIESEL FUELS AND THE ROUTE TO GREENER ALTERNATIVES

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Key Words – maritime decarbonisation, alternative marine fuels, maritime education, skills gap, sustainable supply chain,

1. INTRODUCTION

International shipping is entering a period of profound technological and operational change. Decarbonisation requirements are accelerating the movement away from conventional marine diesel fuels towards a range of lower- and zero-carbon alternatives, including liquefied natural gas (LNG), methanol, hydrogen and ammonia. Yet the transition is not simply a matter of selecting a replacement fuel. Each pathway creates different requirements for production, storage, bunkering, vessel technology, safety, emissions monitoring and workforce competence. Maritime decarbonisation is therefore a supply-chain transformation in which regulation, technology, infrastructure and human capability must develop together.

For Ireland, this challenge is particularly significant. As an island economy dependent on maritime trade, Ireland must remain connected to increasingly decarbonised logistics networks while also responding to European and international regulation. Its offshore renewable energy potential creates opportunities to participate in future green-fuel supply chains, but these opportunities coexist with limited alternative-fuel infrastructure, uncertainty over dominant fuel pathways and concerns about the readiness of existing education and training systems.

This paper evaluates Ireland's readiness to transition from conventional marine diesel fuels to greener alternatives, with particular attention to the alignment between regulatory ambition, infrastructure readiness and workforce capability. It argues that Ireland faces a structural implementation gap: regulation and technological change are advancing faster than the infrastructure, institutional coordination and skills systems required to deliver them. The central research question is therefore not simply which fuel Ireland should adopt, but whether the wider maritime system is capable of adapting to a multi-fuel transition.

2. RELEVANT LITERATURE AND THE TRANSITION CHALLENGE

Regulation and decarbonisation pressure

Maritime fuel transition is being driven by an increasingly demanding regulatory environment. MARPOL Annex VI established controls on air pollution from ships, while subsequent International Maritime Organization (IMO) measures have intensified the focus on greenhouse-gas reduction and energy efficiency. At European level, monitoring, reporting and verification requirements, the European Green Deal and related decarbonisation measures are increasing the commercial and compliance consequences of vessel emissions (European Commission, 2019; IMO, 2023; DNV, 2025). Regulation can create direction and urgency, but compliance ultimately depends on the availability of suitable fuels, infrastructure, technology and competent personnel.

Fuel-pathway uncertainty

No single alternative fuel currently provides a universal solution. Hydrogen can offer zero-carbon operation when produced from renewable energy, but it is energy-intensive to produce and requires substantially greater storage volume than marine diesel (Reusser and Pérez Osses, 2021; Martín, 2022). Ammonia offers a potential zero-carbon energy carrier but presents toxicity, storage and handling challenges (Randall and Tsui, 2002; Ban and Bebi , 2023). Methanol is easier to handle than some alternatives and is gaining commercial momentum, although lifecycle performance depends on its production route. LNG is technologically mature and can reduce some pollutants, but methane slip can undermine its greenhouse-gas performance. Hydrotreated Vegetable Oil (HVO), and other biofuels can offer near-term compatibility advantages, but availability, cost and supply-chain stability remain concerns.

The implication is that transition planning must accommodate uncertainty. Fuel choices affect upstream energy production, port storage, bunkering logistics, vessel design, emergency response and lifecycle carbon accounting. A narrow search for a single 'winning fuel' risks delaying investment while technology and markets continue to evolve. A more resilient approach is to develop adaptive, multi-fuel capability across infrastructure and skills.

Infrastructure and human capability

Alternative fuels cannot be adopted at scale without dependable supply and delivery systems. Ports require confidence in future demand before committing capital, while vessel operators are reluctant to invest without confidence that fuel will be available. This circular dependency is especially difficult in smaller maritime markets. Irish ports have previously expressed caution about major investment while future fuel demand remains unsettled (Lacey et al., 2019).

The same uncertainty affects education and training. New fuels introduce hazards and competencies not fully covered by conventional diesel-focused pathways: dual-fuel propulsion, cryogenic or toxic fuel handling, high-voltage systems, emissions monitoring, lifecycle performance and fuel-specific emergency response. Existing seafarers will remain central to the transition, making continuing professional development as important as the education of new entrants. The literature and policy challenge can therefore be understood as four interdependent transition capabilities: regulatory capability, technological capability, infrastructure capability and workforce capability. If these develop at different speeds, an implementation gap emerges.

3. RESEARCH APPROACH

This conference paper develops and reframes findings from O'Byrne's 2025 master's thesis, using the original interview, survey and case-study evidence while narrowing the analysis to the alignment of regulation, infrastructure and workforce capability (O'Byrne, 2025).

The study adopted a pragmatic, mixed-methods design to capture the technical, regulatory, commercial and human dimensions of Ireland's maritime fuel transition. Six semi-structured interviews were conducted with experienced maritime professionals selected purposively for their operational and strategic expertise. Participants included a former port operations executive, a senior port manager, a technical director from a global cruise operator, a technical lead from a seismic support company, a chief engineer from the Irish Naval Service and a shore-based professional with gas-carrier experience. Interviews lasted 40–60 minutes, were recorded with consent, transcribed and anonymised.

A structured survey of 38 respondents from engineering, operations, training, academia and regulatory backgrounds provided quantitative breadth. Questions addressed awareness of alternative fuels, barriers to adoption, training needs and national preparedness. A comparative case study of the Netherlands, particularly the Port of Rotterdam, was used to benchmark Ireland against a more advanced maritime ecosystem. Secondary evidence from regulation, policy, academic literature and industry sources supported triangulation.

The sample is not statistically representative of the entire Irish maritime sector. Its value lies instead in expert depth and convergence across interviews, survey findings and comparative evidence. The research is therefore interpreted as a diagnostic assessment of sectoral readiness rather than a population-level forecast.

4. RESULTS AND ANALYSIS

Ireland as a reactive actor

A consistent finding was that Ireland is perceived as a follower rather than a leader in maritime decarbonisation. More than 70% of survey respondents described Ireland as behind or significantly behind global leaders. Interviewees linked this position to limited political prioritisation, fragmented policy and a tendency to react to external regulation. One participant stated: "We're waiting for direction, IMO, EU, whoever. But no one here seems willing to take a leadership role." Another described Ireland simply as "a follower", while acknowledging the constraints of a small peripheral market without a large bunkering industry.

Importantly, the evidence did not indicate a lack of industry interest. Participants reported active consideration of dual-fuel vessels and alternative-fuel trials. The problem was the absence of support structures. This distinction is central to the analysis: Ireland exhibits transition willingness without transition readiness.

Infrastructure, investment and policy coherence

Infrastructure emerged as the dominant systemic constraint. Interviewees identified the absence or limited availability of LNG bunkering, green methanol storage, shore power and dependable alternative-fuel supply chains. One port participant described an HVO trial that became exposed when the main supplier exited the market. Another participant summarised the investment dilemma: "We can't invest in new fuel technology without confidence that infrastructure will follow, and right now, there's no certainty it will."

Survey findings reinforced this picture. When asked to identify the most significant barrier, 30.6% selected high initial investment costs, 25% fuel availability and infrastructure, 19.4% technical challenges such as vessel retrofits, and 11.1% limited industry knowledge and training. In a broader question, 87% cited infrastructure as a primary barrier. Responsibility was also viewed as a system-level issue: 50% believed government and regulatory bodies should lead the transition, while a further 25% identified international maritime organisations.

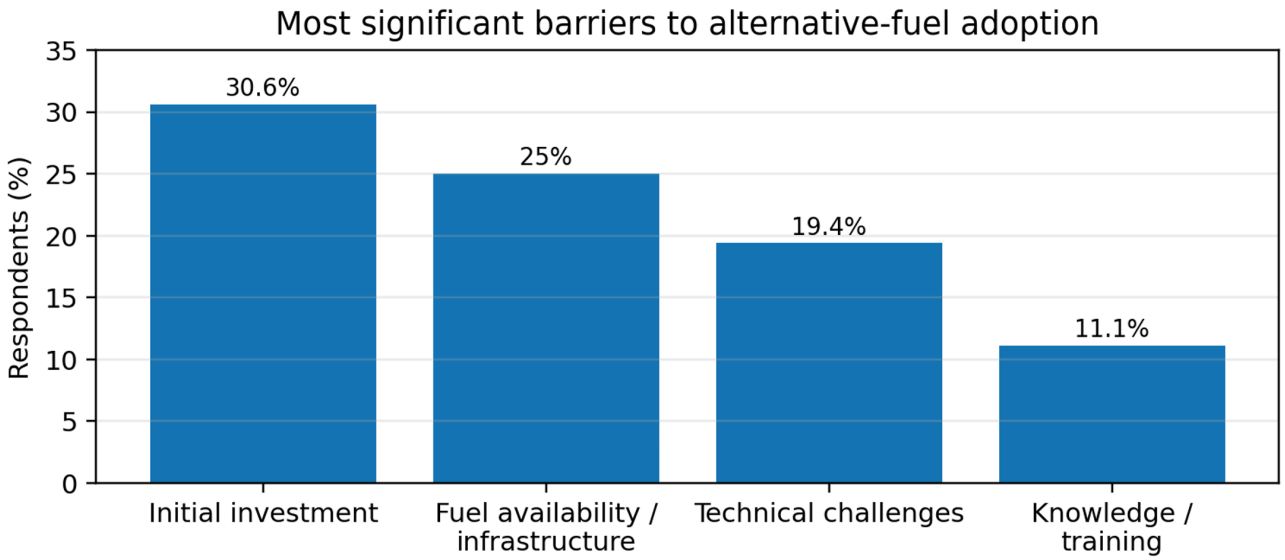

Figure 1: Most significant barriers to alternative-fuel adoption (n=38)

The evidence suggests a coordination failure rather than a single technical bottleneck. Fuel suppliers require demand certainty; ports require policy and market certainty; vessel operators require infrastructure; and training providers require visibility of future competency needs. Where these actors move independently, investment is deferred. As one interviewee put it: "There's no roadmap. There's no joined-up thinking. The result is that nobody moves." From a sustainable supply-chain perspective, this weakens Ireland's ability to participate in emerging green shipping corridors and exposes operators to fuel-price, availability and compliance risks.

Workforce readiness: the human implementation gap

The workforce findings sharpen the central contribution of the paper. Interviewees described maritime education and training as too slow to respond to changing technology. One participant stated: "Most graduates are ill-prepared for the real world systems they'll encounter. We're still sending employees to the Netherlands every year for training because Irish programs haven't evolved fast enough." A second observed: "Our engineers are trained for diesel systems. The gap in knowledge around alternative fuels is substantial."

Survey findings showed that 69% of respondents were open to retraining, either voluntarily or if required, while 58% considered the Irish maritime industry unprepared for transition. The juxtaposition is important: willingness to develop exists, but the system for doing so is underdeveloped. The accepted research proposition is therefore supported by the final thesis evidence: the skills constraint is not simply a shortage of new graduates. It is a structural lag between technological and regulatory change and the capacity to update curricula, instructors, facilities and the existing workforce.

Fuel uncertainty makes this problem more complex. A training system organised around stable, fuel-specific qualifications can become obsolete if it waits for one dominant pathway to emerge. A more resilient response is a modular multi-fuel competency architecture. Common foundations would include low- and zero-carbon propulsion principles, emissions measurement and lifecycle performance, high-voltage and energy systems, risk assessment and emergency response. Fuel-specific modules could then address LNG, methanol, hydrogen, ammonia and other emerging pathways. Such an approach would support both initial education and targeted continuing professional development.

A multi-fuel transition

Interview and survey evidence did not support a single-fuel future. Each option creates a different combination of environmental benefit, maturity, cost, infrastructure and operational risk. HVO may provide short-term compatibility benefits but has demonstrated supply fragility. LNG offers mature technology but raises methane-slip concerns. Methanol is gaining momentum but requires dependable low-carbon supply. Hydrogen and ammonia may offer longer-term potential while imposing substantial production, storage and safety requirements. Ireland's strategy should therefore avoid both premature lock-in and passive delay. The requirement is adaptive capacity: infrastructure and skills capable of evolving as fuel pathways mature.

5. INTERNATIONAL BENCHMARK: THE NETHERLANDS

The Netherlands, particularly the Port of Rotterdam, provides a useful counterpoint. Rotterdam is a major bunkering hub seeking to enable a broad range of low-carbon fuels (Port of Rotterdam, 2025). Its relevance to Ireland is not that it has identified a single correct fuel. Rather, the Dutch system connects policy, port planning, public-private investment, infrastructure and skills development. Environmental objectives are embedded in wider logistics and energy planning rather than treated as a stand-alone compliance issue.

The contrast can be summarised as one between scattered initiatives and coordinated capability. Irish stakeholders described uncertainty over investment, fragmented responsibilities and reactive training. The Dutch case demonstrates how policy clarity can de-risk investment, how infrastructure can be designed for scalability and how education can be informed by industry transition needs. The thesis case study characterised the contrast as one between a coordinated roadmap in the Netherlands and scattered pilot activity in Ireland (O'Byrne, 2025).

Ireland: current pattern	Netherlands: benchmark pattern
Fragmented initiatives	Coordinated roadmap
Investment uncertainty	Policy-backed market development
Limited alternative-fuel infrastructure	Scalable multi-fuel capability
Training reacts to demand	Education aligned with transition needs
Predominantly compliance-led	Strategy-led and system-integrated

Table 1: Comparison of Irish and Dutch transition patterns

6. DISCUSSION: THE MARITIME TRANSITION CAPABILITY GAP

The findings indicate that maritime decarbonisation should be analysed as a capability-alignment problem. Effective implementation requires regulatory, technological, infrastructure and workforce capabilities to advance together. Regulation can set targets, but cannot by itself create fuel supply. Technology can make new fuels technically feasible, but not commercially available. Infrastructure can be built, but cannot be operated safely without competent personnel. Workforce development, in turn, cannot remain relevant without clear engagement with emerging technology and industry investment.

This paper terms the resulting misalignment the Maritime Transition Capability Gap. In the Irish case, regulatory ambition and technology availability are advancing, while infrastructure readiness, workforce systems and national coordination lag. The gap explains why awareness and willingness coexist with slow implementation. It also helps explain why waiting for certainty is itself a strategic risk: every plausible pathway requires capabilities that take years to develop.

The framework extends the discussion beyond a conventional 'skills gap'. The evidence suggests that workforce capability is both an independent constraint and a dependency of the wider system. Training institutions require access to technology, equipment, instructors and industry intelligence. Employers require modular upskilling that does not remove experienced personnel from operations for unnecessarily long periods. Regulators require confidence that competency frameworks reflect new hazards. Ports and operators require a pipeline of personnel capable of commissioning, operating and maintaining emerging systems.

The Netherlands benchmark illustrates the opposite condition. Its advantage is not certainty, but coherence. Policy, infrastructure, market development and education are treated as components of a wider transition system. Ireland need not replicate the scale of Rotterdam, but it can adopt the underlying governance principle: uncertainty should be managed through coordinated, adaptable capability rather than used as a reason to postpone action.

Capability alignment and transition sequencing

The framework also has implications for transition sequencing. Conventional policy approaches often assume a linear process in which regulation creates demand, industry invests, infrastructure follows and training responds. The evidence from Ireland suggests that this sequence is too simplistic. The capabilities are mutually dependent and must be developed iteratively. A port cannot justify specialised infrastructure without credible demand; operators cannot commit to vessels without fuel availability; training providers cannot invest in equipment and instructor capability without visibility of industry pathways; and regulators cannot assume safe implementation without an adequate competency base. The transition is therefore better understood as a coordinated portfolio of interdependent investments rather than a chain of isolated decisions.

This interpretation helps explain the apparent paradox in the findings. Respondents recognised the need for transition and showed a willingness to retrain, yet implementation remained slow. The constraint is not primarily attitudinal. It is institutional: individual actors cannot resolve system-level dependencies alone. The finding that 50% of respondents expected government and regulatory bodies to lead is therefore less a call for the State to choose a fuel than a call for orchestration, credible direction and risk-sharing.

Workforce capability as transition infrastructure

A further implication is that workforce capability should be treated as infrastructure. Physical assets such as bunkering facilities, storage systems and shore power are visible and capital intensive, while skills are often treated as a downstream operational issue. The evidence indicates that this distinction is misleading. Competence in fuel handling, high-voltage systems, emissions management, dual-fuel operation and emergency response is an enabling asset without which physical infrastructure cannot be commissioned, operated or scaled safely.

This is particularly important because the maritime workforce turns over slowly relative to technology cycles. The personnel who will operate much of the transition already work in the sector. Reliance on new entrants alone would create a long implementation lag. A modular continuing-professional-development model can shorten that lag by allowing experienced personnel to add common transition competencies and fuel-specific endorsements as technologies mature. Such an architecture would also reduce the risk of over-specialising the workforce around a pathway that later loses commercial momentum.

Contribution to resilient and future-ready supply chains

Viewed through a global sustainable supply-chain lens, the Maritime Transition Capability Gap has consequences beyond the shipping sector. Fuel availability and port readiness affect route planning, service reliability and the attractiveness of ports within emerging green corridors. Skills shortages can constrain asset utilisation just as directly as shortages of fuel or physical capacity. A maritime economy that develops these capabilities coherently is better positioned to absorb regulatory change, diversify fuel pathways and maintain connectivity during technological uncertainty.

For Ireland, resilience therefore lies in optionality rather than prediction. The objective should be to create sufficient common infrastructure, institutional coordination and human capability to respond as different fuels mature. This does not remove the need for investment choices, but it reduces the risk that uncertainty becomes a rationale for inaction. The Dutch benchmark is instructive precisely because it demonstrates how strategic direction and adaptive capacity can coexist.

7. PRACTICAL IMPLICATIONS

Three integrated actions follow from the findings. First, Ireland requires a national maritime fuel-transition framework connecting transport, energy, port development, industrial policy, regulation and skills. The purpose should not be to prescribe one fuel, but to provide credible direction, clarify responsibilities and create investable pathways.

Second, infrastructure and workforce policy should be designed for multi-fuel adaptability. Ports should assess scalable enabling infrastructure, while national planning should connect maritime demand with Ireland's renewable-energy potential and future green-fuel production. Lifecycle emissions and supply-chain resilience should be considered alongside vessel-level emissions.

Third, maritime education and training should move from reactive course development towards a modular transition-skills architecture. This should combine common cross-fuel competencies with fuel-specific modules and structured continuing professional development. Industry, regulators and education providers should jointly review competency requirements so that curricula, simulation, practical facilities and instructor capability evolve before skills shortages become a binding constraint.

Limitations and future research

The study is exploratory and its survey sample is not statistically representative of the entire Irish maritime sector. Future research should test the capability-gap framework across a larger sample and examine whether similar misalignment occurs in other small maritime economies. Longitudinal research would also help assess whether regulatory, infrastructure and workforce capabilities converge as alternative-fuel projects move from planning to operation.

8. CONCLUSION

Ireland's maritime fuel transition is not constrained by a lack of awareness or willingness alone. The evidence identifies a wider implementation problem in which policy fragmentation, infrastructure uncertainty, investment risk and slow-moving skills systems reinforce one another. Survey respondents and expert interviewees consistently pointed to the absence of coordinated support structures, while the Netherlands demonstrated the value of a whole-system approach.

The principal contribution of this paper is the Maritime Transition Capability Gap: the proposition that regulatory ambition will not deliver decarbonisation when infrastructure, technology and workforce capability develop at different speeds. For Ireland, the priority is therefore not to predict a single winning fuel. It is to build an adaptable maritime system capable of operating safely and competitively across plausible fuel pathways.

The principal strategic risk is waiting for certainty while the infrastructure, workforce and supply-chain capabilities required for every plausible pathway remain underdeveloped. A coordinated national framework, adaptive multi-fuel capability and modular workforce development would allow Ireland to move from reactive compliance towards strategic participation in a decarbonising maritime economy.

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ADOPTION OF DIGITAL TECHNOLOGIES IN CIRCULAR SUPPLY CHAINS: A HUMAN-COMPUTER INTERACTION PERSPECTIVE

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Abstract

Purpose: Despite the perceived usefulness of digital technologies in driving circularity in businesses and supply chains, some managers still hold reservations for technology adoption. This study investigates the essential considerations in the design of user-interface for digital technologies and how this stimulates managers' utilization towards Circular Supply Chain Management (CSCM).

Research approach: Our study follows a qualitative approach. Data was obtained by interviewing 12 managers of e-commerce firms across UK. Using Nvivo, thematic analysis was conducted on the dataset following Braun & Clarke's six steps.

Findings and originality: We unravel some critical behavioural and technical factors responsible for managers' stimulus response to technology adoption for circular economy in supply chains. Specifically, three central themes emerged: Adaptability, Aggregation & Automation (Tripple A's); Muda and user-friendly architecture. The originality of our study lies in the proposed model for synergy between humans and digital technologies to minimize waste towards achieving circularity objectives in supply chains.

Research Impact: We explore the micro-foundations of Human-Computer- Interaction (HCI) and how it stimulates managers response to technology adoption. Through an integration of two principal theories, Stimulus-Organism-Response (SOR) model and Technology Acceptance Model (TAM), we produce a framework; Stimulus-organism-response in technology adoption for CLSCM. Consequently, we extend the arguments of the TAM to include managers' beliefs and stimulus response as core determinants of technology utilization.

Practical impact: Our study argues that user-interface design plays a crucial role in influencing managers' decision to engage digital technologies for CSCM. We therefore offer managers some new considerations for the engagement of digital tools in general and particularly in the utilisation of digital systems for promoting circularity objectives in supply chain management.

Keywords: circular economy, digital technologies, Human-Computer Interface, supply chain management

1.Introduction

Reducing greenhouse gas emissions remains central to the United Kingdom's net zero 2050 agenda. Logistics firms-through traditional operating practices, inefficient activity scheduling, and outdated planning and control systems-constitute a major source of emissions. These shortcomings underscore the urgency of transitioning to circular supply chain models that minimise waste, reduce carbon footprints, and enhance environmental safety.

Circular Supply Chain (CSC) refers to the intentional and designed closing of material loops, guided by a zero waste vision and achieved through the integration and optimisation of forward and reverse flows across multiple product life cycles to enable the restoration and regeneration of technical cycles (Amir et al., 2023). Embedding circular economy (CE) principles into Supply Chain Management (SCM) produces CSC, which strengthens sustainability by reducing waste and mitigating the environmental impacts of production and consumption activities (Lahane et al., 2020).

However, realising circularity within the logistics sector is particularly challenging. The industry's operational characteristics—especially the reliance on fuel powered vehicles that emit harmful gases and pollutants—create persistent environmental hazards. These complexities reinforce the need for digital technologies as enablers of Circular Supply Chain Management (CSCM), providing the tools required for logistics firms to achieve circularity objectives effectively.

Performance measurement for evaluating Circular Supply Chain Management (CSCM) in logistics—within the triple bottom line framework of economic, social, and environmental sustainability—typically centres on four key indicators: resource depletion, carbon footprint, toxicity, and human health (Vegter et al., 2023). Industry 4.0 technologies, particularly the Internet of Things (IoT), play a critical role in improving environmental performance across these indicators and advancing the broader aims of CSCM. While digital transformation is accelerating rapidly in the logistics sector, driven by the adoption of technologies such as blockchain, IoT, artificial intelligence, cloud computing, and big data, this technological shift keeps reshaping competitive dynamics to the extent that logistics firms that fail to adopt these tools risk falling behind (Flores García et al., 2023). Among smart logistics technologies, IoT is one of the most widely deployed (Ding et al., 2021), enabling vehicles, devices, and products to be equipped with sensors—such as RFID—to support enhanced routing, real time tracking, and seamless communication across the logistics network. Leading firms including DHL, Uber, and FedEx leverage IoT to deliver intelligent, efficient, and highly visible logistics services (Morshedi et al., 2026).

Despite these benefits, some logistics managers remain hesitant to adopt IoT, reflecting persistent behavioural and perceptual barriers. Empirical research examining the behavioural factors that impede IoT adoption for CSCM remains limited.

Against this backdrop, this study integrates Behavioural Reasoning Theory (BRT) and the Technology Acceptance Model (TAM) to address this gap. Specifically, it investigates how the interaction between managerial behavioural attributes and the technical characteristics of IoT can facilitate the achievement of circular economy objectives in logistics supply chain management (LSCM). Accordingly, we pose the following research question:

RQ: How does HCI influence circular supply chain management?

The circular economy principles that can be advanced through effective human–technology alignment include product reuse, restocking, maintenance, recycling, returns, and recall. A central objective of this study is to develop a framework that explains how human behavioural attributes interact with digital systems to enable Circular Supply Chain Management (CSCM). The study also expounds how the adoption of digital technologies fosters CSCM from a Human-Compuetr-Interaction approach.

Following this introduction, the paper proceeds as follows. Section 2 reviews the theoretical foundations, focusing on technology acceptance and IoT utilisation in logistics and supply chain management. Section 3 details the methodological approach. Section 4 presents the findings. Section 5 discusses and concludes the paper.

2. Theoretical background

The literature on technology acceptance within the scope of CSCM is quite robust and there is a concentration of studies on technologically inclined models as against models focusing on human behavioural factors. Thus, this section discusses technology adoption and behavioural perspectives to technology utilisation for CSCM.

2.1 Technology acceptance in LSCM

Extant studies on the adoption of digital technologies within the CSCM settings have been underpinned by several theories which could be stratified along two broad dimensions based on their focus: technological and behavioural theories.

Technological theories have their constructs concentrated on the technical factors affecting technology usage. For instance, the Unified Theory of Acceptance and Use of Technology (Venkatesh et al., 2012) with constructs like effort expectancy, performance expectancy and facilitating conditions influencing the behavioural intention to adopt and utilize digital technologies in logistics (Loske et al., 2021). The application of Technological Acceptance Model (Davis et al., 1989) is another direction taken by related studies in which attitude, perceived risks, perceived ease of use, face consciousness and public engagement affect the use of digital systems in logistics operations (Ladeira et al., 2025). Further, the technical, organizational and environmental constraints to technology adoption in logistics have been examined using Technology,

Organisation and Environment (TOE) framework (Ganguly, 2024). Diffusion of Innovation (DOI) theory explains how innovation permeates the adoption of electric vehicles (Yuen et al., 2021). Table 1 bifurcates the different theoretical underpinnings of extant studies on technology adoption in logistics.

Technology acceptance is not, however, dependent on only the technical details of digital systems as there are human factors involved in the functionality of technologies. Stimulus-Organism-Response theory situates organisms at the epicentre of decision making, suggesting that people's beliefs, perceptions, experiences and emotions play a huge role in informing their actions (Yang et al., 2022; Ding and Lee, 2024). Intuitively, at the heart of the decision to engage digital technologies for product reuse, returns, recall, recycling, and remanufacture lies the human values, emotions and belief system.

2.2 Behavioural considerations of technology acceptance for CSCM

Behavioural theories of technology adoption consider the human element of technology utilization, especially the behavioural features such as the attitudes of consumers using the attitude theory (Wang et al., 2020), consumers' subjective norms and behavioural controls using the theory of planned behaviour (Aboelmaged, 2021), as well as social influence, perceived risks and benefits through the theoretical lens of Theory of Reasoned Action (TRA) influence the intent of consumers to utilize digital technologies.

For every digital system to function efficiently, there needs to be an effective synergy between the technical features of such technology and the human elements involved in its operation. A technically strong system supported by managers with inadequate behavioural characteristics might not produce the desired outcome. Likewise competent managers with good attitude towards technology adoption may underperform if the digital system has poor technical qualities. There is therefore no gainsaying the fact that the advent of disruptive technologies has significantly transformed the operational logics of logistics firms thereby creating a "sociotechnical system" in which humans now work with machines to deliver more efficient services in which waste is minimized and outcomes are more sustainable. Intuitively, good digital technologies must be corroborated with adequate human behavioural factors to deliver the objectives of circular economy within logistics supply chain management. This school of thought has thus birthed a new research stream advocating the integration of technological and human elements of production and logistics systems (Sgarbossa et al., 2020), with emphasis on the technical, behavioural and psychosocial factors of technology utilisation in logistics (Morshedi et al., 2025) towards achieving certain outcomes such as waste minimization and enhanced circularity.

Circularity remains imperative for CSCM and this could be realized through effective synergy of human and technical aspects of technology usage for both forward and reverse logistics. A critical enabler of CSCM is reverse logistics which is the process by which manufacturers receives products back from consumers at the product's end of life for recycling or efficient disposal (Meier, et al., 2023) and one way circularity can be achieved is by outsourcing logistics operations to third party logistics (3PL) service providers (Zarbakhshnia et al., 2023). A sizeable proportion of studies on technology adoption in logistics have focused on the consumer side, with limited attention devoted to studies from the managerial perspective. Moreover, there is limited application of BRT in research on IOT adoption for logistics supply chain. Overall, more research is needed to understand how the integration of human behaviour and IOT can help logistics service providers achieve zero waste in their supply chains.

3. Methodology

The preliminary phase of this research has an exploratory design; hence, our study employs qualitative methodology. Data was obtained by interviewing supply chain managers of e-commerce firms in the United Kingdom, who are anonymized in compliance with data protection laws and prior agreements. Altogether, 12 semi-structured interviews were conducted in the summer of 2025 (April-July).

This first phase of our research streams is conducted following Gioia methodology which contains established procedures for exploratory studies (Gioia et al., 2013). In this preliminary stage, we examine how the behavioural features of logistics managers could combine with the technical properties of disruptive technologies such as blockchain, artificial intelligence and robotics to promote CSCM.

Following Braun & Clarke's six steps (Braun & Clarke, 2006), we conducted thematic analysis on our dataset. Beginning with familiarization with the dataset, we identified intuitions emanating from available data, subject to the earlier specified research question. We then proceeded with systematic coding of the materials, with careful consideration, analysis, conceptualization and constant comparison of codes. Next, codes with similar meanings were grouped to form themes. The themes were then examined to ensure distinctiveness, ensuring that each code logically reflects its underlying data extract. We finalized the data analysis by grouping the themes, renaming them and providing explanations regarding their relationships. Double coder technique was employed in which two of the research team members independently coded the data and compared the codes to eliminate researcher bias.

4. Findings

This study seeks to explore the adoption of digital technologies for circular supply chains, through a Human–Computer-Interaction lens, by teasing out the human behavioural and technical factors necessary for effective interaction between managers and digital systems towards waste elimination. Thematic analysis of interview transcripts from 12 UK-based managers of e-commerce supply chains reveals three central themes: Adaptability, Aggregation, and Automation (Tripple A); user-friendly architecture and Muda, as summarised in Table 1.

Tripple A: These three themes emerging from the analysis of interview transcripts hold that digital systems should be designed for people and not vice versa. An adaptable technological design is also one that makes room for data aggregation and automation with limited input from managers.

Table 1. Data structure

First order concepts	Second order themes	Aggregate dimensions
Design for end users	Human-centred design	Adaptability, Aggregation & Automation (Tripple A's)
AI should serve people		
Don't force humans to fit AI		
Tools improve productivity		
I would say they are complimentary from my own		
Automation is very important	Adaptability, Aggregation & Automation	
Adaptability is equally important. Data aggregation is another thing		
A very strong emphasis on automation of processes		
They also need to consider adaptability		
A Good digital system, I believe, for instance, should be able to aggregate data		
So consider the end users of the technology	Adoption behaviour	User-friendly architecture
I mean designing human being to fit AI, not the vice versa		
So you're just designing the AI for the designing sake, not to serve people that use AI	Human design	
This would really centre around openness to adoption		
Embracing the changes that come with digital technologies		
It was easy to navigate because we had made use of codes on SAP Records.	Ease of use	
A UI user experience that is very friendly, you know		
To learn and to partner with technologies	HCI Training	
A process and tools that reduce the complexity		
Yes, I would say LinkedIn courses		
management training programme		
building a good relationship with customers		
Because now you have a global economy	Waste identification	Muda
You need to understand the loopholes that generates waste		
Of course in the process there is waste both material and immaterial waste		
I think it's called Muda. Muda is a Japanese word for waste		
To reduce waste, AI should be able to help you to reduce the time you invest in going through data.	AI-enabled waste management	
They contribute to circular economies by reducing the chances that you generate waste		

5. Discussion and conclusion

Emerging themes from thematic analysis, underpinned by the theoretical framework of stimulus-organism response to technology adoption for CSCM indicate that humans should be at the epicenter of technology-design. Notwithstanding, digital technologies also play important roles in supply chains as they help in process optimization. As exemplified by the data extract:

"A Good digital system, I believe, for instance, should be able to aggregate data in a very large number, like take all the data for all the, let's say, all your distributors, all your partners should be able to aggregate their data and use it for decision making." (Mr K.A, June 27, 2025).

Humans therefore respond to stimulus generated by digital systems' interface design by recognizing their user-friendly architecture; usefulness in maintaining adaptability, agility and automation, as well as their effectiveness in curbing waste and ultimately promoting circularity in supply chains. As evidenced by the data sample:

"So how we try to manage this is to have a process and tools that reduce the complexity. One would be a UI (user interface) that is very friendly," (Mrs NMO, April 26 2025)

Embedding systems with lean techniques that ensure the elimination of non-value adding activities (wastes). Rather than rely on the take-make-waste traditional methods of conducting their business processes, 3PLs therefore embrace circular management techniques, minimizing waste and enabling the reuse and recycling of products, thus closing the supply chain loop. As contained in the data extract:

"They contribute to circular economies by reducing the chances that you generate waste. It's reducing waste to the barest minimum by connecting all the dots in the supply nodes (Mr M.Y. May 18, 2025).

This study makes significant contributions to theory and practice. As a theoretical contribution, we establish the link between TAM and SOR, as we also extend the arguments of TAM to include managers' beliefs and stimulus response. Managerial contributions of this study include the recognition that user-interface design plays a huge role in influencing technology utilization. We also explore the micro-foundations through which HCI fosters CSCM by stimulating managers' response to technology adoption.

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BRIDGING THE GAP BETWEEN RESILIENCE AND SUSTAINABILITY IN NPI SOURCING: THE ROLE OF EARLY SUPPLIER INVOLVEMENT

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Purpose

This paper examines how resilience and sustainability can be embedded into new product introduction (NPI) sourcing decisions through early supplier involvement. It shows that time-to-market, regulatory and cost pressures often override sustainability, despite mature resilience practices. The study moves beyond generic concepts by identifying the governance, metrics and capability changes needed to treat resilience and sustainability as equal design criteria from the earliest stages.

Research Approach

Guided by a critical realist, pragmatist stance, the study adopts an explanatory sequential mixed-methods design. A web-based survey of supply chain professionals (N=20) measures five constructs: resilience, sustainability, integration, early supplier involvement and governance maturity in NPI sourcing. The findings are triangulated with semi-structured interviews with senior Medtech leaders.

Findings and Originality

Findings reveal a clear imbalance within MedTech NPI sourcing. Resilience practices are well established (M = 3.91), supported by risk management, dual sourcing and disruption learning, while sustainability (M = 2.75) and resilience–sustainability integration (M = 2.73) remain underdeveloped and rarely embedded in sourcing decisions. Qualitative insights show that although NPI gate reviews, supplier scorecards and ESG tools exist, they operate in silos. Gate decisions prioritise quality, cost and speed, ESG assessments sit outside core decision forums, and early supplier involvement (ESI) is mainly used for manufacturability and compliance rather than environmental performance. The originality lies in shifting focus from strategy to NPI execution, demonstrating that integration requires aligned governance, metrics and supplier engagement, and translating this into a practical framework for implementation.

Research Impact

This research advances theory on "sustainable resilience" by distinguishing first-order resilience capabilities (e.g., risk reviews, dual sourcing) from advanced integrative capabilities that align resilience and sustainability within NPI governance. It shows that, without shared metrics, clear criteria and cross-functional decision forums, ESI tends to reinforce cost and speed rather than enable sustainability outcomes. The study demonstrates that integration maturity remains incomplete, even in advanced organisations, and is constrained by governance rather than intent.

Practical Impact

Two actionable conclusions emerge for NPI. First, organisations should use NPI gates as the primary integration mechanism, embedding joint resilience-sustainability criteria and involving ESG expertise in decision-making. Second, procurement teams should redesign supplier scorecards and early supplier involvement to include integrated metrics of risk, flexibility, carbon and circularity, supported by shared data. These steps provide a practical path to align ESG commitments with day-to-day sourcing decisions, which was an expressed interest in research.

Keywords: Medtech Supply Chain, New Product Introduction (NPI), Early Supplier Involvement, Resilience, ESG integration.

IMPROVING EFFICIENCY OF CYCLE COUNTING HIGH VALUE MATERIALS IN ULTRA-LOW TEMPERATURES

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Introduction

Inventory cycle counting is a well-established internal control mechanism that is mandated for US listed corporations under the Sarbanes-Oxley (SOX) Act of 2002 Section 404, which requires management to assert and external auditors to attest to the accuracy of a company's Internal Controls over Financial Reporting (ICFR) (Bainbridge, 2023). In standard ambient warehouse environments, the procedural and technological literature addressing cycle counting is extensive, encompassing Pareto or ABC analysis, blind counting protocols, barcode assisted data capture and Radio Frequency Identification (RFID) based inventory management systems (Ferdousmou, et al., 2024; Wilson, 1995).

However, a critical operational context remains absent from this body of work, that is the cycle counting of slow moving high value (SMHV) pharmaceutical materials stored under ultra-low temperature (ULT) conditions, which is defined by ASHRAE as -60oC to -80oC.

In this environment the standard assumptions underpinning cycle counting methodology regarding operator movement and interaction with the inventory are significantly challenged. Warehouse Operatives are subjected to maximum exposure limits of only a few minutes per freezer entry, product is only permitted a short time outside controlled storage (TOCS) without triggering a quality deviation due to potential impact to efficacy or safety and repeated door opening places thermal and mechanical stress on highly specialised refrigeration infrastructure as well as introducing moisture that impacts icing on both the product containers and refrigeration surfaces. These constraints not only compliacte the counting process and risk damaging the product, they also create a direct conflict between the demands for financial complaince and the requiremnt to maintain current Good Manufacturing Process (cGMP).

This paper addresses that gap directly. Using a mixed-methods study conducted across twenty SOX-obligated pharmaceutical sites, supplemented by operational data from a large scale pneumococcal conjugate vaccine (PCV) manufacturing facility and systematic assessment of emerging ULT compatible inventory technologies.

The authors make three specific contributions to the literature. Firstly this is the first detailed discussion of cycle counting practice and performance in ULT pharmaceutical environments including evidence of audit induced inventory shrinkage, substantial rework burden and partial regulatory non-compliance across surveyed sites. Secondly, there is an evaluation of the technical and regulatory feasibility of RFID based cycle counting in ULT as an alternative to manual counting while discussing the constraints faced such as metallic shielding, active tag battery degredation in ULT and the unresolved requirement for tamper evident tag verification that currently precludes full deployment. Thirdly a pathway for full RFID deployment is proposed contingent on auditor aligment and further development in tamperproof tag technology.

This paper is structured as follows: Section 2 covers the literature review, section 3 describes the research methodology, section 4 presents the results and discussion from the primary findings from survey, interview and technology analysis. Section 5 states the conclusions and recommendations while section 6 contains supporting references.

Literature Review

Financial Regulatory Compliance

The accounting scandals of the early 2000s, most notably Enron and WorldCom, prompted the US Congress to enact the Sarbanes-Oxley Act of 2002. Sections 404(a) and 404(b) impose a dual attestation burden on management and external auditors respectively to evaluate and report on the adequacy of a company's ICFR annually (Bainbridge, 2023). The inventory count provision is operationally specific as it requires that physical inventory be verified by direct, witnessed enumeration rather than by record reconciliation or statistical sampling. Any US-listed corporation with a market cap exceeding $75m including foreign companies, are subject to this obligation regardless of the physical conditions under which inventory is stored. Non-adherence carries civil and criminal sanctions of up to $5 million and twenty years' imprisonment. The substitution of indirect verification methods has not been accepted by external auditors as equivalent to physical blind count procedures (AuditBoard, 2024).

Cycle Counting Methodology

Blind cycle counting which is the practice of physically counting inventory without prior knowledge of the expected quantity, to prevent confirmation bias, has been the dominant SOX compliance mechanism for high-value pharmaceutical inventory since the Act's introduction. The ABC (Pareto) stratification model assigns counting frequency according to material value and movement rate: Class A items (high value, fast moving) are counted most frequently – every 2 months while Class C items (high value, slow moving) are counted at least annually (Wilson, 1995). Slow-moving, high-value pharmaceutical materials stored at ULT unambiguously occupy Class C under this classification.

Wijffells, et al.(2016) proposed an enhanced cycle counting approach incorporating historical inventory discrepancy data to prioritise counting effort toward error-prone records, reducing the total count frequency without sacrificing accuracy assurance. While applicable to ambient environments, this methodology assumes unconstrained and repeatable access to storage locations, an assumption that breaks down in ULT settings.

The manual count process itself introduces a well-documented transcription error mechanism. Where product identification requires the verbal communication and manual entry of long alphanumeric strings as is the case with pharmaceutical container lot numbers and serialisation codes.

Ultra-Low Temperature cold chain constraints

ULT is defined as -60°C to -80°C by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), with pharmaceutical vaccine and biologics manufacturers typically operating within this band of -70°C ±10°C. Achieving and sustaining these temperatures requires cascade refrigeration architecture using a two-stage mechanical system in which a high-stage circuit pre-cools an intermediate heat exchanger, which in turn drives a low-stage circuit to reach the target temperature (Ji et al., 2024). The practical consequence of this architecture is that thermal recovery following a door-opening event is slow: each access cycle imposes mechanical stress and increases energy consumption.

Personnel operating within ULT environments face two physiological constraints not present in ambient counting. Firstly, exposure limits will vary between companies based on their risk posture, however, exposure times set at four or five minutes per freezer entry are not unusual Secondly, heavily insulated PPE, while thermally necessary, substantially degrades manual dexterity, increasing the probability of product dropping and the time required to handle individual containers. For walk-in freezer configurations, three-person teams are required, two operators inside and one standby for emergency response meaning that a single recount event mobilises significant unplanned resource.

TOCS or time out of refrigeration (TOR) which the maximum permissible time any product container may remain outside its validated storage condition is product-specific, typically between six and thirty minutes for biological drug substances stored at -70°C. Exceedance triggers a mandatory quality investigation and potential discard, with associated regulatory documentation burden. The financial value of biological drug substance at this stage of manufacture representing several hundred hours complex processing means that even a single TOCS exceedance carries significant cost that is risked during each cycle counting event.

Technology based inventory verification alternatives

Barcode scanning is the most widely deployed automated data capture technology in pharmaceutical inventory management. It eliminates manual transcription error at the point of identification but retains all physical handling requirements, i.e. each container must be individually retrieved from storage, presented to a scanner with sufficient label clarity for optical recognition, and returned. In frozen environments, label readability is compromised by ice accumulation and condensation, frequently requiring manual label clearance before scanning is achievable. Barcode scanning therefore addresses the accuracy dimension of the counting problem without reducing personnel exposure time, TOCS risk, or equipment stress.

RFID technology, operating via electromagnetic coupling between a passive tag and an active reader (Lin, et al., 2019), enables bulk non-line-of-sight identification of multiple items simultaneously. UHF passive tags (860 - 960 MHz) achieve read ranges of one to six metres and read speeds of up to 1,300 tags per second in ambient conditions (Beontag, 2025), making them the dominant technology for pharmaceutical distribution chain traceability and warehouse inventory management (Ferdousmou et al., 2024). HF tags (13.56 MHz, ISO 15693) (Beontag, 2025) provide shorter read ranges of up to one metre, with higher resistance to metallic surface interference which is a significant consideration in freezer environments where shelving and the freezer structure create Faraday cage effects that attenuate UHF signals (RFIDTag, 2026).

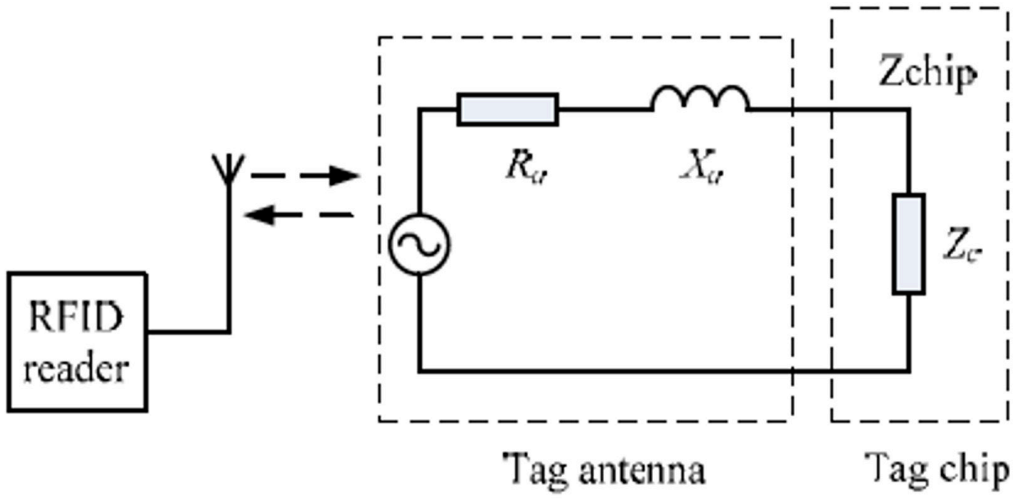

Figure 1 RFID Tag Structure (Lin, et al., 2019)

The physics of RFID performance at sub-zero temperatures introduces constraints not present in ambient environments. Passive tag antenna efficiency and application specific integrated circuit (ASIC) chip response time both degrade with falling temperature, active tag batteries even when manufactured with chemistry designed for low temperatures e.g. Lithium Thionyl Chloride, will fail below approximately -40°C (Jung et al., 2025). Existing literature on RFID performance characterisation in cold chain contexts does not addresses the regulatory requirement that a tag remain physically and verifiably attached to its designated product unit.

Research Approach / Methodology

This study employed a concurrent triangulation mixed methods design, as outlined by Saunders, et al., (2023), collecting and integrating quantitative and qualitative data streams together provided a richer and more comprehensive characterisation of the research problem of ULT cycle counting practice, and an assessment of technological alternatives to improve the efficiency of the process.

The quantitative data was sourced from qualified ERP and Inventory management systems meaning the research results are replicable and trustworthy (Anderson, et al., 2024).

While qualitative research has limitations, such as subjectivity and resource constraints, the methodological application of measures to ensure trustworthiness greatly enhances the precision and reliability of qualitative research (Ahmed, 2024)

Grounded in a pragmatic research philosophy and deductive approach, data collection comprised three components.

- A structured online survey of twenty purposively sampled pharmaceutical supply chain professionals was conducted, targeting organisations that store high value pharmaceutical materials (both drug substance and drug product) in ULT conditions and are obliged to comply with SOX financial controls. There were fifteen respondents and these represented a number of sites across the authors global network and competitor pharmaceutical manufacturers, all confirmed as publicly listed US-traded entities.
- Six semi-structured interviews were conducted with specialist stakeholders that included:
    - The director responsible for the policy governing cycle counting financial controls for a large multi-site global pharmaceutical organisation
    - A director of global supply chains
    - A director of Manufacturing Science and Technology
    - A site based SAP enterprise resource planning (ERP) specialist
    - Warehouse operatives responsible for executing cycle counts in ULT conditions
- A systematic web based technology analysis was conducted to evaluate commercially available RFID tag and reader configurations capable of meeting defined ULT operational requirements. Operational performance data were extracted from the site ERP system across a nine-month period at the primary research site, a large scale pneumococcal conjugate vaccine manufacturing facility operating both under SOX and cGMP regulations.

Research rigour was ensured through pilot testing, which is a crucial step for refining research instruments (Creswell & Creswell, 2023), validated data sources, and established criteria for reliability, validity, and trustworthiness.

Throughout the data collection and analysis the author was aware of their own potential for researcher bias, as cautioned by Saunders, et al., (2023) due to the real and pressing nature of their firsthand experience.

Results and Discussion

Universal operational burden and non-compliance

Survey data confirmed that all of the responding organisations perform cycle counts as a primary mechanism for SOX ICFR compliance with all but 1 explicitly identifying financial regulatory compliance as the driver. The outlier respondent cited GMP inventory control of drug substance as the primary driver, however, as all surveyed organisations are publicly listed US-traded entities, all are unambiguously within the scope of SOX Section 404a and 404b, with require management assessment and external auditor attestation to the accuracy if ICFR (Bainbridge, 2023).

Despite this 27% of respondents reported a variance against their own company financial controls policies. This finding was corroborated by interview data indicating that several sites had ceased counting entirely, citing product TOCS limitations and personnel safety concerns as justifications. This was validated by a senior supply chain director in one organisation who had confirmed during benchmarking with external auditors that all other competitor organisations were counting in some form, making their non-compliance an outlier position of potential regulatory exposure if not addressed.

Audit induced inventory shrinkage and rework burden

Every organisation surveyed reported annual inventory losses attributable directly to the cycle counting process through primary packaging container damage or prolonged exposure to temperatures outside the mandatory storage conditions. This spoilage aligns with the definition of inventory shrinkage by Fan, et al., (2014).

Financial losses of 60,000 per damaged product container are not unusual when accounting for the financial loss of drug substance material, the mandatory quality investigation in the event of product loss (up to 80 man hours), regulatory documentation and disposal costs. The mechanism of damage is well characterised, product containers removed from ULT storage immediately acquire an ice layer and coupled with gloves rated for handling materials at -70oC that negatively impact hand and grip dexterity increase the likelihood of dropping. Product containers and associated filling tubes and closure mechanisms subjected to many years in ULT conditions can lead to embrittlement thus worsening the outcome if mishandled accidentally during the counting process.

The current manual process requires the material to be located and removed from storage locations in the freezers and for an operator to verbally call out and a second to transcribe 37 alphanumeric digits from a frost covered label into the ERP system, thereby registering the count. This step is the documented source of 95% of counting errors. Over a nine month observation period 38 recount events were recorded resulting in approximately 500 man hours of unplanned rework that impacts the execution of the remaining warehouse scheduled works. A single transcription error on a count will trigger a full repeat count of all product containers in that count. In the case of a walk in freezer this requires the remobilisation of a three person team and can consume up to 18 additional unplanned man hours per event.

Direct annual cycle counting labour cost across surveyed organisations commonly exceeds 200,000 per site before breakage is considered with no correlation observed between resource allocation and inventory size, suggesting systemic process inefficiency rather than a scaling issue.

Technology assessment: RFID feasibility and constraints

Barcode scanning eliminates transcription errors by substituting automated data capture for manual digit entry and is compatible with existing product container labels and ERP infrastructure. However, it does not eliminate TOCS, personnel exposure time or stress on refrigeration equipment, as each container must still be individually removed, sufficiently cleared of frost for optical line of sight scanning and then returned to storage.

RFID technology offers a different operational profile, and in the course of this assessment scanning equipment was identified that satisfies all operational requirements. Operating at Ultra-High Frequency (UHF, 860-960 MHz) (Beontag, 2025), IP65/IP67 ingress protection, ruggedised casing, offline data storage / buffering (eliminating Wi-Fi dependency within the freezers), SAP ERP integration, ergonomic operation with heavily gloved hands and rated for -20oC experienced in walk in freezer corridors. The identified scanner can read up to 1,300 RFID tags per second (Beontag, 2025), crucially without line of sight enabling a conservative estimate of one hour to complete a full count of approximately 4,500 containers that may be located in a walk in freezer when prep time, gowning and other administrative activities are included. The current expectation is for a three person team to count approximately 100 containers in an 8 hour shift.

On-metal UHF passive tags (rated to -70oC and designed to the Faraday cage effect of the metallic freezer interior and shelving (RFIDTag, 2026)) are commercially available in form factors compatible with the primary sites existing product containers. HF tags (13.56MHz) provide read ranges up to one meter, sufficient for smaller upright freezers but inadequate for larger, deeper walk in freezers. UHF on-metal tags achieve read ranges of one to six meters which is suited to the both upright and walk in freezers. Active RFID tags, while offering better read distances are unsuitable due to the impact of ULT's resulting in battery failure below -40oC (Jung, et al., 2025).

However, two constraints currently preclude full deployment. Firstly, an interviewee identified a fundamental regulatory objection, that is, non-contact RFID scanning where the product container is not physically identified as present, cannot confirm that a tag remains physically attached to its designed product container, meaning a detached or transferred label would produce a false positive count. This necessitates a tamper evident tag that is destroyed or can report interference upon removal. Secondly, engagement with a number of vendors confirmed that no commercially available tamper evident RFID tag is currently rated for reliable and accurate operation below -40oC against a required operating temperature of -70oC. One specialist vendor confirmed that tags may survive storage at -80oC but become unresponsive or 'sleep' at that temperature due to the impact of these temperatures on the tag antennas material of construction.

This gap between the commercially available and required operating temperature for tamper evident tags in a suitable form factor represents the primary unresolved technical barrier.

Conclusions

This study addresses a research gap in the characterisation of cycle counting practices in pharmaceutical ULT storage environments and demonstrates that the constraints of this environment are fundamentally incompatible with the assumptions embedded in current SOX compliant manual counting methodology, placing an unreasonable financial and safety burden on impacted organisations.

Audit induced inventory shrinkage, substantial rework burden driven by transcription errors and partial regulatory non-compliance across the surveyed population confirm that the current process is operationally unsustainable for sites with large inventories and is a situation that will be exacerbated as inventories grow at the primary research site.

RFID technology is technically viable as a ULT compatible alternative for new inventory prior to freezing with suitable hardware configurations commercially available. Its deployment is currently obstructed by two specific constraints:

• the absence of auditor alignment on non-contact / non visual verification methodology

• the unavailability of tamper evident RFID tags capable of reliable and accurate operation at -70oC

Two recommendations are proposed at the primary research site. Firstly, immediate and full implementation of barcode data capture should be pursued for materials stored in ULT that do not have partial usage. This eliminates the transcription error mechanism for over 95% of recount events and approximately 500 man hours of rework annually, requires no capital investment beyond existing site infrastructure and has been confirmed with the director responsible for the policy governing cycle counting financial controls to be compliant with the policy, without requiring external auditor notification also.

Secondly, prior to any capital commitment to RFID infrastructure, formal alignment should be secured from the organisations internal and external financial auditors regarding the acceptability of tamper evident RFID scanning as a SOX-compliant alternative to physical blind cycle counting in ULT conditions, subject to supporting access control and freezer key management safeguard. Should auditor alignment be obtained, collaborative development of a tamper evident UHF RFID tag with an operational rating to -80oC, capable of being retrofitted to existing frozen inventory, with a specialist label manufacturer should be initiated. Successful development would enable full realisation of projected efficiency gains across the organisations ULT storage network and establish a transferable standard for the wider pharmaceutical industry.

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TOWARDS A QAA SUBJECT BENCHMARK STATEMENT FOR TRANSPORT, LOGISTICS AND SUPPLY CHAIN MANAGEMENT IN THE UK: A TRIPLE HELIX–EXPERIENTIAL LEARNING FRAMEWORK FOR INDUSTRY-INTEGRATED, POLICY-INFORMED EDUCATION

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Abstract

UK transport, logistics and supply chain management (LSCM) education lacks a dedicated Quality Assurance Agency (QAA) Subject Benchmark Statement, leaving provision to be designed against the generalist Business and Management benchmark. This absence compounds a persistent network deficit with limited structured engagement between academia, industry and policy actors, which leaves curriculum design reliant on reactive signals rather than coordinated, forward-looking intelligence. This paper develops a conceptual framework that pairs the Triple Helix model of university-industry-government relations with Kolb's experiential learning cycle, proposing experiential activity such as site visits, employer-set projects, practitioner-led teaching, as the mechanism through which the three spheres connect at curriculum level, and through which locally generated evidence can be aggregated into sector-wide skills intelligence. Brief illustrative material from a UK MSc programme demonstrates the framework's operational feasibility. The paper argues that the framework's value for the sector depends on its institutionalisation through a new QAA Subject Benchmark Statement, and is presented as the conceptual basis for a structured national consultation convened at the CILT Logistics Research Network Conference 2026.

Keywords: Experiential Learning; Logistics Higher Education; Industry Integration; Triple Helix; Network Deficit; Policy-Informed Curriculum; Skills Roadmapping; Subject Benchmark Statement;

1. Introduction and Purpose

UK transport, logistics and supply chain management sits at the centre of the national economy. Logistics UK's evidence to the House of Commons Education Committee places logistics employment at around eight per cent of the UK workforce, underpinning manufacturing, retail and international trade (Logistics UK, 2025a). Yet the discipline that trains the people who run this system occupies an unusual position in UK higher education as it has no dedicated QAA Subject Benchmark Statement of its own. Programmes in transport, logistics and supply chain management are instead designed against the Business and Management Subject Benchmark Statement (QAA, 2023a), a generalist reference point that does not engage with the distinctive content of the discipline such as multimodal freight operations, network design, supply chain resilience and security, or transport decarbonisation.

This absence sits alongside a persistent network deficit with limited structured engagement between academia, industry and policy actors in UK LSCM education, which leaves curriculum design reliant on reactive signals and skills gaps identified only once they have already affected recruitment rather than coordinated, forward-looking intelligence. Current sector data illustrate the consequence. Logistics UK's Q1 2025 Skills and Employment Update records severe recruitment difficulty for vehicle technicians, a contracting and ageing HGV driver workforce, and rising van driver vacancies, alongside a continuing concern that potential entrants do not understand the career routes the sector offers (Logistics UK, 2025b). These figures describe operative and technical entry points rather than the graduate-entry supply chain management roles this paper is concerned with; the perception problem they evidence, a sector whose career structure is poorly understood by potential entrants at every level, is nonetheless the same network deficit symptom this paper addresses at graduate level. These are not new problems as they recur because the channels through which academic provision, employer need and policy priority should inform one another remain thin and ad hoc rather than structural.

This paper develops a conceptual framework based on a Triple Helix model of academia, industry and policy, coordinated through experiential learning as a response to the network deficit, and argues that the framework's value for the sector depends on its institutionalisation through a dedicated QAA Subject Benchmark Statement. The paper is conceptual and it is intended to open, rather than close, a national consultation, and is presented as the underpinning evidence base for a structured consultation workshop convened at the 30th Annual CILT Logistics Research Network (LRN) Conference, September 2026.

2. Literature Review

2.1 The Network Deficit in UK Logistics Education

The relevance gap between management education and industry practice is well established. Bennis and O'Toole (2005) argue that business education has drifted toward academic credentialism at the expense of professional relevance. Within logistics and supply chain management specifically, the gap has been documented repeatedly. Lutz and Birou (2013), reviewing logistics course syllabi across several countries, found that the majority followed a traditional, research-led structure with little systematic industry input on curriculum content. Fawcett and Rutner (2014) note that practitioners often see no clear connection between the research underpinning curricula and the skills they actually need. Jordan and Bak (2016) found that supply chain graduates are expected to combine technical competence with generic employability skills as well as collaboration, problem-solving and self-management skills that traditional content-led delivery does not reliably produce, even where individual professional-development modules exist within programmes, because their provision is uneven across the sector and not coordinated against any shared standard. A UK-focused review of job advertisements by Wong et al. (2014) found that even entry-level logistics roles routinely require prior work experience, exposing a structural tension between what graduates leave with and what employers expect them to already possess. Camps (2017), examining supply chain teaching at a Scottish university, found students ambivalent about traditional lecture and guest-lecture formats but consistently rated real-world exposure and lecturer industry experience as the most valuable contributors to their understanding.

What these studies share is a diagnosis of disconnection rather than of absent effort. Individual modules, guest contributions and site visits exist across the sector, but are not coordinated through any shared structure that lets providers, employers and policymakers act on a common evidence base. This is the network deficit. It produces two visible symptoms. Skills shortages identified by industry only once they have already affected recruitment (Logistics UK, 2025b), and curriculum design that proceeds institution by institution, without a sector-wide reference point against which providers can benchmark consistently. Bak and Boulocher-Passet (2013) show that even where a single institution successfully embeds an industry-facing consultancy module, the model remains local and it does not propagate sector-wide without some mechanism for transferring and standardising practice. That mechanism is what is currently missing from UK transport, logistics and supply chain management education.

2.2 The Triple Helix Model as an Organising Framework

The Triple Helix model of university-industry-government relations, developed by Etzkowitz and Leydesdorff (1995, 2000), offers a way of treating the network deficit as a structural rather than a motivational problem. The model holds that innovation and coordinated development in knowledge-based sectors depend on overlapping, reciprocal relationships between three institutional spheres this of academia, industry, and government or policy, rather than on any one sphere acting alone, or on simple linear transfer from research into practice. Applied to a sector's education system, the model implies that curriculum relevance, skills planning and policy coherence are properties of the relationships between the three spheres, not properties any single university, employer or government department can generate alone.

This framing reinterprets what might otherwise look like separate, local problems. One university's underdeveloped employer relationship, one employer's frustration with graduate readiness, one policy initiative launched without sector consultation as symptoms of the same missing structure, a durable, reciprocal network connecting the three spheres. This paper pairs Triple Helix reasoning with experiential learning theory as complementary tools. The Triple Helix supplies the structural diagnosis of the network deficit where experiential learning supplies the mechanism through which the three spheres can be connected in everyday curriculum practice, rather than only through periodic, set-piece consultation exercises.

2.3 Experiential Learning as the Coordinating Mechanism

Kolb's (1984) theory of experiential learning describes learning as a cycle of concrete experience, reflective observation, abstract conceptualisation and active experimentation, in which knowledge is created through the transformation of direct experience rather than transmitted through content delivery alone. Within logistics and supply chain education, the practical value of the cycle is well attested. Camps (2017) found that students consistently valued real-world exposure and practitioner experience over traditional lecture formats. Bak and Boulocher-Passet (2013) showed that a structured industry consultancy module gives students a concrete problem to work through, with reflection built in by design. Jordan

and Bak (2016) link direct exposure to live supply chain problems to the cross-functional, collaborative skills that employers consistently report graduates lack.

The argument advanced here is that experiential learning is not simply a useful pedagogic technique. It is the mechanism that operationalises the Triple Helix at curriculum level. Site visits, employer-set live projects and practitioner-led teaching are, in Triple Helix terms, points where the academic and industry spheres physically and informationally connect. When policy priorities such as decarbonisation, digitalisation, supply chain resilience are built into the design of those activities, the policy sphere is drawn into the same connection, rather than communicated to students second hand. Each well-designed experiential activity is therefore simultaneously a pedagogic intervention and a small, repeatable instance of Triple Helix coordination, generating evidence of student outcomes, employer feedback, project results that can be aggregated into sector-level intelligence about emerging skills needs, rather than lost as a one-off departmental record. This reframing, from isolated pedagogic activity to aggregable sector intelligence, is the paper's original conceptual contribution.

2.4 The QAA Benchmarking Landscape and the Structural Gap

QAA Subject Benchmark Statements describe the academic standards and threshold expectations for graduates in a defined subject area, and are used by providers in designing, delivering and reviewing courses, often informed by professional, statutory and regulatory body (PSRB) and employer expectation (QAA, 2023a). No dedicated Subject Benchmark Statement currently exists for transport, logistics or supply chain management. UK providers instead design against the Business and Management Subject Benchmark Statement (QAA, 2023a), which addresses organisations, management and the wider business environment in general terms, but does not engage with the distinctive content areas of LSCM such multimodal freight and network design, port and maritime operations, supply chain risk and resilience, or transport decarbonisation and the net-zero transition, including its upstream manufacturing and engineering dimensions as well as downstream transport operations.

This is the structural barrier that a Triple Helix-experiential learning framework cannot remove on its own. An individual provider can adopt the framework, embed experiential learning, and build strong local employer relationships, several already do, but without a shared sector reference point, the resulting practice is not benchmarked, not comparable across institutions, and not capable of aggregating into the coordinated, sector-wide skills intelligence the network deficit calls for. QAA's Recognition Scheme for Subject Benchmark Statements sets out four principles against which a proposal for a new statement is judged. Whether the subject has sufficiency and a distinctive subject community, whether the proposal is representative of, and supported by, that community and cognate communities, the extent to which existing statements are insufficient for the subject and the extent to which a new statement is necessary. Three of these four are already addressable on the evidence above as a distinctive subject community evidently exists. However, the Business and Management Statement is demonstrably insufficient for the discipline's distinctive content (and, as Section 2.5 sets out, the Engineering Statement is no better fit) and the network deficit, structurally unresolved by individual institutional effort, establishes necessity. Representativeness is the one test a conceptual paper alone cannot establish as it requires the structured, evidenced sector consultation this paper is written to open.

2.5 The Hybrid, Multi-Sectoral Nature of the Discipline

Transport, logistics and supply chain management does not sit neatly within a single existing benchmark because it is not a single-discipline subject in the way Business and Management is. It functions simultaneously as a business and management discipline with procurement, commercial strategy, demand planning and supply chain governance and as an engineering discipline with network design, terminal and port operations, vehicle and infrastructure systems, and the technical analysis of freight and passenger flows. QAA's Engineering Subject Benchmark Statement (QAA, 2023b) is, in this respect, as partial a fit as the Business and Management Statement therefore neither was written with this discipline's combination of commercial and technical content in mind. This hybridity is institutionally visible, not theoretical. he UK MSc programme used as the illustrative case in Section 4 sits within a school of engineering and the built environment rather than a business school, a positioning repeated in different forms across UK providers, and one the existing benchmark landscape does not accommodate.

The same hybridity runs through the curriculum in a second sense as teaching has to span sourcing and manufacturing at one end of the value chain through to retail and final-mile delivery at the other, and span shipping and maritime operations through to multimodal land transport and distribution networks, with no benchmark currently defining threshold expectations across that breadth. The subject community the proposed Statement would serve is correspondingly broad. CILT(UK) alone organises specialist forums spanning, among others, ports, maritime and waterways, freight forwarding, rail freight, retail, warehouse technology and materials handling, supply chain and operations management, and construction logistics (CILT(UK), n.d.).

2.6 Government Recognition and the Case for Engineering-Based Delivery

Government apprenticeship policy provides independent confirmation of this hybridity. The Institute for Apprenticeships and Technical Education classifies the Supply Chain Leadership Professional (Integrated Degree) standard, ST0548, as a Level 6 integrated degree apprenticeship under the Transport and Logistics occupational route, with the bachelor's degree (360 credits) embedded within the apprenticeship and graded through independent end-point assessment (IfATE, 2018). Achievement carries professional recognition across four bodies whose remits themselves span the business/engineering divide: Member (MILT) status with CILT, Affiliate membership of the Chartered Institute of Procurement and Supply, Expert-level membership of the Institute of Supply Chain Management, and Associate membership of the Institute of Export and International Trade. A standard recognised this broadly, and routed through Transport and Logistics rather than generic Business and Administration, is itself government-level evidence that the occupation does not belong to one disciplinary tradition alone.

There is also direct UK precedent for engineering-based delivery, not only a theoretical case for it. A comparable UK precedent exists at another institution with a multidisciplinary department of applied science, technology and engineering, and a centre for the High Value Manufacturing Catapult, delivers a CILT- and CIPS-accredited MSc in Supply Chain and Logistics Management alongside an MSc in Programme and Project Management, within the same engineering-oriented department. The co-location is not incidental as the digital supply chain technologies, network optimisation, simulation, robotics and automation in warehousing, digital twins and project management methodology with programme scheduling, systems integration, risk management draw on the same quantitative and systems-engineering foundations an engineering faculty already teaches and resources, through laboratories, simulation software and technical electives a business school does not typically hold. The illustrative case programme's own positioning within a school of engineering and the built environment, discussed in Section 2.5, follows the same logic rather than departing from convention. Government classification and existing institutional practice therefore both support locating supply chain management provision in engineering as well as business faculties – precisely the flexibility a single, subject-specific benchmark, rather than a benchmark written for either discipline alone, would need to accommodate.

3. Research Approach: A Triple Helix-Experiential Learning Framework

The study adopts a design-oriented, conceptual approach. Rather than testing a hypothesis against collected data, it constructs a framework intended to be operationally useful and tests its coherence against the literature reviewed above and against current practice in a single illustrative case. This is appropriate to the paper's purpose as it is the first stage of a multi-year, multi-method programme of work, opening a consultation rather than reporting its results, and the framework is designed to generate the structured evidence that later, empirical stages for a sector-wide survey and a formal QAA proposal that will depend on.

The framework brings together the two theoretical strands reviewed in Section 2. Table 1 sets out how each Triple Helix sphere connects to curriculum practice through a specific experiential mechanism, and what evidence that mechanism is designed to generate. The model is presented here at sector-general level. How the mechanism plays out differently across upstream functions such as sourcing and manufacturing, downstream functions such as retail and final-mile delivery, and across sub-sectors including maritime, freight and warehousing, is not differentiated at this conceptual stage and is identified in Section 7 as a priority for the sector-wide survey.

Triple Helix Sphere	Curriculum Mechanism	Evidence Generated
Academia	Curriculum design built around live, current problems rather than constructed case studies alone	Assessed project outcomes; student reflective evaluation
Industry	Site visits, employer-set project briefs, practitioner-led teaching	Employer feedback on graduate readiness; direct skills specification
Policy / PSRB	Decarbonisation, digitalisation and resilience priorities built into project briefs; structured PSRB engagement	Alignment data against national skills priorities; PSRB endorsement
Coordinated reference point	Aggregation of the evidence above across multiple providers, convened by a PSRB	A shared sector reference point in QAA terms, a Subject Benchmark Statement

Table 1: The Triple Helix–Experiential Learning Coordination Model

The first three rows of Table 1 describe activity that, in some form, already exists at individual UK institutions and this is demonstrated in Section 4. The fourth row is the part of the model that does not yet exist for this discipline, and it is the part that converts good local practice into sector-wide standardisation. A Subject Benchmark Statement is, in these terms, not a compliance requirement imposed on existing good practice, it is the missing aggregation layer the Triple Helix model identifies as structurally necessary, and that individual institutions cannot supply alone, however well they perform the first three rows. This is the paper's central conceptual claim. The network deficit is not principally a deficit of pedagogic effort and will not be closed by individual institutions doing more of what they already do well. It is a deficit of structural coordination, requiring a structural response for a sector-wide reference point, convened by a body positioned to represent the whole subject community across academia, industry and policy.

A professional body such as CILT(UK) is well placed to perform this convening role precisely because it already sits across all three spheres such as academic members and accredited programmes, industry membership across logistics, freight and transport, and an established relationship with government skills and transport policy and is the natural route through which a proposal for a new Subject Benchmark Statement would be submitted to QAA under the Recognition Scheme.

4. Findings and Originality

This paper's principal finding is conceptual rather than empirical and is set out in full in Section 3. Experiential learning, conventionally a pedagogic choice internal to a single programme, can be reframed as the operational mechanism of a Triple Helix structure, and the evidence it generates can in principle be aggregated into sector-level skills intelligence rather than retained only at programme level. This is the paper's original contribution, and it addresses a gap in the literature reviewed in Section 2 where existing studies diagnose the academia-industry relevance gap in detail (Bennis and O'Toole, 2005; Lutz and Birou, 2013; Fawcett and Rutner, 2014; Jordan and Bak, 2016) but stop short of proposing a structural mechanism, beyond individual module redesign, through which the gap could be closed at sector level. The framework developed here supplies that mechanism.

Brief illustrative material from current practice demonstrates the framework's operational feasibility, without making empirical claims about its effects; that empirical evidence is the purpose of the consultation and survey stages described in Section 7. The illustrative case MSc programme which is CILT accredited supplies the policy/PSRB connection in Triple Helix terms. Students currently embeds several of the mechanisms set out in Table 1 such as direct contribution from sector practitioners across maritime, port and freight operations through structured site visits, including access to full-mission bridge and engine room ship simulators, which place students inside operational decision-making environments rather than describing them at a distance and applied project work in which postgraduate students engage with live or recent industry problems rather than constructed case studies alone. Several of these activities already carry an explicit policy dimension in port decarbonisation, freight network resilience, supply chain risk and reflecting current national priorities rather than a static curriculum.

What this case illustrates is feasibility, not effect. The components the framework calls for employer-connected teaching, live project work, simulator-based experiential learning and PSRB engagement already exist within at some UK programmes, without having required new institutional infrastructure. What does not yet exist is the sector-wide mechanism for aggregating this activity, undertaken at multiple institutions in different combinations and degrees, into a single, comparable reference point that the fourth row of Table 1, and precisely the gap a Subject Benchmark Statement would close. Illustrative practice at one institution cannot substitute for sector-wide consultation and standardisation and it can only demonstrate that the standardisation proposed is asking institutions to formalise something achievable, not speculative.

5. Research Impact

The central research impact claim of this paper is direct as this study provides the conceptual underpinning for the development of a new UK Subject Benchmark Statement for transport, logistics and supply chain management, and supports, rather than merely discusses, the case for initiating that process through the QAA Recognition Scheme. Table 2 summarises the specific gap, against both existing benchmarks, on which this claim rests.

Distinctive LSCM Content Area	Business and Management Benchmark (QAA, 2023a)	Engineering Benchmark (QAA, 2023b)
Multimodal freight operations and network design	Not addressed	Partially addressed – general systems design, not freight-specific
Port, maritime and terminal operations	Not addressed	Not addressed
Supply chain risk, resilience and security	Partially addressed – generic risk management only	Not addressed
Transport decarbonisation and the net-zero transition, including upstream manufacturing	Partially addressed – sustainability in general business terms	Partially addressed – technical systems only, not supply chain or policy context
Procurement, commercial strategy and supply chain governance	Addressed	Not addressed
Vehicle, infrastructure and technical systems	Not addressed	Addressed

Table 2: Distinctive LSCM Content Areas Against Existing QAA Subject Benchmark Statements

This claim follows from the argument built across Sections 2 to 4 rather than asserting it independently. The literature establishes that the academia-industry-policy relevance gap in logistics education is well documented but has not, to date, been linked explicitly to the absence of a dedicated Subject Benchmark Statement as its structural cause (Section 2). The Triple Helix-experiential learning framework developed here supplies the missing mechanism for closing that gap at sector level, rather than only at module or programme level (Section 3). The illustrative case demonstrates that the framework's components are already operational in current UK provision, removing the objection that the proposal is impractical (Section 4). Together, these three contributions directly satisfy three of the four evidential principles in QAA's Recognition Scheme which are subject sufficiency and distinctiveness evidenced not only by CILT membership generally, but by the specific, multi-sectoral breadth of the existing subject community (Section 2.5). The insufficiency of both the Business and Management and the Engineering Statements for this hybrid discipline, and the necessity of a new statement given that the network deficit cannot be resolved by individual institutional effort.

The paper therefore does not present a case for a Subject Benchmark Statement as one possible implication among several. It presents the absence of such a Statement as the structural barrier the rest of the argument has been built to identify, and the development of a new Statement as the appropriate policy response. The fourth Recognition Scheme principle of representativeness across the whole subject community is explicitly not claimed here. That evidence is generated through the structured national consultation this paper underpins, convened at the LRN Conference 2026, and through the sector-wide survey that follows it. This paper's research impact is deliberately sequential and it establishes the case sufficient to justify opening a national consultation, rather than claiming to have already concluded one.

6. Practical Impact

For individual programmes, the framework offers a practical structure for auditing employer engagement. Table 1 can be used directly as a checklist against which a provider can assess whether its site visits, guest contributions and project work generate usable evidence, or remain isolated pedagogic activities of value independent of any QAA outcome.

For professional bodies, sector forums and learning partners such as CILT(UK), the framework provides a structured basis for convening evidence-based dialogue on skills priorities, curriculum coherence and future capability needs, translating dispersed teaching activity across institutions into actionable intelligence for national coordination, rather than relying on individual relationships or anecdote. It also has direct relevance to existing initiatives: Logistics UK and CILT(UK)'s Generation Logistics campaign already addresses the awareness barriers in current skills data (Logistics UK, 2025a, 2025b); a Subject Benchmark Statement complements that work by addressing the supply side what graduates are actually taught rather than only the demand side of attracting entrants.

For policymakers, the framework offers a route to embedding national priorities such as decarbonisation, digitalisation, supply chain resilience feeding directly into curriculum design. For employers, a benchmarked standard would reduce the current need to assess and bridge inconsistent graduate readiness case by case, a cost borne disproportionately by smaller operators without dedicated graduate training capacity.

7. Conclusion and Next Steps

This paper has argued that the persistent network deficit in UK transport, logistics and supply chain management education is a structural problem requiring a structural response, and has proposed a Triple Helix-experiential learning framework as the conceptual basis for that response. It has identified the absence of a dedicated QAA Subject Benchmark Statement as the specific structural barrier preventing locally successful practice from becoming sector-wide standard, and has shown, through brief illustrative material, that the framework's components are already operationally feasible within current UK provision.

This paper is the opening stage of a longer programme of work, not its conclusion. It underpins a structured consultation workshop convened at the 30th Annual CILT Logistics Research Network Conference, September 2026, in which the framework will be tested against the views of a mixed academic and industry delegate community, with outcomes captured as formal consultation evidence. That evidence will inform a sector-wide survey conducted between September and November 2026, and a formal Expression of Interest submitted to QAA through CILT(UK) as proposing body, initiating the Recognition Scheme process for a new Subject Benchmark Statement in transport, logistics and supply chain management the first such statement in the discipline's history. Future research, including a formal proposal against the Recognition Scheme's four principles, will report the empirical findings this conceptual paper has been written to make possible.

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DEMAND AND CAPACITY REQUIREMENTS OF COMMERCIAL PORTS BEYOND 2040: PRELIMINARY QUALITATIVE INSIGHTS

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Abstract

Purpose
This paper examines how Irish port authorities and terminal operators understand commercial port demand and capacity requirements beyond 2040, reframing capacity as effective system performance rather than physical space alone.

Research Approach
The study forms part of the DECAP 2040+ project and uses an exploratory sequential mixed-methods design. It reports preliminary qualitative insights from the first seven stakeholder interviews, analysed alongside policy, grey literature, port masterplans and academic literature.

Findings and Originality
Early findings suggest that land, berth availability, gate systems, grid connections, planning lead times and hinterland access determine whether physical capacity becomes usable throughput. Dublin concentration remains commercially sticky, while ORE and resilience require stronger network coordination.

Research Impact
The paper contributes by linking qualitative interview evidence to scenario-based demand and capacity modelling under deep uncertainty.

Practical Impact
The findings highlight the need to align port investment, funding models, planning processes, grid readiness and hinterland access with long-term objectives for trade, energy transition and resilience.

Keywords
Port capacity; demand forecasting; Ireland; maritime logistics; scenario planning; qualitative insights.

Introduction

Commercial ports face a strategic planning problem that cannot be reduced to a single traffic forecast. The demand in the post-2040 period will be shaped by decarbonisation efforts, offshore renewable energy (ORE) projects development, changing shipping routes, industrial policy, digitalisation, land-use pressure, hinterland access and the institutional ability to deliver major infrastructure (UNCTAD, 2024). Decarbonisation is a system-wide transition in which progress across vessels, fuels and port infrastructure has to advance together, so port capacity cannot be treated in isolation from the wider maritime energy system (DNV, 2025). Port assets are long-lived and often require planning, consent, funding and construction decisions many years before demand is visible in throughput statistics, and these investment choices increasingly must be made under climate and transition uncertainty (Xia, Mishra and Adulyasak, 2024). The result is a deep uncertainty problem, where the future may be structurally different from the past while decisions still have to be made in the present (Walker et al., 2013; Haasnoot et al., 2013). These pressures are especially acute for a trade-exposed island economy such as Ireland, where post-Brexit route restructuring, ORE ambition and a heavy concentration of traffic on the east coast sharpen every one of them.

This paper reports preliminary qualitative insights from the first seven interviews undertaken as part of the Demand and Capacity Requirements of Commercial Ports Beyond 2040 (DECAP 2040+) project. This research sets out an exploratory sequential mixed-methods design in which qualitative evidence informs scenario construction and later quantitative demand and capacity modelling. The present paper does not present final forecasts. Instead, it examines what early interviews with port authorities and terminal operators reveal about how capacity, demand and resilience are understood by those who must plan, fund and operate Ireland's port system. Specifically, it asks how port authorities and terminal operators define and bound capacity under these conditions, and what that implies for the drivers and assumptions carried into scenario-based demand and capacity modelling.

Literature and Policy Context

Forecasting under structural uncertainty

Port demand forecasting has traditionally drawn on historical throughput, macroeconomic relationships and trade indicators, but the literature increasingly questions forecast-first planning where structural breaks are likely (Meersman, Van de Voorde and Vanelslander, 2014; Parola et al., 2021; Solak Fiskin and Cerit, 2021). Forecasting models remain necessary, but they become weaker when the assumptions linking GDP, trade intensity, route choice and port throughput are unstable. For Ireland, such instability arises from post-Brexit route restructuring, decarbonisation costs, ORE-related cargoes, changing shipping-line network design and the potential movement of industrial activity linked to energy transition policy.

Scenario and foresight methods therefore provide a bridge between qualitative uncertainty exploration and quantitative modelling. Schoemaker (1995) argues that scenarios are useful when decision makers face high uncertainty and high consequence decisions. Halim, Kwakkel and Tavasszy (2016) show how scenario discovery can be used to examine global container-system uncertainty, while Haasnoot et al. (2013) link scenarios to adaptive pathways and decision triggers. This is directly relevant to post-2040 port planning: the purpose is not to predict one future, but to test whether capacity decisions remain robust across plausible futures.

Capacity as effective system performance

A second body of work argues that port capacity should be assessed as effective capacity rather than theoretical physical capacity. Berth length, depth, yard area and equipment matter, but so do berth occupancy, dwell time, gate performance, pilotage, labour, storage, customs, planning conditions, hinterland access and reliability (Saeed and Larsen, 2016; Notteboom, Pallis and Rodrigue, 2022). Queuing and simulation studies are particularly useful because they show how service reliability can deteriorate before a port appears to be physically full (Legato and Mazza, 2020; Guo, Wang and Wang, 2023). Effective capacity is therefore a relational concept: it depends on the interaction between maritime access, terminal operations, landside flows, information systems and acceptable service levels.

Strategic port management research also stresses that port authorities require organisational and stakeholder capabilities, not only assets, when developing capacity under uncertainty (O'Connor, Evers and Vega, 2023). Large infrastructure decisions depend on project development capability, stakeholder management, financial capacity, public-agency coordination and the ability to translate market demand into bankable investment. This shifts attention from the question 'how much land or quay exists?' to 'what combination of assets, governance and operational capability can produce reliable throughput under stress?'.

Decarbonisation, digitalisation and resilience

The decarbonisation literature further widens the definition of capacity. Shore power, alternative fuels, electric cargo-handling equipment and low-carbon shipping corridors require grid capacity, storage, safety zones and operational coordination. Port-side decarbonisation can reduce emissions, but it can also create new bottlenecks if electricity, land and safety systems are not delivered in time (Bullock, Hoolohan and Larkin, 2023; Hsu et al., 2024). Digitalisation and automation may raise effective capacity through gate systems, port community systems, data sharing and improved asset utilisation, yet their benefits depend on governance, interoperability and cyber resilience (Inkinen, Helminen and Saarikoski, 2021).

Resilience studies similarly suggest that port capacity should be examined at network level. COVID-19, the Suez Canal blockage, weather events and geopolitical shocks demonstrate that disruption is transmitted through shipping networks, inland corridors, labour availability, customs processes and terminal operations (Komaromi, Cerdeiro and Liu, 2022; Russell, Ruamsook and Roso, 2022). For an island economy, resilience cannot be understood only as spare capacity in one location; it also depends on substitutability, route diversity, recovery time and whether cargo owners and carriers can switch services without unacceptable cost or delay.

Irish policy and grey literature

The Irish policy and grey-literature context reinforce this wider view. The Review of National Ports Policy identifies capacity, accessibility, climate change, ORE, circular economy flows, technology, governance and funding as central issues (Department of Transport, 2024). Ireland's Offshore Wind Industrial Strategy positions ports as potential construction, operations, energy and green industrial nodes, with targets of 20 GW by 2040 and 37 GW by 2050 (Department of Enterprise, Trade and Employment, 2024). The Irish Ports Capacity Study (Arup and EY, 2023) and individual port masterplans add more applied evidence: planned projects, land constraints, east-coast capacity debates, regional port roles, ORE readiness, rail and road access, and funding challenges. These sources indicate that capacity is not simply a response to freight growth; it is also an enabling condition for energy, industrial and regional policy.

Research Approach

DECAP 2040+ adopts an exploratory sequential mixed-methods design (Creswell and Creswell, 2018). The first stage reviews academic, policy, grey-literature and port masterplan evidence. The second stage uses semi-structured stakeholder interviews to test and refine the initial driver set, scenario logic and definition of capacity. Later stages will translate the refined scenarios into quantitative demand modelling, capacity-gap analysis and policy recommendations.

This paper focuses on the first seven interviews with executives from port and terminal-operators.Interviews were coded thematically (Braun and Clarke, 2006) using a codebook developed from the literature review and updated inductively during analysis. The dominant coded themes in the initial dataset were market and demand drivers, capacity and infrastructure, policy alignment and governance, strategic scenarios and future, sustainability and environment, and resilience and risk. Direct quotations below are anonymised and lightly edited for clarity. The findings should therefore be read as preliminary qualitative insights rather than representative sector conclusions.

Alignment with Scenario Development

The interview analysis was designed to refine the scenario structure rather than sit separately from it. Scenarios were developed using policy, grey literature, academic evidence and port masterplans to identify demand drivers and critical uncertainties. These were organised around two axes: demand and industrialisation intensity, and transition delivery capacity. The early interviews provide operational evidence on whether those axes make sense to port actors and whether additional variables should be carried into quantitative modelling.

Grey-literature analysis provided the first version of the scenario logic. National policy emphasises port capacity, accessibility, governance, ORE, climate adaptation and integrated logistics. Port masterplans identify planned capacity, spatial strategies and local constraints, but they are not the same as delivered capacity. The Irish Ports Capacity Study and policy consultation material point to system-level issues: Dublin concentration, east-coast capacity, hinterland access, funding constraints, ORE readiness and the need to distinguish commercial port returns from wider national benefits. These documentary sources created the initial driver list; the interviews then tested whether those drivers are visible in operational practice.

The alignment is strongest around transition delivery capacity. Interviewees repeatedly described planning lead times, grid limits, road access, port land, funding models and institutional coordination as decisive for whether demand becomes handled throughput or congestion. This is consistent with Scenario 1, Green Industrial Acceleration, where high demand is matched by high delivery capacity; Scenario 2, Regional Resilience and Network Rebalancing, where moderate demand is managed through coordinated network roles; and Scenario 3, Fragmented Transition and Capacity Stress, where demand persists but capacity delivery lags. The qualitative evidence therefore grounds the scenario architecture by grounding it in the language and constraints of port authorities and terminal operators.

This alignment also creates a practical handover to the next phase of the research. Interview themes should become model assumptions, sensitivity bands and monitoring signposts. For example, 'land availability' becomes a capacity constraint; 'grid connection' becomes an ORE and shore-power readiness variable; 'Dublin concentration' becomes a route-share and port-choice assumption; and 'planning lead time' becomes a timing risk on capacity delivery. In this way, the interviews do not simply illustrate the scenarios. They help determine which variables must be quantified, stress-tested and monitored.

Preliminary Qualitative Insights

Capacity is being defined as a performance threshold

Interviewees repeatedly treated capacity as an operating condition rather than a static inventory. Rather than defining capacity only by quay length, hectares or equipment, participants described the point at which service performance begins to deteriorate.

"If we are at 70% capacity, we are now starting to become inefficient and our performance is starting to drop."

This practical threshold matters because it gives the modelling work a performance-based definition of capacity. A port may still have theoretical space or berth availability, but if vessel turnaround, storage, gates or hinterland flows are already degrading, additional demand will create congestion rather than handled throughput.

"What limits throughput for us at the moment is the available land space."

The second quotation illustrates how physical land, operational practice and throughput are inseparable. The evidence also suggests that smaller operational constraints can create system-level effects. Interviewees referred to vessels at anchor, delayed lashing, pilotage restrictions, gate systems, dwell time, single access points and storage shortages. For modelling purposes, the next phase should therefore include utilisation thresholds, vessel waiting time, yard dwell time, truck turn time, power availability and hinterland reliability alongside conventional capacity indicators.

Dublin concentration is sticky, but not uncontested

A strong theme was the economic pull of Dublin. Interviewees noted that unitised freight follows population, distribution centres and service frequency. This was expressed in direct market terms by one participant:

"70% of the unitised trade in and out of Dublin goes within the M50 motorway and the surrounds."

Another participant made the same point more broadly, linking port choice to the location of final markets and logistics demand.

"For cars, containers, ferries and oil... Dublin is the market."

These comments caution against assuming that regional rebalancing will happen simply because alternative capacity exists.

At the same time, several participants argued that the national system needs a more explicit network model. Regional ports were seen as important for bulk, agri-food, ORE, energy transition cargoes and resilience. One participant stated that logistics companies 'gravitate towards Dublin', but that policy makers may need to say 'there is other capacity here'. The emerging insight is therefore not Dublin versus the regions, but how route economics, policy incentives and hinterland access determine credible network rebalancing.

Delivery capacity is a critical uncertainty

The interview data lends early support to the scenario document's second axis: transition delivery capacity. Stakeholders did not only ask whether demand will grow; they asked whether planning, finance, roads, rail, grid, land and governance can arrive in time. One participant summarised the lead-time problem as follows:

"You have to be 10, 15 years ahead of the game because of pre-planning, planning, procurement and construction."

The same theme appeared in comments on funding. Interviewees described a mismatch between ports' commercial mandates and the national strategic value of some infrastructure.

"There is an issue with funding ports as strategic enablers of major infrastructure and expecting the market to pay for it up front."

This theme is especially important for ORE and green industrial development. Port authorities may be asked to create capacity before customers, auctions, grid connections or revenue streams are secured. Interviewees pointed to the gap between policy ambition and bankable demand. This creates a timing problem: infrastructure must be built in advance, but commercial semi-state ports cannot always justify the risk on their balance sheets. The practical implication is a need for funding models that distinguish commercial port returns from national resilience, decarbonisation and industrial-policy benefits.

Decarbonisation changes both demand and capacity

The energy transition appeared in the interviews as both an opportunity and a constraint. ORE could create demand for marshalling, laydown, heavy-lift quay space, operations and maintenance, cables, hydrogen, ammonia, grid connections and green industrial clusters. Yet interviewees also described uncertainty over route-to-market, developer uptake, auctions, planning and the ability of ports to finance facilities before revenue is certain. One participant reduced the infrastructure requirement to a simple operational need:

"We need a 400-metre quay for offshore renewables."

This quotation is important because it turns a policy ambition into a concrete capacity requirement. In scenario terms, ORE is not only a demand driver; it creates requirements for quay length, load bearing, laydown, dredging, safety arrangements, grid and access.

Decarbonisation also changes effective capacity. Shore power, alternative fuels and electric cargo-handling equipment require grid capacity, land, safety rules and operating time. One interviewee noted that the incoming grid supply to ports was an issue and that connecting two ships could use around half of it. Another argued that fuel and emissions costs could suppress demand or alter behaviour, especially in an imbalanced island market. The preliminary evidence therefore supports treating decarbonisation as a capacity variable, a cost variable and a demand-composition variable.

Resilience is a network property

Disruption examples featured prominently: Brexit, COVID-19, the Suez Canal incident, Holyhead disruption, weather closures, pilotage disruption and geopolitical shocks. One participant captured the point succinctly:

"It is a nice and simple model, the ports and shipping, until it is disrupted."

Another stressed that a port analysis for Ireland has to include 'the other side', whether Britain or continental Europe, because route resilience depends on linked corridors, not only Irish quay capacity.

This points to the need for scenario-conditioned modelling. Resilience is not simply spare capacity at one port; it is the ability of the network to absorb traffic, reroute flows, maintain service frequency and recover after shocks. The first seven interviews suggest that resilience should be measured through network recovery time, substitution options, access reliability, operational redundancy and the cost of disruption, including demurrage and diverted traffic.

Theme	Preliminary insight	Illustrative quotation	Scenario implication
Effective capacity	Capacity becomes visible when utilisation damages performance.	"If we are at 70% capacity... performance is starting to drop."	Model thresholds, not only asset totals.
Dublin and network balance	Dublin's market pull remains strong, but regional roles matter.	"The logistics companies all gravitate towards Dublin."	Test credible rebalancing rather than assumed diversion.
Delivery capacity	Planning, funding and access lead times shape whether capacity arrives.	"You have to be 10, 15 years ahead of the game."	Use delivery capacity as a scenario axis.
Energy transition	ORE and decarbonisation create new cargoes, costs and capacity demands.	"We need a 400-metre quay for offshore renewables."	Treat ORE, grid and OPS as model variables.
Resilience	Disruptions expose the networked nature of Irish port capacity.	"It is a nice and simple model... until it is disrupted."	Model substitution, recovery and disruption cost.

Table 1: Preliminary themes from the first seven DECAP 2040+ interviews

Discussion

The preliminary findings indicate that the qualitative phase is not merely preparatory; it changes what should be modelled. Capacity should be translated into operational performance thresholds and policy constraints before quantitative scenarios are run. Second, the findings support the scenario matrix. Demand intensity matters, but stakeholders repeatedly emphasised transition delivery capacity: the ability to align planning, funding, grid, access, data and institutional coordination. Third, the evidence indicates that port policy should be evaluated at network level, because local bottlenecks, shipping-line behaviour and corridor disruptions can shift demand quickly.

The findings also complicate simple rebalancing narratives. Regional ports may provide capacity, resilience and ORE opportunities, but shipping lines, hauliers and cargo owners respond to cost, frequency, journey time and service reliability. This means that national policy cannot rely on spatial aspiration alone. If rebalancing is going to be the focus, this requires credible hinterland access, digital visibility, port-specific roles, investment sequencing and incentives that reflect the national value of resilience and decarbonisation.

Conclusions

This paper set out to examine how port authorities and terminal operators define and bound capacity under conditions of deep uncertainty, and what that implies for the drivers and assumptions carried into scenario-based demand and capacity modelling. The preliminary evidence from the first seven interviews point to a consistent answer. Port actors bound capacity as a performance threshold rather than an asset inventory, treating the point at which service reliability begins to deteriorate as the operative limit rather than nominal quay length or yard area. This supports a shift from physical capacity to effective capacity, and from forecast-led modelling to scenario-conditioned analysis. It also reshapes what the modelling must carry, since utilisation thresholds, waiting and dwell times, land availability, grid and shore-power constraints, hinterland reliability and delivery times become variables rather than background conditions. On these early findings, Ireland's post-2040 port challenge will depend as much on delivery capability as on aggregate demand growth.

The paper's main limitation is that these findings draw on an initial interview set from a single stakeholder group. The analysis will be refined as further interviews are completed with shipping, logistics, energy, policy and regional stakeholders, which may qualify or extend the picture set out here. The next stage will integrate these qualitative insights with the DECAP scenario structure and capacity evaluation, before translating them into quantitative assumptions for demand forecasting and capacity-gap modelling.

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CHARTING THE COURSE TO NET-ZERO: STRATEGIES FOR MARITIME DECARBONIZATION UNDER REGULATORY AND TECHNOLOGICAL UNCERTAINTY

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Introduction

The maritime sector is under increasing pressure to decarbonize in response to global climate ambitions and emerging environmental regulations regarding sustainable transport. International shipping accounts for a large share of global greenhouse gas emissions. In recent years, the sector has faced a rapidly evolving set of regulations, such as the International Maritime Organization's (IMO) greenhouse gas strategy, the European Union's Fit for 55, FuelEU Maritime, and the EU Emissions Trading System (EU ETS). Simultaneously, technological development related to alternative fuels, electrification, digitalization, and energy efficiency has accelerated.

Despite increasing momentum toward decarbonization, maritime actors, such as ports and shipping lines, continue to face regulatory and technological uncertainty. Shipping lines must make long-term investment and operational decisions in contexts where future fuel pathways, infrastructure requirements, regulatory frameworks, and market conditions remain unclear. Competing alternatives such as methanol, ammonia, hydrogen, LNG, biofuels, electrification, and energy-efficiency solutions are developing simultaneously, yet differ in terms of technological maturity, infrastructure, and market readiness. At the same time, evolving regulations and unclear governance structures make it difficult for maritime actors to plan long-term investments and strategic priorities (Styhre et al., 2026).

These uncertainties are particularly challenging because maritime decarbonization entails highly capital-intensive investments with long asset lifetimes and substantial risks of technological lock-in. Decisions concerning vessels, bunkering infrastructure, and electrification may shape operations for decades. Consequently, shipping lines must make careful decisions to maintain strategic flexibility under deep uncertainty to future-proof their operations.

Existing research on maritime decarbonization has examined how environmental regulation and institutional pressures shape sustainability transitions in shipping and port operations (Styhre et al., 2026), while other studies have emphasized the importance of fuel availability, infrastructure development, stakeholder coordination, and regulatory frameworks for enabling the adoption of alternative fuels (Balci et al., 2024). Research has also shown that although a wide range of energy-efficiency and low-carbon solutions is available, their implementation is often constrained by economic, organizational, and market-related barriers (Rehmatulla and Smith, 2015). Collectively, these studies provide important insights into decarbonization pathways and barriers, but less attention has been paid to how maritime organizations make strategic decisions amid regulatory and technological uncertainty. As a result, there remains limited empirical understanding of how shipping companies and ports navigate uncertainty as they prioritize investments and develop long-term decarbonization strategies.

This paper addresses this gap by examining how shipping companies navigate decarbonization-related decision-making under regulatory and technological uncertainty. The study draws on semi-structured interviews with senior managers, technical directors, and executives from European shipping companies.

The paper adopts a real options lens to analyze organizational decision-making under uncertainty. Real options theory suggests that under conditions of uncertainty and irreversible investment costs, organizations seek to preserve flexibility through staged investments, experimentation, adaptive strategies, and delayed commitment to lock-ins (Trigeorgis and Reuer, 2017). This perspective is particularly relevant for maritime decarbonization, where actors face uncertainty regarding future fuels, infrastructure standards, and regulatory developments.

Theoretical lens: Real options theory and decision-making under uncertainty

This chapter introduces the theoretical lens for analyzing decision-making under uncertainty in maritime decarbonization. The chapter first outlines the key principles of real options theory and then explains the mechanisms through which organizations manage uncertainty.

Real options theory

Real options theory provides a useful lens for understanding organizational decision-making under uncertainty (Trigeorgis and Reuer, 2017). Originally developed to explain investment decisions under uncertain futures, the theory argues that when investments are costly, largely irreversible, and subject to uncertain outcomes, organizations derive value from maintaining strategic flexibility. Hence, real options theory suggests that uncertainty increases the value of preserving future choices until additional information becomes available.

An important assumption of this theory is that organizations actively respond to uncertainty by adopting strategies that preserve flexibility and reduce exposure to irreversible commitments. Organizations may choose to defer investments until uncertainty decreases, thereby avoiding commitments to investments that may prove unfavorable later. They may also pursue staged investments, where smaller-scale initiatives are undertaken to generate information and learning before larger commitments are made. Such strategies enable organizations to balance progress with caution in situations where future conditions are unknown.

In contexts characterized by competing technologies and uncertain market developments, such as maritime fuel developments, maintaining multiple future options may be more valuable than pursuing a seemingly optimal solution based on current information. The theory, therefore, shifts attention from choosing the “best” alternative to keeping all doors open as uncertainty decreases.

Strategic responses to uncertainty

Trigeorgis and Reuer (2017) identify several mechanisms through which organizations can manage uncertainty. One such mechanism is deferral, which means postponement of irreversible investments until there is greater clarity about future market, technological, or regulatory conditions. A second mechanism involves staged investments, where pilot projects, demonstration initiatives, or incremental investments are used to generate learning while limiting risk. A third mechanism involves preserving flexibility through investments that maintain the ability to switch between future pathways (“doors”) as conditions change.

Real options theory also highlights that investment decisions often extend beyond the boundaries of a single organization. The value of an investment may depend on complementary investments undertaken by other actors, creating what Trigeorgis and Reuer (2017) describe as interacting or compound options. Such situations are highly relevant in maritime decarbonization, where investments in vessels, fuel production, bunkering infrastructure, and port facilities are highly interdependent. Consequently, organizations must not only navigate uncertainty about technologies and regulations, but also about the actions and commitments of ecosystem actors.

In this study, we draw on real options theory to explain how maritime actors make decarbonization-related decisions under conditions of uncertainty. Specifically, we use the theory to interpret the strategic responses identified in the empirical material, including delaying major commitments, investing incrementally through pilot projects, preserving flexibility across technologies, and prioritizing low-regret investments. Real options theory provides a framework for understanding how ports and shipping lines manage uncertainty while pursuing decarbonization objectives.

Research design

We adopt a qualitative research design to explore how shipping companies make decarbonization-related investment decisions amid technological and regulatory uncertainty. Given the exploratory nature of the research and the need to understand managerial decision-making processes, semi-structured interviews were selected as the primary data collection method.

Empirical data were collected through eight semi-structured interviews conducted between November and December 2025 with representatives from leading shipping companies operating in different maritime segments. The sample included container shipping, tanker shipping, RoRo and RoPax shipping. Respondents held senior positions related to sustainability, fleet management, technical development, operations, and strategic decision-making. The interviews focused on decarbonization strategies, energy-efficiency measures, investment decision-making, regulatory and technological uncertainty, and future fuel pathways.

All interviews were recorded, transcribed verbatim, and analyzed using thematic analysis. Initial coding was guided by the interview protocol and concepts derived from real options theory, including uncertainty, flexibility, staged investments, and option preservation. The analysis focused on identifying common patterns regarding sources of uncertainty and the strategic responses employed by shipping companies.

Findings

The findings reveal that shipping companies operate in an environment characterized by multiple and interrelated sources of uncertainty. Respondents consistently described uncertainty related to future regulations, fuel and technology development, and the actions of other actors within the maritime ecosystem. At the same time, the interviews showed that shipping companies have developed various strategies to navigate these uncertainties while continuing to progress toward decarbonization objectives. Accordingly, the findings are structured around (1) the sources of uncertainty influencing decarbonization decisions and (2) the strategic responses adopted to manage these uncertainties.

Sources of uncertainty

The empirical findings indicate that shipping companies operate in an environment characterized by substantial uncertainty. Three interrelated sources of uncertainty were particularly prominent across the interviews: regulatory uncertainty, technological and fuel uncertainty, and ecosystem uncertainty. These uncertainties shape strategic decision-making and influence both the timing and nature of decarbonization investments.

Regulatory uncertainty emerged as one of the most frequently discussed challenges. Respondents highlighted the increasing influence of the EU ETS, FuelEU Maritime, and IMO climate regulations on strategic decision-making. While these regulations provide direction for decarbonization, respondents emphasized that uncertainty remains regarding future policy developments, implementation details, compliance costs, and the long-term competitiveness of different technologies. Several respondents noted that vessel investments typically extend over 20–30 years, making it difficult to assess whether current investment decisions will remain compliant and economically viable throughout the asset lifecycle. As a result, many shipping lines expressed caution regarding irreversible investments until there is greater regulatory clarity.

A second source of uncertainty concerned future fuel pathways and the development of alternative fuel and propulsion technologies. Respondents consistently stated that there is no clear consensus within the shipping industry regarding the dominant fuel for future shipping. While electrification was widely viewed as suitable for short-sea shipping and land-based operations, respondents also discussed methanol, ammonia, hydrogen, biofuels, batteries, and wind-assisted propulsion as potential fuel pathways. The suitability of these alternatives was perceived to depend on vessel type, route characteristics, infrastructure availability, technological maturity, and future regulation. Several respondents emphasized that the rapid pace of technological development makes it difficult to commit to a single pathway, particularly given the risk of technological lock-in.

A third source of uncertainty concerned the broader maritime ecosystem. Respondents also highlighted uncertainty arising from the interdependent nature of maritime decarbonization. Investment decisions were often described as dependent on actions taken by ports, fuel suppliers, regulators, customers, and technology providers. Several respondents noted that shipping companies are reluctant to invest in alternative-fuel vessels without confidence that bunkering infrastructure will be available, while ports and infrastructure providers hesitate to invest without sufficient market demand. Port representatives similarly emphasized challenges related to permitting processes, stakeholder coordination, safety requirements, and land-use constraints. These dependencies create uncertainty regarding the timing and scale of investments across the maritime ecosystem.

Strategic responses to uncertainty

One common response to uncertainty was the postponement of major investment commitments. Rather than committing to a specific fuel pathway or large-scale infrastructure investment, many respondents adopted a wait-and-see approach while monitoring technological, regulatory, and market developments. They also indicated that investments in fuel infrastructure, alternative-fuel vessels, and large-scale technological transitions were delayed until stronger market signals and regulatory certainty became available. This approach was particularly evident regarding ammonia and hydrogen, where respondents acknowledged potential future importance but emphasized that significant uncertainties remain.

Experimenting through pilots

Instead of making large, irreversible investments, many shipping lines pursued pilot projects and demonstration initiatives. Respondents described ongoing experimentation with battery-electric vessels, hydrogen projects, wind-assisted propulsion technologies, digital optimization systems, and alternative-fuel trials. Pilot projects were viewed as opportunities to generate learning, reduce uncertainty, develop internal competencies, and evaluate future business potential while limiting financial exposure. These initiatives enabled organizations to explore emerging technologies without committing fully to a single long-term solution.

Preserving flexibility

Instead of making large, irreversible investments, many of the shipping lines pursued pilot projects and demonstration initiatives. Respondents described ongoing experimentation with battery-electric vessels, hydrogen projects, wind-assisted propulsion technologies, digital optimization systems, and alternative-fuel trials. Pilot projects were viewed as opportunities to generate learning, reduce uncertainty, develop internal competencies, and evaluate future business potential while limiting financial exposure. These initiatives enabled organizations to explore emerging technologies without committing fully to a single long-term solution.

Prioritizing “low-regret” investments

Across all interviews, energy-efficiency measures emerged as the most widely adopted decarbonization strategy. Respondents consistently highlighted engine optimization, speed management, digital monitoring systems, battery integration, and improved energy management as investments that generate immediate economic and environmental benefits regardless of future fuel developments. Unlike alternative-fuel investments, these measures were perceived as carrying limited risk because they reduce fuel consumption, lower emissions, and improve competitiveness under multiple future scenarios. Consequently, energy-efficiency initiatives were frequently prioritized by the shipping lines while they awaited greater certainty regarding future fuel pathways.

Discussion

The findings indicate that shipping lines respond to different forms of uncertainty by adopting strategies that preserve flexibility. In Table 1, we interpret the empirical findings through the theory of real options. The chapter is structured according to the themes in the table.

Discussion theme	Empirical evidence	Real options interpretation	Contribution
Uncertainty increases the value of flexibility	Regulatory uncertainty, competing fuel pathways, infrastructure uncertainty, long asset lifetimes	High uncertainty increases the value of maintaining future strategic choices rather than committing prematurely	Explains why shipping lines hesitate to commit to specific fuels and technologies despite decarbonization pressure
Shipping lines preserve flexibility through option-like strategies	Delaying investments, pilot projects, fuel-ready vessels, technology trials, adaptable solutions	Deferral, staged investments, and switching options enable firms to reduce downside risk while retaining future opportunities	Shows how shipping lines actively manage uncertainty rather than simply delaying decarbonization
Decarbonization involves interdependent options	Dependence on fuel suppliers, ports, customers, technology providers, and regulators when making investment decisions	The value of investments depends on complementary actions by other actors, resembling compound or interdependent options	Highlights that decarbonization decisions are shaped by both firm-level uncertainty and by expectations regarding the actions of ecosystem partners

Table 1: Interpreting shipping lines' decarbonization decision-making through real options theory

The findings demonstrate that maritime decarbonization decisions are shaped by regulatory uncertainty, technological and fuel uncertainty, and ecosystem uncertainty. Drawing on Real Options Theory, the results suggest that uncertainty does not simply act as a barrier to investment. Instead, uncertainty increases the value of strategic flexibility and influences how shipping companies approach decarbonization-related decisions. Rather than committing immediately to irreversible investments, firms seek to preserve future choices while continuing to make progress through lower-risk initiatives.

Uncertainty increases the value of flexibility

The findings indicate that regulatory and technological uncertainty increase the importance of maintaining flexibility in decarbonization strategies. Respondents highlighted uncertainty regarding future regulations, fuel pathways, infrastructure availability, safety standards, and technology maturity. Given the long lifespan of vessels and the significant capital investments involved, organizations were reluctant to commit to a single technological pathway too early. Instead, many respondents emphasized the importance of keeping multiple future options open until stronger market signals and greater regulatory clarity emerge. This finding is consistent with real options theory (Trigeorgis and Reuer, 2017), which argues that uncertainty increases the value of preserving future decision alternatives. When investments are costly and difficult to reverse, delaying commitment can reduce downside risk while allowing organizations to benefit from future learning and market developments. In the context of maritime decarbonization, uncertainty therefore encourages strategic flexibility rather than immediate commitment to a specific fuel or technology pathway.

This finding complements recent optimization-based studies that examine fleet transition pathways under uncertain fuel prices, carbon costs, and market conditions. For example, Wang and Iris (2025) demonstrate that no single alternative fuel dominates across future scenarios and that fleet renewal strategies remain are sensitive to evolving economic and regulatory conditions. While Wang and Iris (2025) identify economically optimal fleet transition pathways under uncertainty, our findings provide insight into how shipping lines interpret and respond to these uncertainties in practice. Rather than attempting to identify a single optimal pathway, respondents emphasized maintaining flexibility until stronger signals regarding fuel availability, regulation, and infrastructure are in place.

Shipping lines preserve flexibility through option-like strategies

The findings further demonstrate that shipping companies actively preserve flexibility through a range of option-like strategies. These include delaying major investments, conducting pilot projects, investing in demonstration initiatives, adopting fuel-ready technologies, and designing vessels that can accommodate future technological modifications.

Rather than pursuing large-scale transitions immediately, many respondents preferred incremental approaches that generated learning while limiting financial exposure. Pilot projects involving batteries, hydrogen, wind-assisted propulsion, alternative fuels, and digital optimization technologies allowed firms to explore future opportunities without making irreversible commitments. Similarly, investments in adaptable vessel designs and fuel-ready engines enabled organizations to maintain the ability to switch pathways as technologies and regulations evolve.

These findings closely align with the central mechanisms proposed by Real Options Theory. Deferral strategies allow organizations to postpone commitments until uncertainty decreases, while staged investments generate information and learning that can support future decision-making. Switching options preserve adaptability by enabling organizations to respond to future technological and regulatory developments. These strategies illustrate how maritime actors manage uncertainty while advancing decarbonization objectives.

Maritime decarbonization involves interdependent options

A particularly important finding concerns the interdependent nature of maritime decarbonization investments. Respondents consistently described situations in which investment decisions depended on complementary actions by other actors within the maritime ecosystem. Shipping companies often delayed investments in alternative-fuel vessels until fuel infrastructure became available, while ports hesitated to invest in infrastructure until sufficient vessel demand emerged. Similar dependencies were observed between fuel producers, regulators, technology providers, and customers.

From a real options perspective, these investments can be understood as compound or interdependent options, where the value of one investment depends on the realization of complementary investments by other actors. Consequently, maritime actors cannot exercise decarbonization options independently. Instead, investment decisions become interconnected across the broader ecosystem, creating coordination challenges and mutual waiting behaviour.

This finding extends previous research on maritime decarbonization by highlighting that uncertainty is not limited to technology and regulation alone. The actions of ecosystem actors also influence investment timing and strategic decision-making. As a result, successful decarbonization requires technological innovation and supportive regulation, as well as greater coordination across the maritime value chain. These findings align with recent research emphasizing the interdependent nature of maritime decarbonization. Styhre et al. (2026), for example, argue that the transition depends on coordinated development across shipping companies, ports, fuel suppliers, and transport purchasers, and identify misalignments between these actors as an important barrier to implementation. Our findings support this view and further suggest that these interdependencies influence organizational decision-making by creating uncertainty. Respondents frequently described postponing investments because the realization of expected benefits depended on complementary actions by other actors. As a result, uncertainty extended beyond technological and regulatory developments to include future investments, infrastructure development, fuel availability, and long-term commitments from ecosystem partners.

Conclusions

This study contributes to the maritime decarbonization literature by examining how shipping companies make strategic

decisions under conditions of uncertainty. The findings show that maritime actors face multiple sources of uncertainty related to regulations, technologies, fuels, and ecosystem dependencies. Rather than responding through immediate large-scale investments, organizations adopt strategies that preserve flexibility, including delaying commitments, conducting pilot projects, maintaining switching options, and prioritizing low-regret investments such as energy-efficiency measures.

The study further demonstrates the usefulness of real options theory for understanding maritime decarbonization decision-making. The findings reveal that uncertainty increases the value of flexibility, encourages the use of option-like strategies, and creates interdependencies between investments across the maritime ecosystem. Maritime decarbonization should therefore be understood not only as a technological transition but also as a strategic process of managing uncertainty while preserving future opportunities.

From a practical perspective, the findings suggest that clearer regulatory signals and stronger coordination among ports, shipping companies, fuel suppliers, and infrastructure providers could reduce uncertainty and accelerate investment decisions. Future research could further explore how different maritime actors coordinate complementary investments and how ecosystem-level governance mechanisms can support the transition toward net-zero shipping.

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DIESEL AND HYDROGEN ENERGY TRANSITION ANALYSIS FOR TRUCKS IN SEAPORT

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Abstract

Growing concerns over greenhouse gas (GHG) emissions and air pollution have intensified the need for cleaner transportation solutions in seaport operations. As diesel-powered trucks remain a major source of air pollution and carbon emission within ports, stakeholders are increasing exploring alternatives energy sources, including hydrogen, to promote sustainable and low-carbon freight transportation. This study evaluates the feasibility of hydrogen as a primary energy source for truck operating in seaport and identifies the technical and logistical challenges associated with its implementation. A quantitative research approach was adopted using a structured questionnaire survey distributed to stakeholders involved in porta transportation and logistics, including logistics coordinators, port authority representatives, fleet managers, fuel suppliers, and sustainability officers. Purposive sampling was employed to obtain responses from individuals with relevant industry expertise, while the collected data were analysed using descriptive statistical methods. The findings reveal a generally positive perception towards the adoption of hydrogen-powered trucks, as most respondents considered hydrogen a viable future energy source capable of supporting heavy cargo transportation and demanding operational tasks. However, several challenges remain, including safety concerns related to hydrogen storage and containment, fuel cell reliability, supply chain readiness, transportation logistics, storage capacity, and fuel price volatility. The study is limited by its relatively small sample size and reliance on stakeholder perceptions rather than real operational data. Future research should involve larger sample sizes, comparative port case studies, and economic feasibility assessments to provide a more comprehensive understanding of hydrogen integration in seaport transportation systems.

Keywords: Hydrogen fuel, energy transition, seaport logistics, and sustainable transportation

1. Introduction

Seaports serve as essential nodes in worldwide supply chains, making the marine industry critical to global trade. However, growing concerns over climate change and environmental sustainability have intensified pressure on the industry to minimize greenhouse gases (GHGs) emissions and air pollution. Among port-related operations, heavy-duty trucks used for cargo and container transportation contribute significantly to port emissions due to their dependency on diesel fuel (Yu et al., 2025). According to the International Maritime Organization (IMO, 2023), diesel-powered vehicles working in ports continue to contribute significantly to coastal air pollution, emphasizing the need for cleaner transportation alternatives.

Previous studies have demonstrated the environmental impacts of diesel-powered transportation in port environments. Terminal tractors and other land-based vehicles have been identified as major sources of carbon emissions at container terminals, generating 0.011335 tCO2e every twenty-foot equivalent unit (TEU) handled (Kara et al., 2022; Okşaş 2023). In reducing the carbon dioxide (CO2), nitrogen oxide (NO2), and particulate matter emissions, stricter vehicle emission requirements and replacing older diesel vehicles are required (Zhao et al., 2024). These findings highlight the needs of exploring alternative energy sources that can support sustainable freight transportation in seaport operations.

Hydrogen has emerged as a possible alternative fuel for heavy-duty vehicles since it can significantly reduce emissions while creating only water as a byproduct during operation (Qazi, 2025). Nonetheless, the adoption of hydrogen-powered trucks remains constrained by issues such as refuelling infrastructure, fuel storage, safety, and supply chain readiness. Hence, the purpose of this study is to evaluate the feasibility of hydrogen fuel as a primary energy source for trucks operating at seaports and to assess the technical and logistical challenges associated with its deployment. The findings are expected to provide valuable insights for port authorities, policymakers, and industry stakeholders seeking to advance sustainable and low-carbon port transportation systems. The remainder of this paper presents the literature review, methodology, results and discussion, and conclusion.

2. Literature Review

2.1 Diesel-Powered Truck Operations in Seaports

Diesel fuel remains the primary energy source for heavy-duty freight transportation due to its high energy density, operational dependability, and well-established refuelling infrastructure (International Energy Agency, 2023). Diesel-powered trucks are widely employed for cargo and container transportation at seaports due to their ability to sustain long operating hours and heavy payload requirements. The increasing availability of diesel supply chains reinforces its position in freight transportation systems (Saidi, 2023).

Despite these benefits, diesel dependence poses considerable environmental risks. Diesel combustion emits pollutants such as NOx, SOX, particulate matter (PM), and CO2, leading to air pollution and climate change (de Vries, 2021). According to Agarwala and Saengsupavanich (2023), continuous truck movements, engine idling, and container handling activities increase the noise levels in port locations, harming both neighbouring residents and natural ecosystems. Heavy-duty vehicles contribute disproportionately to transportation-related emissions, accounting for a significant fraction of GHG emissions, although making up a small proportion of total cars on the road (Gentilucci et al, 2025).

2.2 Hydrogen as an Alternatives Energy Source for Freight Transportation

Hydrogen has emerged as a promising alternative fuel for enabling low-carbon transportation systems, as it offers high energy content and produces only water as a by-product when used in fuel cells (Dawood et al., 2020). Hydrogen production can be achieved through several methods, including electrolysis, steam methane reforming, and biomass gasification, with renewable-powered electrolysis considered the most environmentally sustainable option (Hou & Yang, 2024). Furthermore, increasing government support and technological advancement are expected to accelerate hydrogen adoption across transportation sectors (Smolinka & Garche, 2021).

Hydrogen-powered trucks have various advantages, including zero tailpipe emissions, high energy density, and ranges equivalent to conventional diesel vehicles (Cunanan et al., 2021; Roy et al., 2024). Compared to battery-electric alternatives, hydrogen fuel systems have a higher energy density per mass, making them ideal for freight applications that demand long-distance operations and high payload capabilities. Furthermore, advancements in hydrogen storage technologies and renewable hydrogen production pathways continue to enhance the viability of hydrogen-powered transportation systems (Anand et al., 2025).

2.5 Transition from Diesel to Hydrogen in Seaport Trucking

From an environmental perspective, hydrogen fuel offers substantial emission reductions and contributes to achieving global decarbonization objectives (Mio et al., 2025). However, economic and infrastructure challenges remain severe. Hydrogen-powered trucks are not yet fully cost-competitive with diesel alternatives due to high vehicle purchase prices, hydrogen production costs, and insufficient refuelling infrastructure (Danielis et al., 2024). Nevertheless, forecasts indicate that lower hydrogen production costs and technology developments could significantly increase hydrogen trucks' economic competitiveness beyond 2030 (Burke et al., 2024). Thus, the shift to hydrogen-powered freight transportation is likely to necessitate ongoing technological innovation, supportive policy frameworks, and deliberate investments in hydrogen infrastructure.

3. Methodology

3.1 Research Design

This study adopts a quantitative research design to assess the potential transitions from diesel-powered trucks to hydrogen-powered trucks in seaport operations. Quantitative methods are appropriate for examining stakeholder perceptions and determining factors influencing the adoption of hydrogen fuel technology in the maritime logistics sector. According to Caesar (2024), quantitative approaches offer a systematic method of gathering measurable data to assist in objective analysis and decision-making. Data were obtained using a structured questionnaire survey and evaluated using descriptive statistical techniques to identify patterns and trends related to hydrogen energy adoption.

The research framework was developed to provide a systematic approach for analyzing the transition from diesel to hydrogen fuel in seaport trucking operations. The study begins with identifying the research problem, followed by the formulation of research objectives and development of appropriate data collection instruments (Figure 1).

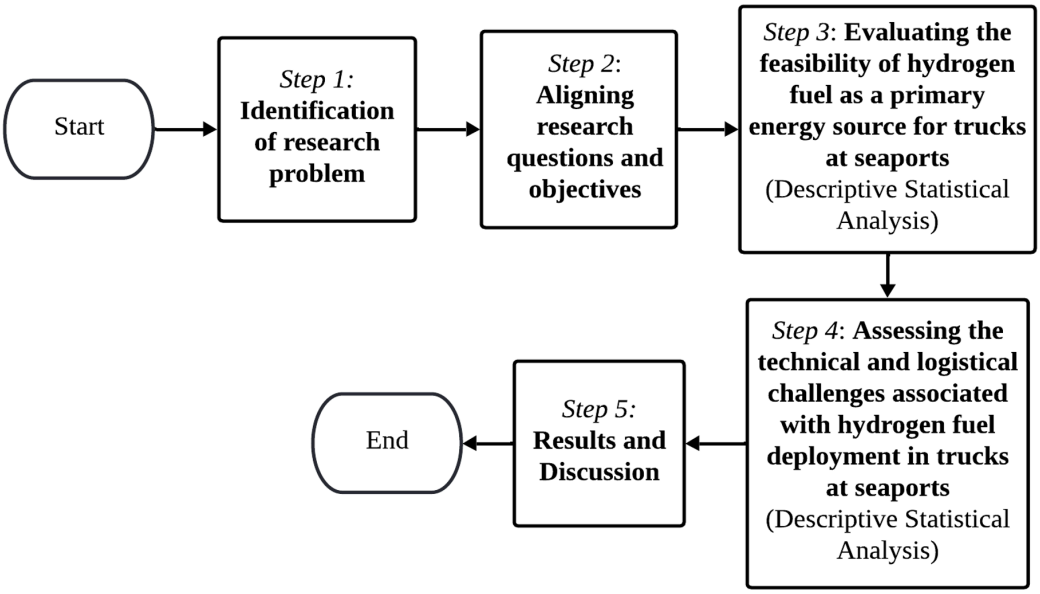


Figure 1: Research Framework of Hydrogen Energy Transition Analysis for Truck in Seaport

Next, the framework addresses the two research objectives through questionnaire-based data collection and descriptive statistical analysis. The findings are then used to assess the viability of hydrogen fuel adoption and identify significant deployment challenges. Finally, conclusions and recommendations are developed to aid future decision-making related to sustainable port transportation systems.

3.3 Data Collection and Sampling

Primary data were collected through an online questionnaire survey targeting stakeholders involved in seaport transportation and logistics activities. The questionnaire was designed to obtain respondents' perspective on the feasibility, operational performance, economic viability, safety, an infrastructure readiness of hydrogen-powered trucks.

Purposive sampling was employed to ensure that responses were obtained from individuals with relevant expertise and experience in port operations, freight transportation, and alternatives fuel technologies. Oosterhuis (2025), stated that purposive sampling enables researcher to choose individuals who can provide useful information relevant to the study objectives. The target respondents included port authorities, transportations companies, hydrogen fuel suppliers, equipment manufacturers, policymakers, and industry practitioners. These stakeholders were chosen as they have direct involvement with operational, technical, and policy elements of freight transportation and energy transition initiatives within seaport environments.

3.5 Data Analysis

The collected data were analysed using descriptive statistical methods. Descriptive statistics provide a systematic method for organizing, summarizing, and presenting quantitative data in an understandable manner. This technique enables the identification of response patterns, central tendencies, and relative importance of factors influencing hydrogen fuel adoption.

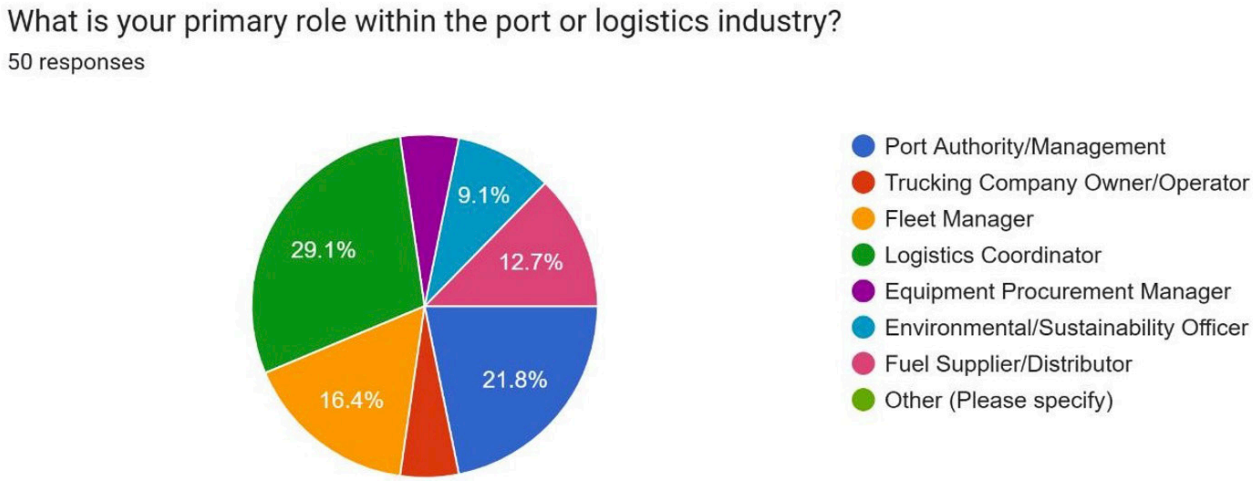
Frequency distributions, percentages, mean scores, and response rankings were used to evaluate stakeholder opinions on the feasibility of hydrogen fuel and the challenges affecting their implementation. The findings provide a practical framework for analyzing the sector's readiness to support a transition to cleaner energy alternatives.

4. Results and Discussion

4.1 Respondent Profile

50 respondents involving logistics coordinators, port authority representatives, fleet managers, fuel suppliers, and sustainability officers were involved in this study. Logistics coordinators represent most of the respondent's group (29.1%), followed by port authority/management workers (21.8%), and fleet managers (16.4%). The diverse range of respondents provides a thorough industry viewpoint on the transition from diesel-powered trucks to hydrogen-powered alternatives in seaport operations (Figure 2).

Figure 2: Respondents Background



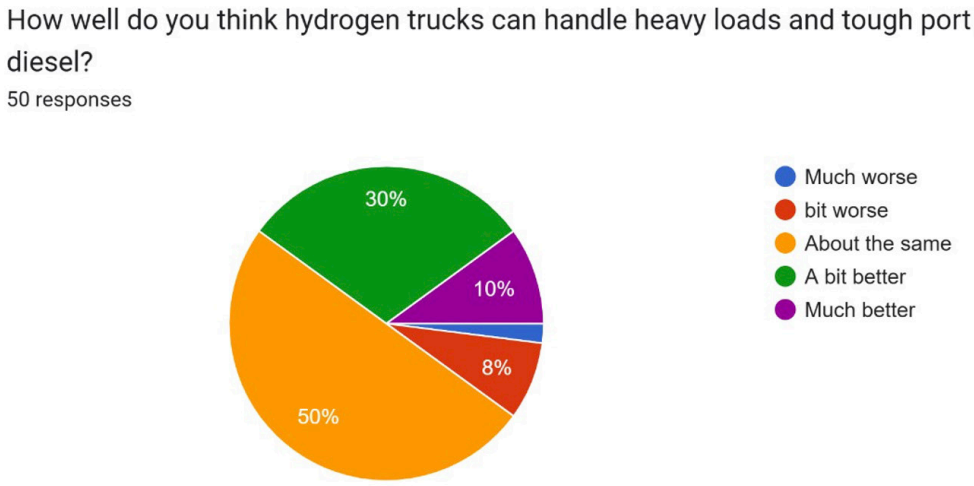
The findings also show that respondents had significant industrial experience. More than half of the respondents (56%) reported having six to ten years of experience, with 28% having eleven to twenty years of experience. The involvement of high-level professional experience strengthens the credibility of responses, as participants are likely familiar with operational requirement, fuel management practices, and infrastructure challenges within port environments.

4.2 Feasibility of Hydrogen as a Primary Energy Source for Seaport Trucks

The findings reveal a cautiously optimistic outlook regarding the future adoption of hydrogen-powered trucks in seaports. Most of the respondents considered hydrogen likely (32%) or very likely (13%) to become an energy source within the next decade, while 34% remained neutral. The acknowledgement by industry stakeholders shows there is potential for hydrogen technology, but they remain uncertain about the rate of technological development and infrastructure readiness required for large-scale deployment.

Perception of vehicle performance contributes to the practicality of hydrogen adoption. Approximately 50% of respondents expressed that hydrogen-powered trucks will perform comparably to diesel-powered vehicles when handling heavy cargo and performing difficult port duties (Figure 3). Meanwhile, 40% of the respondents perceived hydrogen trucks to perform somewhat or significantly better than diesel vehicles. These findings indicate that performance capability is not viewed as a major obstacle to adoption, indicating a confidence in the operational suitability of hydrogen-powered trucks for seaport logistics activities.

Figure 3: Hydrogen-Powered Trucks vs. Diesel-Powered Trucks: Perceived Performance

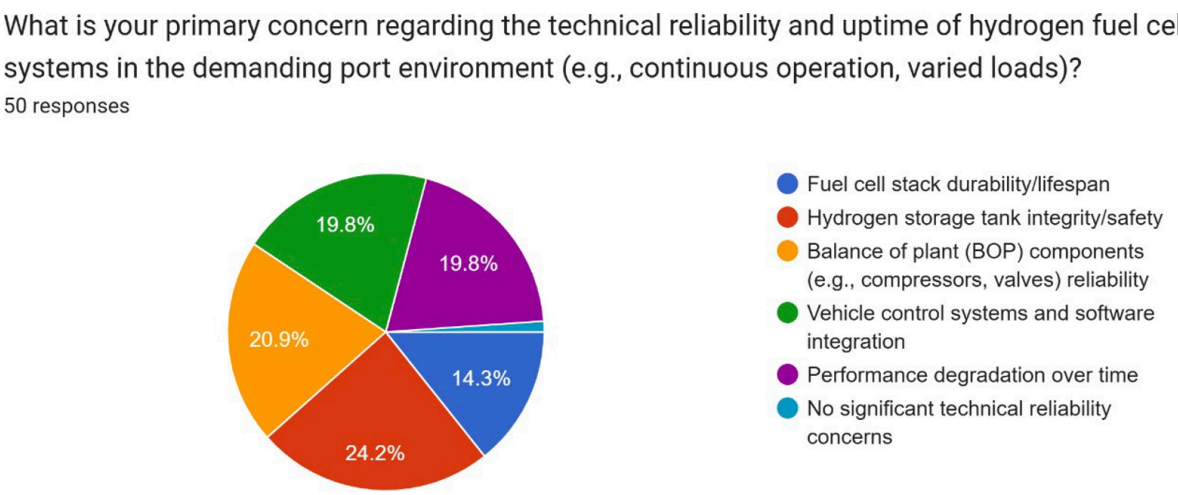


4.3 Safety and Technical Reliability Concerns

Despite positive perceptions regarding feasibility, respondents identified several technical challenges that could hinder implementation. Safety concerns appeared as the most pressing issue, with 24.2% of respondents expressing concerns about hydrogen containment and storage technologies (Figure 4). Due to the nature of hydrogen, which is highly combustible, stringent safety measures are required, making containment reliability crucial in gaining stakeholders' confidence.

Another concerning issue involving fuel cell durability (19.8%), balance-of-plant components (20.9%), and vehicle control system integration (14.3%). These findings indicate that respondents are not only concerned with fuel storage safety but also with the long-term operational reliability of hydrogen-powered vehicles. Since seaport operations require high equipment availability and low downtime, consistent fuel cell performance and system integration are essential for successful implementation.

Figure 4: Hydrogen Fuel Cell Concerns

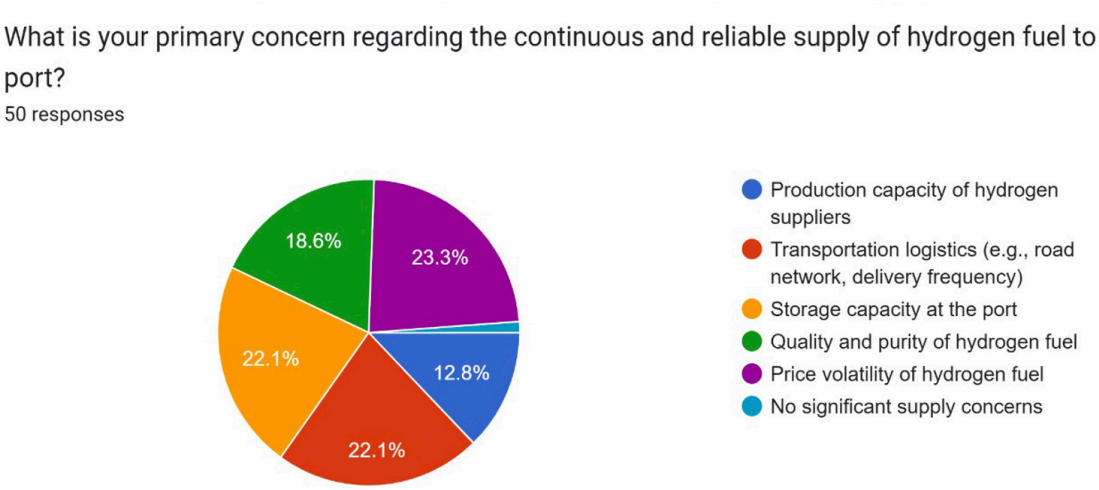


4.4 Supply Chain and Economic Challenges

Another significant issue affecting the transition process was the reliability of hydrogen supplies. Hydrogen price volatility has emerged as the most major concern, accounting for 23.3% responses (Figure 5). Transportation logistics and on-site storage capacity were both identified as key challenges, accounting for 22.1% of response.

This study implies that uncertainty about fuel costs could hinder investment decisions and hamper long-term operational planning for operators and logistics companies. Besides, there is a need for creating a fully integrated hydrogen supply chain capable of ensuring continuous fuel availability. Without reliable transportation networks and suitable storage facilities, operational disturbance could jeopardize the effectiveness of hydrogen-powered truck fleets in port settings.

Figure 5 Primary Concern of Hydrogen Fuel Supply



Overall, the findings indicate that hydrogen-powered trucks have significant potential to support the decarbonization of maritime transportation operations. Most of the respondents respond positively to the operational performance of hydrogen trucks and acknowledge the availability of space for future fuelling facilities. These data suggest that the technological viability of hydrogen adoption is increasingly recognized in the industry. However, the transition remains constrained by significant technical, economic, and logistical obstacles. Therefore, while hydrogen technology shows promise as an alternative to diesel fuel, its effective implementation will depend on improvements in infrastructure deployment, supply chain reliability, regulatory clarity, safety assurance, and operational planning.

5. Conclusion

This study examined the feasibility of transitioning from diesel-powered trucks to hydrogen-powered trucks in seaport operations while identifying the technical challenges associated with hydrogen deployment. The findings indicate that industry stakeholders acknowledge the potential of hydrogen as a cleaner alternative fuel that supports the decarbonization of port transportation activities. Respondents demonstrated positive perceptions regarding the operational performance of hydrogen-powered trucks, indicating that vehicle capabilities are unlikely to be a major challenge to adoption. These findings highlight the growing recognition of hydrogen technology as a potential solution towards sustainable freight transportation in seaport environments.

While it appears to have a promising potential, several challenges hinder the implementation of hydrogen-powered trucks. Safety concerns related to hydrogen storage and containment, fuel cell durability, supply chain reliability, transportation logistics, storage capacity, and hydrogen price volatility were recognized as critical barriers. To enable widespread adoption, reliable refuelling infrastructure, stable hydrogen supply networks, supportive regulatory frameworks, and improved safety standards would be required. This study's limitations include a small sample size and dependence on stakeholder views rather than real operational data from hydrogen-powered vehicle deployment. Furthermore, the combination of selective sampling and descriptive statistical analysis may reduce the conclusion generalizability. Future research may broaden the

scope of the investigation by incorporating larger sample sizes, comparative port case studies, and economic feasibility assessments to provide a more comprehensive understanding of hydrogen integration in seaport transportation systems.

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HOW TECHNOLOGY ADOPTION UNLOCKS THE SUSTAINABILITY VALUE OF RESILIENCE CAPABILITIES IN MULTI-TIER EV SUPPLY CHAINS

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1. Introduction

The rapid expansion of the global electric vehicle (EV) industry has transformed upstream raw-material sourcing, battery manufacturing, and downstream assembly, positioning China as a central actor in this transition. Evidence indicates that this growth has resulted in a complex, multi-tier supply chain architecture extending beyond original equipment manufacturers (OEMs) to Tier-3 suppliers, thereby increasing the potential for disruption propagation and systemic vulnerability in the face of geopolitical decoupling, raw-material constraints, and natural hazards (Zhong & Um, 2024; Nayal et al., 2023; Ivanov, 2021; Birkel & Hartmann, 2020). Consequently, EV firms encounter a dual imperative: to enhance supply chain resilience (SCR) while achieving sustainable supply chain performance (SSCP) across economic, environmental, and social dimensions (Wieland & Durach, 2021; Jain et al., 2024; Ooi et al., 2025; Cui et al., 2022).

Analysis of paired multi-tier data from 413 firms demonstrates that resilience capabilities, defined as supply chain visibility and supply chain collaboration, are positively associated with higher SSCP. However, the magnitude and consistency of these effects vary, which may explain the mixed findings reported in previous studies (Cui et al., 2022; Ooi et al., 2025). The results highlight a 'conversion black box,' wherein investments in visibility and collaboration do not consistently yield measurable sustainability improvements when supply chains lack transparency, information asymmetry exists across tiers, and coordination costs increase in lower-tier relationships (Sinkovics et al., 2021; Adlakha, 2026). This phenomenon is especially pronounced in EV supply chains, where significant environmental and social risks originate upstream, such as in mining and component sub-suppliers, and are insufficiently managed by focal-firm routines (Sinkovics et al., 2021; Chowdhury et al., 2021).

Digital technology adoption serves as a moderating factor in the relationship between resilience and sustainability. In line with Information Processing Theory, digital tools such as IoT, big data analytics, cloud computing, and blockchain enhance information-processing capacity and facilitate more agile, higher-quality decision-making cycles. This transformation enables visibility and collaboration to function as dynamic, value-creating capabilities rather than static resources (Bag et al., 2021; Dubey et al., 2021; Zhou et al., 2024). From the perspectives of the Resource-Based View (RBV) and Dynamic Capabilities Theory, digital technology acts as a boundary condition that accounts for the divergent sustainability outcomes observed among firms with varying levels of digital maturity, despite similar resilience investments (Amui et al., 2020; Bouloiz, 2020). In practice, resilience initiatives that lack concurrent digital infrastructure development tend to produce weaker sustainability outcomes, whereas digitally enabled visibility and collaboration facilitate more credible monitoring, flexible exception handling, and more reliable cross-tier alignment.

From a managerial perspective, the findings suggest that OEMs should regard digital adoption as essential for effective ESG implementation and leverage digital platforms to disseminate standards, data interfaces, and traceability practices to upstream small and medium-sized enterprises (SMEs), thereby mitigating 'weak-link' vulnerabilities across supply chain tiers (Bag et al., 2021; Dubey et al., 2021). By expanding the unit of analysis from the focal firm to the multi-tier network, this study addresses focal-firm bias and demonstrates that sustainable value creation relies on digitally enabled coordination throughout the entire EV supply chain (Sinkovics et al., 2021; Zhong & Um, 2024).

2. Literature Review and Theoretical Framework

2.1 Supply Chain Resilience and Sustainability

SCR has evolved from a reactive recovery mechanism to a proactive strategic capability that is critical for managing global volatility. SCR is conceptualized as a multidimensional construct, with visibility, defined as the capacity to track products and information across supply chain tiers, and collaboration, characterized by joint planning and problem-solving with partners, serving as foundational elements (Wieland & Durach, 2021; Jain et al., 2024). Visibility facilitates early risk detection, whereas collaboration enables coordinated agility and flexible realignments. Collectively, these elements enable firms to absorb shocks and sustain operational continuity (Ivanov, 2021). Concurrently, SSCP is delineated by a triple-bottom-line framework:

environmental stewardship, such as carbon reduction and waste management; social responsibility, including labor rights and safety; and economic viability, such as cost efficiency and delivery reliability (Ooi et al., 2025; Cui et al., 2022).

In theory, resilient supply chains are expected to provide the operational stability necessary for long-term sustainability investments (Bouloiz et al., 2020). However, empirical findings on the relationship between SCR and SSCP are inconclusive. Some studies report a positive correlation, indicating that resilience mitigates disruptions that increase environmental and social risks (Cui et al., 2022), while others find weak or insignificant effects (Ooi et al., 2025). This inconsistency highlights a contextual gap: resilience capabilities may not automatically lead to sustainable outcomes without specific enabling conditions. Critics contend that much of the existing literature treats resilience as a static resource, failing to address the dynamic processes required to convert disruption management into sustainable value creation, especially in complex multi-tier networks characterized by high information asymmetry (Sinkovics et al., 2021; Adlakha, 2026).

2.2 Digital Technology Adoption as a Moderating Factor

To resolve these theoretical ambiguities, this study integrates the Resource-Based View (RBV), Dynamic Capabilities Theory, and Information Processing Theory. RBV posits that resources confer competitive advantage only when they are valuable, rare, and non-substitutable. Within this framework, the adoption of digital technologies, specifically the Internet of Things (IoT), cloud platforms, and real-time analytics, is conceptualized as a strategic resource that enhances the value of existing resilience capabilities (Craighead et al., 2020; Dubey et al., 2021).

Complementing RBV, Dynamic Capabilities Theory explains how firms reconfigure resources to address rapidly changing environments (Amui et al., 2020). Digital technologies act as the micro-foundations of dynamic capabilities, enabling firms to “sense” disruptions through enhanced visibility and “seize” opportunities for sustainable innovation through deeper collaboration (Zhou et al., 2024). Furthermore, Information Processing Theory suggests that supply chain uncertainty creates information processing requirements that exceed human cognitive limits. Digital infrastructure reduces this uncertainty by optimizing information flows, thereby improving decision-making quality regarding sustainability trade-offs (Birkel et al., 2023). Consequently, digital adoption is hypothesized to act as a critical boundary condition, determining the efficacy of resilience capabilities in driving sustainability.

2.3 Hypothesis Development

Building on the Resource-Based View, supply chain visibility and collaboration constitute strategic resources that directly enhance Sustainable Supply Chain Performance (SSCP). Visibility enables the precise tracking of environmental footprints and social compliance across tiers, transforming opaque risks into manageable variables (Grimm et al., 2016; Jain et al., 2024). Concurrently, collaboration facilitates the pooling of resources for joint green innovation and circular economy initiatives, directly improving triple-bottom-line outcomes (Cui et al., 2022; Ooi et al., 2025). Thus, we propose:

- H1: Supply chain visibility has a significant positive impact on sustainable supply chain performance.
- H2: Supply chain collaboration has a significant positive impact on sustainable supply chain performance. However, possessing these capabilities does not guarantee value creation; their efficacy is contingent on the firm’s information processing capacity. In complex multi-tier networks, raw visibility data can lead to information overload, while collaboration often suffers from coordination lags without real-time connectivity (Birkel et al., 2023). Here, digital technology adoption serves as a critical boundary condition. Drawing on Information Processing Theory, digital tools (e.g., IoT, big data) convert passive visibility into predictive analytics, enabling proactive sustainability interventions (Zhou et al., 2024). Furthermore, aligned with Dynamic Capabilities Theory, digital platforms reduce transaction costs, allowing collaborative intentions to rapidly reconfigure into tangible green actions (Teece, 2007; Dubey et al., 2021). Without high digital maturity, resilience capabilities remain static and underutilized. Therefore, digital adoption amplifies the conversion of resilience into sustainability:
- H3: Digital technology adoption positively moderates the relationship between supply chain visibility and SSCP.
- H4: Digital technology adoption positively moderates the relationship between supply chain collaboration and SSCP.

3. Methodology

3.1 Data Collection and Sample

To address the focal-firm bias identified in existing supply chain literature (Grimm et al., 2016), we targeted a multi-tier network within China's electric vehicle (EV) industry, including Original Equipment Manufacturers (OEMs) and Tier-1 to Tier-3 suppliers. We employed a stratified sampling strategy to ensure representative coverage across the supply chain. Data were collected using a structured questionnaire, which underwent rigorous pre-testing and pilot validation to ensure content validity. Following established procedural remedies for common method bias (CMB), such as ensuring respondent anonymity and separating predictor and criterion variables in the survey design (Podsakoff et al., 2003), we distributed the survey through industry associations and direct corporate contacts. The final dataset consists of 413 valid paired responses, yielding an effective response rate of 28.4%. The sample demonstrates balanced representation across firm tiers (OEM: 12%, Tier-1: 28%, Tier-2: 35%, Tier-3: 25%), ownership structures (state-owned, private, foreign), and employee sizes, providing a robust empirical basis for analyzing cross-tier dynamics.

3.2 Measures

All constructs were measured using established seven-point Likert scales adapted from prior high-impact studies to ensure construct validity. Supply chain visibility and collaboration were operationalized using scales from Scholten and Schilder (2015) and Cui et al. (2022), capturing the extent of real-time information sharing and joint planning activities. SSCP was assessed as a multidimensional construct encompassing environmental (e.g., carbon reduction), social (e.g., labor safety), and economic (e.g., cost efficiency) outcomes, following the framework by Ooi et al. (2025). The moderator, Digital Technology Adoption, was constructed as a composite index reflecting the intensity of IoT, cloud computing, and big data analytics implementation, based on measures by Dubey et al. (2021). Control variables included firm tier, size, ownership, and age to isolate the specific effects of resilience and digitalization.

3.3 Analytical Approach

Data analysis followed a two-step SEM approach using AMOS, which is appropriate for complex models with moderating effects and non-normal data distributions (Hair et al., 2019). First, we evaluated the measurement model for reliability and validity using Cronbach's alpha, Composite Reliability (CR), and Average Variance Extracted (AVE). Second, the structural model was used to assess the hypothesized direct relationships. To rigorously test the moderating role of digital technology, we employed Multi-Group Analysis (MGA), dividing the sample into "high" and "low" digital adoption groups based on a median split. This approach enables examination of path coefficient differences without assuming linear interaction terms, providing a nuanced understanding of how digital maturity influences the resilience-sustainability relationship (Henseler et al., 2015). Harman's single-factor test confirmed that CMB was not a critical threat to the validity of our findings.

4. Results

4.1 Sample Characteristics and Descriptive Statistics

To ensure objectivity and representativeness, data were collected from a diverse cross-section of China's electric vehicle (EV) supply chain. The final sample comprises 413 valid responses, with a balanced gender distribution (49.9% male, 49.6% female) and a workforce primarily in their prime career stages (70.7% aged 25–35). Respondents exhibit high educational attainment (89.1% holding at least a Bachelor's degree) and substantial industry experience (78.2% with over six years of work history), supporting the professional reliability of the perceptual data. The sample includes a comprehensive multi-tier network structure: Original Equipment Manufacturers (OEMs) represent 52.1%, while Tier-1, Tier-2, and Tier-3 suppliers account for 15.3%, 20.8%, and 9.4%, respectively. This distribution addresses the traditional focal-firm bias by incorporating significant upstream perspectives. Furthermore, the inclusion of firms with varying tenures (74.1% operating for over five years) and sizes (predominantly medium-to-large enterprises) ensures that the results reflect the dynamics of both established industry leaders and growth-stage organizations.

The result presents the descriptive statistics and Pearson correlation matrix for the study variables. Preliminary analysis identifies distinct associative patterns: Supply Chain Visibility exhibits a strong positive correlation with Environmental

Performance (r=0.42, p<0.01) and Social Performance (r=0.39, p<0.01), but demonstrates a negligible association with Economic Performance (r=0.08, n.s.). In contrast, Supply Chain Collaboration is significantly correlated with all three dimensions of Sustainable Supply Chain Performance (SSCP): Environmental (r=0.45, p<0.01), Social (r=0.41, p<0.01), and Economic (r=0.36, p<0.01). These initial findings indicate that while visibility and collaboration are interrelated, they may influence specific sustainability outcomes through distinct mechanisms, highlighting the need for further structural investigation.

4.2 Measurement Model Assessment

The structural model demonstrated an excellent fit to the data, validating the proposed theoretical framework. The goodness-of-fit indices met all rigorous thresholds: 2/df was within the acceptable range, indicating a parsimonious model; the Root Mean Square Error of Approximation (RMSEA) was below 0.08; the Root Mean Square Residual (RMR) indicated minimal residual variance; and both the Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) exceeded 0.90. These metrics collectively confirm that the hypothesized model accurately represents the underlying data structure, providing a robust basis for hypothesis testing.

4.3 Hypothesis Testing: Main and Moderating Effects

While the main effect analysis revealed that Supply Chain Collaboration positively drives all dimensions of Sustainable Supply Chain Performance (SSCP), and Supply Chain Visibility selectively benefits environmental outcomes, the core contribution of this study lies in the moderating role of Digital Technology Adoption. Table 3 presents the results of the moderation analysis, which uncovers a critical “digital enablement” mechanism.

Contrary to the mixed main effects, the interaction terms reveal that digital maturity fundamentally alters the efficacy of resilience capabilities. Specifically, digital technology adoption exerts a significant positive moderating effect on the relationship between Visibility and all three performance dimensions (Environment: $\beta int=0.461, p<0.01 \beta int=0.461, p<0.01$; Economic: $\beta int=0.500, p<0.01 \beta int=0.500, p<0.01$; Social: $\beta int=0.415, p<0.05 \beta int=0.415, p<0.05$). This indicates that while visibility alone may incur costs or lack social impact (as seen in the main effects), high levels of digital adoption transform raw visibility into actionable intelligence, thereby unlocking significant economic and social value that was previously inaccessible.

Conversely, the analysis reveals a significant negative moderating effect for Collaboration across all dimensions (Environment: $\beta int=-0.041, p<0.001 \beta int=-0.041, p<0.001$; Economic: $\beta int=-0.048, p<0.05 \beta int=-0.048, p<0.05$; Social: $\beta int=-0.059, p<0.01 \beta int=-0.059, p<0.01$). This counter-intuitive finding suggests a substitution effect: in highly digitalized environments, the marginal benefit of traditional, resource-intensive collaboration diminishes. Digital platforms appear to automate and streamline information exchange, rendering heavy-handed collaborative processes less critical or even redundant for achieving sustainability goals. In essence, digital tools substitute for the need for intense manual collaboration, whereas they act as a catalyst that amplifies the value of visibility.

These results strongly support H3 and H4 but refine their interpretation: digital technology does not merely “strengthen” all resilience capabilities uniformly. Instead, it acts as a complement to visibility (making data useful) and a substitute for traditional collaboration (making processes efficient). This nuanced finding resolves the earlier inconsistencies in the main effects, establishing digital adoption as the decisive boundary condition that determines whether resilience capabilities translate into sustainable competitive advantage.

5. Discussion

5.1 Interpretation of Key Findings

The results of this study reveal a complex and unexpected mechanism through which resilience capabilities affect sustainable supply chain performance (SSCP) in the electric vehicle (EV) sector. Contrary to the prevailing assumption that both visibility and collaboration uniformly enhance sustainability, the findings demonstrate a divergent pattern. Supply chain collaboration emerges as a strong and direct driver across all three dimensions of SSCP: environmental, economic, and social. This underscores the importance of joint problem-solving and resource pooling in addressing systemic sustainability challenges (Cui et al., 2022; Ooi et al., 2025). In contrast, supply chain visibility exerts a significant negative direct effect on

economic performance and does not significantly influence social or environmental outcomes. These results suggest that, in the absence of enabling conditions, visibility may act primarily as a cost center by generating data overload and monitoring expenses without yielding actionable insights or operational efficiencies (Grimm et al., 2016).

The principal contribution of this research is the resolution of this paradox through the examination of Digital Technology Adoption. The moderation analysis indicates that digitalization serves not only as an additional resource but also as a critical boundary condition that fundamentally redefines the value of resilience capabilities. Specifically, digital adoption demonstrates a strong positive moderating effect on visibility, converting it from a cost burden into a strategic asset. In highly digitalized environments, advanced analytics and Internet of Things (IoT) technologies transform raw data into predictive insights, enabling firms to mitigate the bullwhip effect and optimize resource allocation, thereby reversing negative economic impacts and generating environmental and social benefits (Birkel et al., 2023; Zhou et al., 2024). In contrast, a significant negative moderating effect is observed for collaboration, indicating a substitution effect. In highly digitalized networks, automated platforms and real-time data sharing reduce reliance on traditional, resource-intensive manual collaboration. Digital tools streamline coordination, making extensive collaborative processes less essential for achieving sustainability outcomes (Dubey et al., 2021). This finding challenges the assumption that increased collaboration is universally beneficial, suggesting that digital maturity enables firms to achieve comparable or superior coordination efficiency with reduced frictional overhead.

5.2 Theoretical Implications

These findings contribute to supply chain theory in three significant ways. First, the Resource-Based View (RBV) and Dynamic Capabilities Theory are advanced by clarifying the mechanism through which static resources, such as visibility, are transformed into dynamic capabilities. The results indicate that digital infrastructure serves as the micro-foundation enabling firms to identify and capitalize on opportunities within complex data streams, supporting Teece's (2007) assertion regarding the centrality of technology in dynamic reconfiguration. Second, by identifying the substitution effect between digitalization and collaboration, this study refines Information Processing Theory. The evidence suggests that as information processing capacity increases through digital tools, the need for structural coupling, or intense collaboration, decreases. This provides a more detailed understanding of how firms address uncertainty in multi-tier networks (Kamble et al., 2019). Finally, the research addresses the focal-firm bias in existing literature by presenting empirical evidence from a deep multi-tier network (OEM to Tier-3). The findings demonstrate that the effectiveness of resilience strategies varies across supply chain depth and depends on the digital maturity of the entire network (Zhong & Um, 2024).

5.3 Managerial and Policy Implications

These results provide a strategic framework for practitioners. EV managers should recognize that investing in visibility without simultaneous development of digital infrastructure may undermine economic performance. Digital transformation must be regarded as a strategic requirement for achieving environmental, social, and governance (ESG) objectives, rather than merely an IT support function. Firms are advised to prioritize the implementation of AI-driven analytics and cloud platforms to fully utilize visibility data. Additionally, the observed negative moderation of collaboration indicates that in highly digital ecosystems, managerial focus should shift from frequent manual joint meetings to the optimization of automated data-sharing protocols. This approach can reduce coordination costs while maintaining high sustainability standards.
For policymakers, particularly in emerging markets such as China, the findings highlight the importance of subsidies and incentives aimed at enhancing digital capabilities throughout the supply chain, especially for lower-tier small and medium-sized enterprises (SMEs) in Tier-2 and Tier-3. Without raising the digital baseline of upstream suppliers, the resilience and sustainability initiatives of focal original equipment manufacturers (OEMs) will remain constrained, impeding the industry's overall transition to a circular economy.

6. Conclusion and Future Research

6.1 Summary of Contributions

This study aimed to address a persistent paradox in supply chain literature: the frequent failure of resilience capabilities to yield sustainable performance. By integrating the Resource-Based View, Dynamic Capabilities Theory, and Information Processing Theory within the context of China's multi-tier electric vehicle supply chain, we offer a comprehensive explanation. Our empirical analysis of 413 firms indicates that digital technology adoption serves as the primary catalyst for realizing the potential value of resilience. Specifically, we show that supply chain collaboration consistently promotes sustainability across all dimensions, while supply chain visibility, often presumed universally advantageous, can negatively affect economic performance in low-digital environments due to information overload and increased monitoring costs. In contrast, high levels of digital adoption reverse this effect, positioning visibility as a strategic asset that improves environmental, social, and economic outcomes.

The identification of a negative moderating effect on collaboration indicates a significant paradigm shift. Drawing on Transaction Cost Economics and Information Processing Theory, this study contends that advanced digital ecosystems generate a substitution effect that diminishes reliance on traditional, structurally embedded collaboration. Automated data flows, algorithmic decision-making, and real-time connectivity substantially reduce transaction costs, including search, monitoring, and negotiation friction, which are typically associated with manual cross-tier coordination. As a result, digital infrastructure supplants resource-intensive manual coordination, offering a more efficient and agile pathway to sustainability by separating operational alignment from relational friction. These findings collectively demonstrate that digital infrastructure functions not merely as a supportive tool but as a fundamental boundary condition that shapes the effectiveness of resilience strategies in achieving the triple bottom line (Birkel et al., 2023; Zhou et al., 2024).

6.2 Study Limitations

Several limitations should be acknowledged. First, the cross-sectional design restricts the ability to establish causal relationships concerning the long-term evolution of the resilience-sustainability nexus. Although the theoretical framework and robust statistical controls address endogeneity concerns, longitudinal dynamics, such as the progression of digital maturity and its impact on these relationships, remain unexamined (Cui et al., 2022). Second, the sample is limited to the Chinese electric vehicle industry. While this context is significant due to China's global market dominance, differences in culture, regulation, and infrastructure may constrain the generalizability of the findings to other regions or industries with distinct supply chain structures (Zhong & Um, 2024). Third, reliance on self-reported perceptual data may introduce common method bias, even with rigorous procedural and statistical controls (e.g., Harman's single-factor test and CFA). Future research utilizing objective archival data could further substantiate these relationships.

6.3 Future Research Directions

Future research should address three key areas. First, longitudinal studies are necessary to examine the temporal dynamics of digital transformation. Researchers should analyse how the substitution effect between digitalization and collaboration changes as firms progress from early adoption to full digital maturity, and whether the initial costs of visibility eventually result in diminishing returns. Second, expanding the scope to include other high-volatility industries, such as semiconductors and pharmaceuticals, would help determine whether the moderating mechanisms identified are universal or industry-specific (Craighead et al., 2020).

Third, further investigation into the heterogeneity of digital technologies is warranted. Instead of treating digital adoption as a composite index, future studies could disaggregate specific technologies (e.g., blockchain for immutable traceability, artificial intelligence for predictive agility) to identify which are most effective in enhancing visibility or streamlining collaboration. Additionally, examining the influence of external institutional pressures, such as government regulations and customer activism, as second-order moderators could provide a more comprehensive understanding of the ecosystem in which digital-resilience interactions occur (Ooi et al., 2025). Addressing these areas will enable the academic community to refine theoretical frameworks for sustainable digital transformation in global supply chains and further decode the boundary conditions of resilient value creation.

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A RETRIEVAL-AUGMENTED GENERATION TOOL FOR SEMANTIC EVALUATION OF RAILWAY EDUCATION CURRICULA

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Abstract

The European rail sector is facing two major challenges: the loss of expertise associated with an ageing workforce and the changing competence demands created by digitalisation, automation, and data-driven systems. These challenges increase the need for railway higher education programmes to remain aligned with evolving industry requirements. However, curriculum evaluation in this area is still largely manual, time consuming, resource intensive making systematic comparison across programmes difficult, especially where similar competencies are expressed through different terminology. This paper presents the development and preliminary testing of an AI-assisted curriculum evaluation tool for railway higher education. The tool transforms unstructured curriculum documents into comparable representations and combines rule-based comparison with semantically informed analysis. The study adopts a design-based research approach and reports a comparative case study of two European Master's-level rail-related programmes, focusing on learning outcomes and subject areas. The preliminary test showed that the tool could extract and structure curriculum information from both programmes and support comparison at both syntactic and semantic levels. It identified patterns of alignment, partial overlap, and apparent gaps, including cases where conceptually related content was expressed differently across programmes. The study shows the feasibility of using such a tool to support more systematic curriculum evaluation in a specialised engineering domain. While the findings are preliminary, they indicate the potential of semantically informed curriculum evaluation as a decision-support approach for railway higher education.

Keywords: railway higher education; curriculum evaluation; artificial intelligence in education

1 Introduction

The European rail sector is navigating a dual challenge that threatens its long-term competitiveness and capacity for innovation and that has direct implications for higher education. The first is demographic: an ageing workforce and impending retirements raise concerns about the loss of sector-specific skills and institutional knowledge (European Commission Adopts 9th Report on Development of the Rail Market, 2025; European Labour Authority, 2025; Shinde et al., 2025a; Shinde et al., 2025b). The second is technological: digitalisation, automation, artificial intelligence, and data-driven systems are reshaping professional practice across rail planning, operations, maintenance, and systems integration (Shinde et al., 2025a). Together, these developments are changing and redefining the competencies expected of future railway professionals and increasing pressure on universities to ensure that their programmes remain aligned with emerging sector needs.

These challenges increase the importance of curriculum design and review in railway higher education. Universities are expected not only to maintain core disciplinary foundations, but also to respond to new requirements in areas such as digital systems, automation, and interdisciplinary problem-solving. Yet curriculum review in this area continues to rely heavily on manual approaches (Shinde et al., 2025b). These are time-consuming and difficult to apply systematically, particularly when programme documents vary in structure, level of detail, and terminology. As a result, alignment is not always easy to judge, especially where related competencies are expressed differently across programmes.

Recent developments in artificial intelligence offer a possible way forward. Natural language processing and large language models make it increasingly feasible to analyse documents at a level that goes beyond keyword matching alone (Naveed et al., 2023). In particular, retrieval-augmented generation offers a means of grounding semantic interpretation in the source material being analysed (Kan et al., 2025), which is potentially useful for curriculum comparison in specialised domains. While AI has been widely discussed in relation to student learning, assessment, and educational administration, its use in domain-specific curriculum evaluation remains less developed (Shinde et al. 2025b).

This paper addresses that gap through the development and preliminary testing of an AI-assisted curriculum evaluation tool for railway higher education. The tool is designed to transform unstructured curriculum documents into comparable

representations and to support analysis at both syntactic and semantic levels. In this paper, the approach is demonstrated through a comparative case study of two European Master's-level rail-related programmes.

It also speaks to a broader question in education and training research: how AI-assisted methods might support more evidence-informed curriculum review in fields where workforce change, technological transition, and cross-institutional comparability are increasingly important.

2 Research aim

The aim of this study is to propose, develop, and preliminarily evaluate a retrieval-augmented tool for the semantic evaluation of specialised engineering curricula, using railway higher education as the case context. More specifically, the study examines whether a tool that combines rule-based comparison with semantically informed analysis can support structured comparison of curriculum documents and assist in identifying areas of alignment and gaps across programmes.

3 Research approach

This study adopts a design-based research approach centred on the development and preliminary testing of a curriculum evaluation tool for railway higher education. The work was motivated by a practical methodological problem: how to compare curriculum documents in a way that is more systematic than manual reading alone, while remaining sensitive to differences in wording and structure across programmes.

The study proceeded through the design of a prototype tool capable of extracting relevant curriculum elements from unstructured programme documents and converting them into forms suitable for comparison. In this paper, the analysis is limited to two curriculum criterias: learning outcomes and subject areas. These were selected because they provide a workable basis for examining both the intended educational aims of a programme and its stated areas of curricular coverage.

To examine the feasibility of the approach, the tool was applied in a comparative case study involving two European Master's-level rail-related programmes: M.Sc. Rail Freight Logistics (University A) and M.Sc. Railway Systems Engineering and Integration (University B). The purpose of this comparison was not to rank the programmes or to make broad claims about curriculum quality. Rather, it was to test whether the tool could support systematic identification of areas of alignment and gaps across programmes whose content is organised and expressed differently.

Methodologically, the approach combines two forms of analysis. The first is rule-based and supports explicit comparison of extracted curriculum elements. The second is semantically informed and is intended to identify conceptual similarity and difference where direct wording alone is insufficient. Together, these two layers form the basis of the prototype evaluation process reported in this paper.

The study should therefore be read as a preliminary demonstration of method rather than a comprehensive validation exercise. Its contribution lies in showing how an AI-assisted tool can be used to structure curriculum comparison in railway higher education, and in illustrating the kinds of alignment and gap analysis such an approach can support at this stage of development.

4 Technical Development of the Curriculum Evaluation Tool

This section details the design and implementation of the curriculum evaluation tool. The development was conducted using the Cursor AI-assisted code editor, which significantly accelerated the prototyping and integration of various components by facilitating code generation, refactoring, and debugging. The tool is architected as a modular, retrieval-augmented generation (RAG) pipeline that transforms raw curriculum documents into structured data, performs deterministic and semantic comparisons, and delivers insights via a web interface. An overview of the complete system pipeline is presented in Figure 1 and each pipeline is explained in section 4.1.

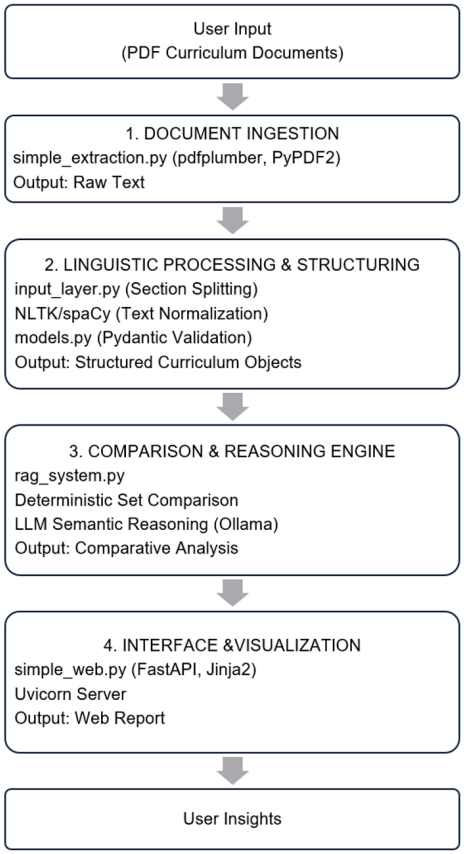


Figure 1: System architecture and data flow diagram

This section details the design and implementation of the curriculum evaluation tool. The development was conducted using the Cursor AI-assisted code editor, which significantly accelerated the prototyping and integration of various components by facilitating code generation, refactoring, and debugging. The tool is architected as a modular, retrieval-augmented generation (RAG) pipeline that transforms raw curriculum documents into structured data, performs deterministic and semantic comparisons, and delivers insights via a web interface. An overview of the complete system pipeline is presented in Figure 1.

4.1 Core Pipeline Components

The system's functionality is decomposed into five core Python modules, each responsible for a distinct stage in the evaluation workflow.

4.1.1. Document Ingestion and Text Extraction (simple_extraction.py)

This initial module handles the parsing of input PDFs. While PyPDF2 provides a baseline extraction capability, pdfplumber is employed for its superior fidelity in handling complex layouts, preserving textual order, and extracting tabular data where present. The module operates agnostically to content meaning, converting the document into a contiguous block of plain text. This step is analogous to "peeling the envelope before reading the letter inside," providing the raw material for subsequent processing.

4.1.2. Text Structuring and Normalization (input_layer.py)

The raw text is passed to this layer, which imposes a preliminary structure. Using rule-based heuristics and pattern matching (e.g., for headers like "Learning Outcomes," "Modules," or "Subject Areas"), it segments the text into logical units. It performs basic normalisation such as standardising whitespace, punctuation, and list formatting. It outputs a semi-structured Python dictionary. This step is critical for transforming unstructured text into a form where specific curriculum elements can be reliably identified.

4.1.3. Structured Curriculum Representation (models.py)

To ensure data consistency and validity, the system employs Pydantic models for rigorous data definition and validation. Key models include:

institution: str

program_name: str

learning_outcomes: List[LearningOutcome]

subject_areas: List[SubjectArea]

These models enforce type checking, detect missing or malformed fields early in the pipeline, and provide a clean, typed interface for the reasoning engine. This stage performs semantic normalization, ensuring that all downstream components operate on well-defined objects.

4.1.4. Retrieval-Augmented Reasoning Engine (rag_system.py)

This module is the core analytical component. It accepts two validated Curriculum objects and performs a two-stage comparison:

Retrieval- It first computes direct overlaps and differences between learning outcomes and subject areas using set operations and keyword matching. This provides a transparent, baseline analysis.

Generation- The structured data from the first stage, along with crafted prompts, are sent to a locally hosted Large Language Model (LLM) via Ollama. The LLM is instructed to interpret the results, identifying semantic similarities between differently phrased outcomes, assessing the conceptual significance of gaps, and generating context-aware recommendations for alignment. This is where the system becomes interpretive, not merely extractive. This RAG approach ensures the LLM's reasoning is grounded in the retrieved curriculum data, mitigating hallucination.

4.1.5. Web Interface and Deployment (simple_web.py)

User interaction is managed through a lightweight web application built with FastAPI. The module defines endpoints (e.g., /upload, /compare) for file upload and processing. Jinja2 templates render the user interface and present the final comparative report in a clear, human-readable format. The application is served using Uvicorn, providing an accessible platform for curriculum designers without requiring command-line expertise.

4.2 Implementation Environment and Key Libraries

The entire implementation is written in Python, chosen for its strong support for text processing and machine learning workflows.

Key dependencies include:

- Backend & web framework- FastAPI (for Application Programming Interface (API) construction), Uvicorn (Asynchronous Server Gateway Interface (ASGI) server), Jinja2 (templating).
- Document Processing- PyPDF2, pdfplumber (for PDF text extraction).
- Linguistic Processing- Natural Language Toolkit (NLTK) (for tokenization, stop-word removal) and spaCy (for part-of-speech tagging and lemmatization which can help normalize different forms of the same concept (e.g., "analysing" and "analysis"), enabling future semantic refinement).
- Data Validation & Modelling- Pydantic (for enforcing data structures and types).
- Local LLM Integration- Requests library to communicate with the Ollama API, running open-source models like Llama 2 for privacy and cost efficiency.

This pipeline combines the reliability of rule-based data extraction and deterministic comparison with the nuanced understanding of a locally hosted LLM. The result is a scalable, objective, and semantically rich tool that supports data-informed curriculum design and evaluation in the railway engineering sector.

5 Comparison reference

To support comparison across programmes, the tool used a baseline curriculum as a structured reference. This baseline was not treated as a prescribed model of what every railway programme should contain. Rather, it functioned as a comparative frame intended to represent industry-relevant areas of knowledge and competence in a form that could support more systematic evaluation.

The baseline was developed from sectoral evidence and prior project work concerned with skills needs and educational alignment in the railway field, particularly ASTONRail and STAFFER. Its purpose was to translate dispersed evidence about railway roles, competencies, and emerging requirements into a reference structure that could be used in curriculum analysis.

Methodologically, the baseline was constructed through three linked steps: identification of relevant railway job roles, mapping of associated skills and competencies, and synthesis of these into a structured curriculum model. In the present paper, the baseline is used only to provide a common comparison frame for examining programme learning outcomes and subject areas. It therefore supports the analysis reported here but is not itself the primary object of investigation.

Using a baseline in this way helps address a practical problem in curriculum comparison. Programmes may differ not only from one another, but also in how explicitly they reflect emerging sectoral requirements. A shared reference frame makes it possible to interpret areas of correspondence and apparent omission more consistently, while still treating the results as analytical rather than prescriptive.

6 Preliminary test

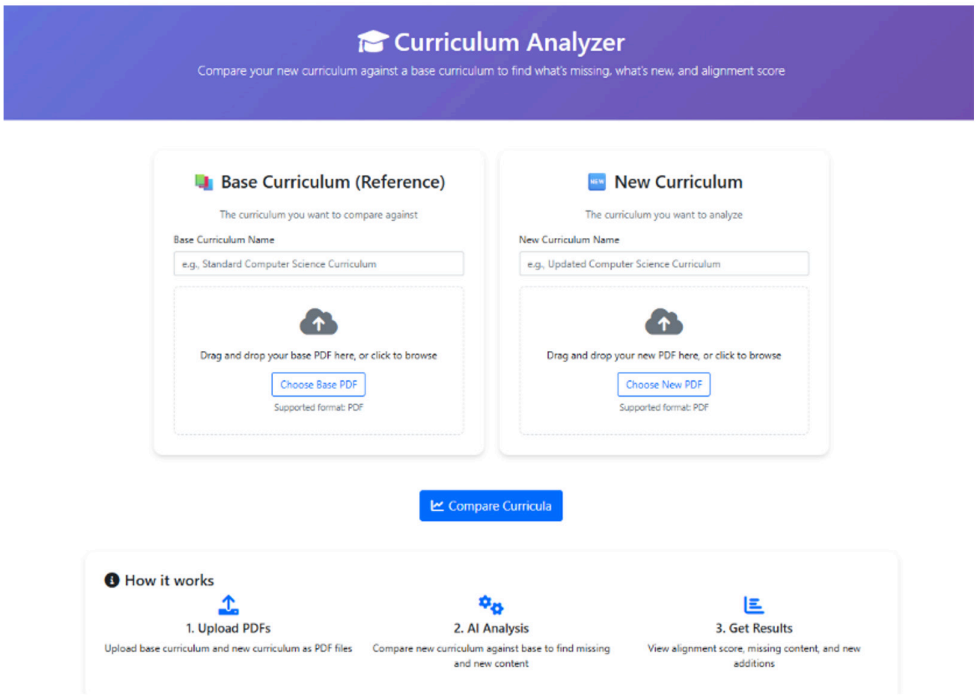
The tool was tested by comparing two European Master's programmes: an M.Sc. Rail Freight Logistics (University A) and an M.Sc. Railway Systems Engineering and Integration (University B). Figure 2a shows the clean web interface where users upload PDFs for analysis. The results page (Figure 2b) presents the evaluation results.

Metric	University A	University B
Overall alignment score	0.6%	3.8%
Learning outcome alignment	0%	0%
Subject area alignment	2.1%	13.5%
Processing time	3 second	3 second

Table 1: Summary of evaluation results

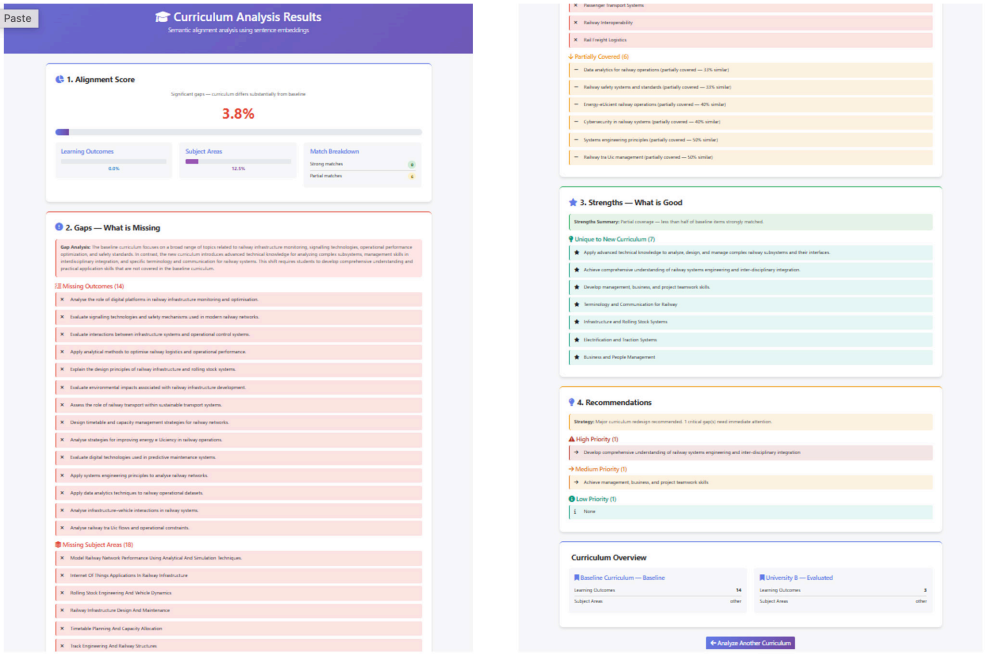
The comparison indicated that the tool could identify patterns at more than one level. At the syntactic level, it highlighted explicit areas of overlap and gaps in the stated curriculum content. At the semantic level, it supported interpretation of conceptually related material that was expressed in different terms across the two programmes. This is important in a field such as railway education, where similar competencies may not always be described through the same vocabulary. The tool processed and compared both curricula against baseline curriculum in under 90 seconds on the first run and under 3 seconds on subsequent runs on standard hardware, demonstrating practical efficiency compared to manual analysis.

The demonstration also showed that the two programmes did not align uniformly. Some areas appeared to correspond more closely, while others suggested differences in emphasis or more limited coverage relative to the comparison frame. In this respect, the tool was useful not because it reduced the curricula to a single judgement, but because it made visible a more differentiated pattern of correspondence, partial overlap, and apparent gaps.



(a)

Figure 2a: Web interface for curriculum upload and comparison.



(b)

Figure 2b: Web interface for evaluation result for University B.

Taken together, the results support the feasibility of the approach at a preliminary level. They show that structured extraction combined with semantically informed comparison can assist curriculum evaluation. For the purposes of this paper, the contribution of the demonstration lies in showing what this form of analysis can make visible, rather than in claiming comprehensive validation of the tool.

7 Conclusion

This study has presented a preliminary AI-assisted tool for the semantic evaluation of railway education curricula. Its main contribution lies not in replacing academic judgement, but in providing a more structured, efficient, user-friendly basis for comparing curriculum documents that differ in wording, format, and emphasis. By focusing on learning outcomes and subject areas, and by combining explicit matching with semantically informed analysis, the tool makes it possible to examine alignment and gaps in a more systematic way than surface-level comparison alone allows.

The comparative demonstration with two Master's-level railway programmes suggests that this approach is workable for identifying patterns of stronger correspondence, partial overlap, strengths, and apparent gaps. In that respect, the study shows the value of treating curriculum evaluation as an analytical problem of representation and interpretation, rather than as a simple exercise in topic listing or keyword matching. This is particularly relevant in specialised domains such as railway higher education, where related competencies may be described differently across programmes.

At the same time, the contribution should be read within the limits of the study. The demonstration is based on two programmes and a restricted set of curriculum criteria, and the analysis is bounded by what is explicitly stated in the source curriculum documents and by the comparison frame used. Curriculum evaluation typically encompasses additional dimensions, such as assessment methods, delivery approaches, credit allocation, and module structure. The findings therefore remain indicative rather than comprehensive. They support the feasibility of the approach, but do not amount to full evidence of reliability across a wider range of institutional contexts or curriculum types.

Within those boundaries, the paper contributes an early domain-specific tool for AI-assisted curriculum evaluation in railway higher education and shows how such a tool can support more evidence-informed comparison across programmes. This provides a basis for further development. Later work has suggested that the underlying approach can be refined into a more functional, tailored, and reliable system; however, that subsequent development should be understood as an extension of the proof of concept reported here.

8 Disclaimer

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SYNOPTICS: ELIMINATING PRODUCTION LINE RISK THROUGH REAL-TIME LOGISTICS INTELLIGENCE

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Abstract

Modern automotive manufacturing environments require continuous operational visibility to minimise production risk and maintain uninterrupted material flow. Delays in identifying logistics discrepancies may result in incorrect stock delivery, operational disruption, and production line stoppages with significant financial consequences. This paper presents SynOptics, a real-time operational intelligence platform developed and deployed within Jaguar Land Rover's Battery Assembly Centre operations supported by Rudolph & Hellmann Automotive and Unipart Logistics.

SynOptics integrates SAP automation, Python-based processing, Power Query refresh mechanisms, live dashboard visualisation, automated alerting, and resilience-focused recovery workflows into a unified operational monitoring framework. The platform continuously monitors operational activity, identifies discrepancies, validates SAP connectivity, and supports automated escalation and recovery processes.

The implementation adopted an industry-based case study methodology within a live automotive logistics environment. Since deployment, SynOptics has achieved an approximate 98% reduction in operational errors, reduced discrepancy detection time from hours to approximately 3–5 minutes, while eliminating production downtime associated with incorrect stock delivery. In addition, the system improved operational visibility, accelerated response capability, and reduced operational exposure to production interruption risks.

The findings demonstrate how lightweight and cost-effective digital technologies can deliver substantial operational improvements without requiring large-scale enterprise infrastructure transformation. Overall, SynOptics highlights the practical value of real-time operational intelligence systems in improving supply chain visibility, operational resilience, and manufacturing continuity within modern logistics environments.

Keywords: Real-time logistics, operational intelligence, warehouse optimisation, SAP automation, supply chain visibility, digital transformation, operational resilience, automotive manufacturing

1. Introduction

Modern automotive manufacturing environments operate under highly time-sensitive conditions, where material availability and operational continuity are critical to maintaining uninterrupted production flow. In such environments, delays in identifying logistics discrepancies can rapidly escalate into production line stoppages, resulting in significant operational and financial consequences. At Jaguar Land Rover's Battery Assembly Centre (BAC), line interruptions may incur penalties of approximately £1,000 per minute, emphasising the importance of proactive operational monitoring and rapid issue resolution. Operational visibility and rapid responsiveness are increasingly recognised as critical factors for supply chain resilience within modern manufacturing operations (Christopher, 2016).

Traditional warehouse monitoring methods rely on manual checks, delayed reporting, and reactive responses, limiting visibility and increasing risks such as incorrect deliveries and misplaced inventory. Additionally, fragmented system-to-team visibility hinders real-time operational awareness, reducing organisational responsiveness within high-demand manufacturing environments (Wang, Gunasekaran, Ngai and Papadopoulos, 2016).

To address these issues, SynOptics was developed as a real-time operational intelligence platform designed to provide continuous monitoring of warehouse and line-side logistics operations. The system integrates SAP operational data, automated processing workflows, live dashboard visualisation, and automated alerting mechanisms into a unified monitoring framework. SynOptics was developed and deployed within operations supported by Rudolph & Hellmann Automotive (RHA) and Unipart Logistics (UL) at Jaguar Land Rover's Battery Assembly Centre.

This paper presents the development, deployment, and operational impact of SynOptics within a live automotive logistics environment. The research demonstrates how lightweight integrated digital solutions can significantly improve operational visibility, reduce production risk, and support proactive logistics management without requiring large-scale infrastructure transformation.

2. Literature Review

Digital transformation has become increasingly important within supply chain and logistics operations as organisations seek to improve operational visibility, responsiveness, and resilience. Real-time operational intelligence systems enable organisations to monitor operational activities continuously and respond more rapidly to disruptions within manufacturing and warehouse environments (Christopher, 2016).

Supply chain visibility plays a critical role in reducing operational risk and improving decision-making. Christopher (2016) highlights that enhanced visibility improves organisational responsiveness and supports faster mitigation of operational disruptions. Similarly, Ivanov and Dolgui (2020) emphasise that resilient supply chains increasingly depend on digital technologies capable of supporting dynamic operational monitoring and rapid intervention. Wamba, Akter, Edwards, Chopin and Gnanzou (2015) further identify data-driven operational intelligence as an important enabler of organisational performance improvement within modern supply chains.

Recent developments in logistics digitalisation have focused on integrating enterprise systems, automation technologies, and live monitoring platforms to improve operational performance. Real-time dashboards and automated alerting systems support data-driven operational management by improving responsiveness and reducing dependency on delayed reporting (Wang, Gunasekaran, Ngai and Papadopoulos, 2016). In addition, agile and technology-enabled operational frameworks have become increasingly important in supporting manufacturing responsiveness and operational continuity (Gunasekaran, Yusuf, Adeleye and Papadopoulos, 2018).

However, many industrial implementations remain constrained by infrastructure limitations and high implementation costs. Consequently, lightweight operational intelligence solutions capable of integrating with existing enterprise systems present significant practical value. SynOptics contributes to this area by demonstrating how accessible technologies including Python automation, Excel integration, Power Query, and SAP automation can be combined to improve operational visibility, responsiveness, and resilience within a live automotive manufacturing environment.

3. Operational Challenges at JLR BAC

Before the implementation of SynOptics, operational monitoring within the Battery Assembly Centre relied heavily on manual observation, delayed reporting processes, and reactive intervention methods. Although operational data was available within enterprise systems, the absence of continuous real-time visibility limited the ability of operational teams to identify and respond to logistics discrepancies rapidly.

One of the primary operational challenges involved incorrect scanned locations and stock discrepancies. Errors were often identified hours later or during next-day reporting cycles, increasing the risk of incorrect stock delivery to production lines. In a high-demand automotive manufacturing environment such as Jaguar Land Rover BAC, production interruptions may result in financial penalties estimated at approximately £1,000 per minute, making rapid intervention operationally critical.

Manual operational checks also reduced monitoring efficiency and increased dependency on repetitive verification activities. Limited real-time visibility further complicated operational coordination and delayed escalation of issues requiring corrective action.

To address these limitations, SynOptics was developed to provide automated real-time monitoring, continuous operational visibility, rapid discrepancy detection, and automated escalation capabilities (Table 1).

Before SynOptics	After SynOptics
Error detection took hours or next-day reporting	Detection within 3–5 minutes
Manual operational checks	Automated real-time visibility
Reactive interventions	Proactive interventions
Risk of production line stoppage	Eliminated
Delayed operational escalation	Automated email notifications
Limited operational visibility	Continuous live dashboard monitoring
Manual SAP recovery processes	Automated SAP recovery workflows

Table 1. Operational Comparison Before and After SynOptics

4. SynOptics System Architecture

SynOptics was designed as a lightweight operational intelligence platform capable of integrating with existing enterprise infrastructure while providing near real-time operational visibility. The architecture combines SAP automation, Python-based processing, Excel and Power Query integration, live dashboard visualisation, automated alerting mechanisms, and resilience-focused recovery workflows.

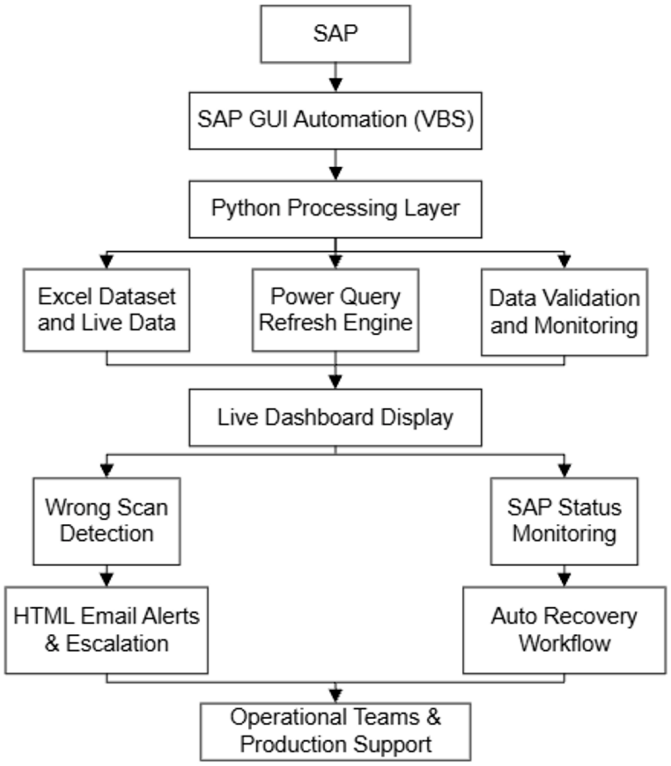

Figure 1. SynOptics real-time operational monitoring and recovery workflow

The system operates through a continuous automated monitoring loop that validates SAP connectivity, extracts operational data, refreshes dashboard outputs, identifies operational discrepancies, and distributes alerts to operational teams. The platform was designed to support rapid deployment using existing operational infrastructure while minimising disruption to ongoing production activities (Fig. 1).

Operational data is extracted automatically from SAP through SAP GUI automation and transferred into the live monitoring environment for processing and visualisation. Power Query refresh mechanisms continuously update operational datasets, enabling near real-time visibility of warehouse and line-side activities.

The live operational dashboard provides continuous monitoring of:

• Correct scanned locations

• Wrong scanned locations

• Product information

• Handling Unit (HU) data

• SAP connection status

• Live operational activity

Incorrect scanned locations are identified automatically and escalated through formatted HTML email notifications distributed to operational stakeholders. Operational records are simultaneously archived automatically while duplicate archive entries are prevented through validation logic using Handling Unit and timestamp verification.

Operational resilience forms a core component of the architecture. SynOptics continuously monitors SAP system availability and automatically initiates recovery workflows when interruptions are detected. The system supports automated SAP reconnection, operational recovery monitoring, escalation notifications, and restoration of live dashboard functionality following successful recovery.

In addition to continuous monitoring and alert handling, SynOptics generates automated daily operational reports to support ongoing operational review and performance monitoring.

The architecture was intentionally developed using accessible and cost-effective technologies including Python, Excel, Power Query, SAP GUI automation, and automated email frameworks. This lightweight design enabled rapid implementation within a live automotive manufacturing environment without requiring extensive enterprise infrastructure transformation.

5. Research Methodology

This research adopts an industry-based case study methodology focused on the development and deployment of a real-time operational intelligence platform within a live automotive logistics environment. The study was conducted within operations supported by Rudolph & Hellmann Automotive (RHA) and Unipart Logistics (UL) at Jaguar Land Rover's Battery Assembly Centre (BAC).

The research methodology combined iterative software development, operational observation, workflow integration, and live production deployment. Development of SynOptics began in November 2024 with the objective of improving operational visibility and reducing production risk associated with delayed discrepancy detection.

An initial pilot deployment was conducted during December 2024 to evaluate dashboard responsiveness, automated alerting functionality, SAP automation stability, and operational compatibility. Following successful validation during the pilot phase, the system transitioned into live operational deployment during December 2024 and has remained in stable production operation since January 2025.

The implementation strategy prioritised minimal disruption to existing operational workflows while enabling continuous monitoring and rapid operational intervention. Python automation, SAP GUI scripting, Excel-based operational processing, Power Query refresh mechanisms, and live dashboard visualisation were integrated into a unified operational framework capable of supporting near real-time logistics monitoring.

Operational effectiveness was evaluated through continuous observation of discrepancy detection speed, operational response capability, production continuity, and error frequency. Comparative observations between pre-implementation and post-implementation operational states were used to assess performance improvements.

The research also incorporated resilience testing through automated SAP recovery workflows, dashboard continuity validation, and alert escalation mechanisms. Automated monitoring loops were evaluated under live operational conditions to verify system stability and response capability during SAP interruptions and operational anomalies.

6. Results and Operational Impact

The implementation of SynOptics delivered significant operational improvements within the Battery Assembly Centre environment. Prior to deployment, operational discrepancies such as incorrect scanned locations and stock delivery errors were often identified hours later or through next-day reporting processes. This delayed visibility increased operational risk and reduced the ability of teams to intervene before escalation.

Following deployment, discrepancy detection time was reduced from hours to approximately 3–5 minutes through continuous real-time monitoring. This enabled operational teams to respond proactively to issues shortly after occurrence, significantly improving responsiveness and reducing dependency on manual monitoring activities.

Operational observations indicated an approximate 98% reduction in operational errors compared to pre-implementation processes. Automated monitoring, dashboard visibility, and immediate email escalation workflows enabled faster intervention and reduced the likelihood of incorrect stock reaching production lines.

One of the most significant outcomes of the implementation was the elimination of production downtime caused by incorrect stock delivery. Within the Jaguar Land Rover Battery Assembly Centre environment, production interruptions may result in financial penalties estimated at approximately £1,000 per minute. By enabling continuous visibility and rapid corrective action, SynOptics substantially reduced operational exposure to these risks.

The implementation also improved operational communication and coordination across teams. Automated HTML email notifications provided immediate escalation of wrong scanned locations, replacing delayed reporting and manual escalation workflows. This improved awareness and supported faster corrective action within operational areas.

In addition to operational improvements, SynOptics demonstrated the effectiveness of lightweight digital transformation approaches within live manufacturing logistics environments. The platform achieved measurable operational gains using existing infrastructure and accessible technologies including Python, Excel, Power Query, and SAP GUI automation, without requiring large-scale enterprise system replacement.

The successful deployment of SynOptics further demonstrated how real-time operational intelligence can improve supply chain visibility, reduce operational risk, and support proactive logistics management within high-demand manufacturing environments.

7. Discussion

The deployment of SynOptics demonstrates how lightweight operational intelligence platforms can significantly improve visibility, responsiveness, and resilience within high-demand manufacturing logistics environments. The findings of this study highlight the practical value of integrating automation, real-time monitoring, and automated alerting into existing operational infrastructures without requiring large-scale enterprise transformation, supporting findings presented by Ivanov and Dolgui (2020) regarding digital resilience within modern supply chains.

One of the most significant outcomes of the implementation was the transition from reactive operational management to proactive operational control. Reducing discrepancy detection from hours to approximately 3–5 minutes enabled operational teams to intervene rapidly before issues escalated into production-impacting events. In manufacturing environments where production interruptions carry substantial financial consequences, such responsiveness represents a major operational advantage and aligns with agile operational management principles discussed by Gunasekaran, Yusuf, Adeleye and Papadopoulos (2018).

The study also demonstrates the importance of operational resilience within digital logistics systems. Through continuous SAP monitoring, automated recovery workflows, and escalation mechanisms, SynOptics improved operational continuity while reducing dependency on manual intervention during system interruptions.

Another important contribution of the platform is the demonstration that meaningful digital transformation can be achieved using accessible and cost-effective technologies. By integrating Python automation, SAP GUI scripting, Excel processing, Power Query refresh mechanisms, and automated email frameworks, SynOptics delivered measurable operational improvements while remaining compatible with existing enterprise infrastructure, consistent with observations by Wamba, Akter, Edwards, Chopin and Gnanzou (2015) regarding the operational value of accessible data-driven technologies.

Although developed within the Battery Assembly Centre environment, the overall operational framework may also be applicable to other warehouse and manufacturing operations requiring continuous monitoring, rapid discrepancy detection, and automated operational escalation.

Despite the positive operational outcomes, several limitations should be acknowledged. The study reflects deployment within a specific operational environment and may therefore require adaptation for implementation within alternative warehouse systems or enterprise structures. Additionally, future development could incorporate predictive analytics, enhanced cross-system integration, and advanced operational forecasting capabilities.

Overall, the findings demonstrate that real-time operational intelligence systems can provide substantial operational, financial, and resilience benefits within modern manufacturing logistics environments.

8. Conclusion

This paper presented SynOptics, a real-time operational intelligence platform developed and deployed within Jaguar Land Rover's Battery Assembly Centre operations supported by Rudolph & Hellmann Automotive and Unipart Logistics. The system was designed to improve operational visibility, reduce production risk, and support proactive logistics management within a high-demand automotive manufacturing environment.

The implementation demonstrated that accessible digital technologies can deliver substantial operational improvements without requiring extensive enterprise infrastructure transformation. Through the integration of SAP automation, Python-based processing, Power Query refresh mechanisms, live dashboard visualisation, automated alerting, and resilience-focused recovery workflows, SynOptics enabled continuous operational monitoring and rapid discrepancy management.

The deployment achieved measurable operational benefits including a 98% reduction in operational errors, reduction of discrepancy detection time from hours to approximately 3–5 minutes, and elimination of production downtime caused by incorrect stock delivery. Overall, the findings demonstrate how real-time operational intelligence frameworks can significantly improve supply chain visibility, operational resilience, and manufacturing continuity within modern logistics environments.

The framework may also provide practical value for other warehouse and manufacturing operations seeking cost-effective real-time operational monitoring solutions.

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A NOVEL SYSTEMS THINKING APPROACH FOR A MORE INTEGRATED AND SUSTAINABLE SUPPLY CHAIN

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Introduction

Intense competition and an ever-changing global landscape require organisations and their supply chains to be efficient and agile, whilst still achieving good levels of financial performance to sustain the business(s). In addition are today's environmental sustainability related challenges, including the need to reduce carbon footprints and for supply chains to become more circular. The topic of circular supply chains (csc) is becoming more prominent in supply chain management research (Montag, 2022), including areas such as reuse and recycling. In addition is the incorporation of green thinking within processes for managing sustainability objectives within operations (Silva and Gomes, 2025).

For businesses to successfully navigate through such challenges, it is recognised that essential to the management of related supply chains is the need for organisations to not function in isolation (Kamal and Irani, 2014). This includes attaining more efficient and effective flows (e.g. between departments or supply chain functions), such as financial, information and goods, in essence, improve supply chain integration (Tiwari, 2021). Therefore, this paper explores a systems thinking based approach to performance improvement in vertically integrated supply chains, and how the approach can be leveraged to improve key areas such as supply chain integration and environmental sustainability. The paper builds on research conducted for the development and testing of a systems thinking influenced conceptual model, combined with empirical knowledge accrued through fact finding stages of action research.

Discussion of Literature

Prominent in the literature for improving supply chain and business performance are the well-known approaches of lean and six sigma. Gupta et al (2015, p1026) summarises varied definitions of lean as "an integrated multidimensional approach encompassing a wide variety of management practices based on a philosophy of eliminating waste through continuous improvement." Garcia – Buenda (2021) highlights that the application of lean to supply chains for improving business performance is called Lean Supply Chain Management (LSCM) and is an enabler for elimination of waste, reducing costs and making improvements in quality (of service/product). To further expand the context of supply chain, Tortorella (2017) argues that LSCM includes linkages with organisations either downstream or upstream (of an organisation) regarding the flow of products, information and services. Application of lean is often combined with aspects the six sigma methodology, which has a focus on reducing variability in products/service (Patel et al, 2021) and incorporates techniques such as statistical process control. Using the DMIAC (Define, Measure, Analyse, Improve, Control) approach, Nascimento et al (2019) highlights six sigma as a structured approach which is highly disciplined. The combined approach of lean and six sigma (LLS) has grown significantly, with many conceptual frameworks being created, however, there is a lack of actual validation of the frameworks in the implementation case studies (Patel et al ,2021).

Progressing the lean/six sigma literature is the concept of sustainable supply chain management (Sarker et al, 2021), which includes the cleaning (or removal) of waste (or resource wasteful activities) within production systems, a concept that can be expanded to the wider supply chain through adopting approaches such as Green – Lean. Whilst Green-Lean practices can be driven by external factors such as regulations (Kumar and Rodrigues, 2020), application to a supply chain evokes less wasteful processes, which can lead to a reduction in energy usage, or reduced use of natural resources (Duarte and Cruz-Machado, 2019). Silva and Gomes (2025) present the concept of incorporating green thinking (in supply chains) to lean management systems, whilst highlighting that organisations may trade operational efficiency perspectives to benefit environmental targets (goals). This view is echoed by Rahman (2024), who argues that balancing profitability with environmental responsibility is a critical factor in sustainable supply chain management. More specific to circularity in relation to Co2 reduction, some literature presents the case that the recycling of certain types of material is more energy intensive and increases the use of fossil fuels, vis a vis increases Co2 emissions (Allwood, 2014; Molinaro and Sarkis, 2026).

A review of the literature concerning supply chain integration highlighted that to improve the management (vis a vis performance) of a supply chain, partners (i.e. functions) need to be integrated and that no function can perform better in isolation (Cohen and Roussel ,2013; Sabir et al, 2014; Kamal and Irani ,2014). Key for achieving a high level of supply chain performance is the strategic alignment of functions and processes (Tiwari (2021), with extensive integration enabling critical interactions between core processes (Cohen and Roussel, 2013). Examples of key interactions are identified as the integration of areas such as finance, planning and control, and knowledge integration (the exchange of knowledge, a deeper relationship than required than for information integration). However, whilst the benefits of supply chain integration have a high presence in the literature, there are barriers to successful integration. These include poor alignment of strategy (Bakker et al, 2012), and behavioural factors (such as lack of information sharing) preventing the supply chain being managed as a system, leading to silo working and the notion of functional silo's (Bakker et al ,2012; Christopher, 2016; Tai et al, 2022).

Holmberg (2000) avocadoes the use of Systems Thinking to make sense of the complex interdependencies (in supply chains) and to analyse the relevant contexts.

'System' is common term used within the literature in the context of viewing the supply chain as a system, or in a holistic way. Wang and Ahmed (2003) argue systems thinking offers an approach for understanding and managing a supply chain more holistically, Marshall (2012) highlights a systems thinking approach, presenting the notion that problems (e.g. in business processes) are systematic and cannot be viewed in isolation. Gerst (2013) refers to the work of Deming (1994) and presents that the aim of the system should be understood by all within the organisation(s). Whilst the topic of systems thinking is extensive within the literature, with authors such as Wang and Ahmed (2003) and Zexian and Xuhui (2010) building on the earlier work of systems thinkers such as Flood, Jackson and Checkland, the literature specific to the application within a supply chain context is less common. A particular gap exists in the application of Seddon's (2003,2008) method to a supply chain context. Core to Seddon's (2003) method is the notion that performance targets drive negative behaviour amongst staff (e.g. between departments), and that a systems view is looking 'outside in'. In essence viewing performance and value from the customers perspective, translated into the notion of 'purpose', which needs to be understood by everyone. Such core concepts have potential value when considering the modern challenges of supply chains, especially when considering the notion of conflicting targets (goals) bestowed on supply chains and their different internal/external functions.

Research Methods

Model Development/Design

For the conceptual model design a literature review was undertaken, analysing and evaluating themes to be converged to inform the model, combined with valuable practitioner knowledge (of the author) gained over many years working in industry. This reflects a combined approach that draws from the work of Nadeem (2019) and Garza-Reyes et al (2016) who highlights that practitioner's roles can play a critical role in the development of frameworks designed for application in industry.

Model Verification

To verify the model (model constructed in a considered and robust manner and could theoretically achieve the desired purpose if applied to an organisation), a modified Delphi method (Avella, 2016) was chosen. According to Njuangang et al (2017), Delphi methods have become more popular following work undertaken in the 1960's and are now used across many disciplines in different sectors - including sporadic use in the context of supply chain management (Förster et al,2014). The Delphi method for the model verification stage was deemed a logical, efficient and coherent method for seeking timely opinion from subject experts from both academic and practitioner groups. Other advantages and rationale are highlighted by Avella (2016) and Fink-Hafner et al (2019) and include:

- No limits to geographic areas of experts
- Avoids confrontation between experts (there would be no face-to-face contact between panel members or the researcher, with Delphi surveys being conducted online)
- More than one interaction with the respondent, thus giving more opportunity to think about the concept – iterative process
- Anonymity of panel results in freedom of expression

In addition, whilst establishing the level of verification, using the Delphi method also gave opportunity to further enhance the model through application of changes informed from each survey round – upon results, two survey rounds were deemed sufficient.

Model Validation – Case Study and Action Research

The verification process gives a theoretical insight to the model being applied; however, it was deemed necessary to discover whether the model can be applied in practice, in essence moving from concept to application. Empirical testing of the model (selected areas) within a carefully selected case organisation enabled application of core concepts, that were developed through further evolvement of the supply chain improvement literature (Zhang et al, 2015; Mangan and Lalwani, 2016; Vanpoucke et al, 2017; Tai et al, 2022). The collection and subsequent analysis of qualitative data (Saunders, 2012) enabled further understanding of the model concepts and the convergence of the supporting theories.

Building from the case study testing of the model, fact finding steps for future action research have been undertaken through experience gained within the minerals and construction sectors. This enabled identification of areas for leveraging the concepts of the model to areas of environmental sustainability.

Results and Analysis

The literature review and subsequent analysis enabled exploration of topics and concepts, which through evaluation were converged to inform the structure and content of the model. Key theories included systems thinking theory (Seddon, 2003), supply chain integration theory, together with business improvement and strategic leadership theory.

The structure of the model is comparable with sequential models (e.g. DMIAC approach) and has 5 stages – 1) Feasibility check, 2) Knowledge Generation, 3) New design, 4) Pilot, 5) Roll out. Whilst these stages have a familiarity with approaches such as DMIAC, the model is unique regarding an approach for understanding the potential negative impact of performance targets on performance. This was presented through the concept of an Interdepartmental Impact Audit (IIA); the key features are presented in Fig 1.

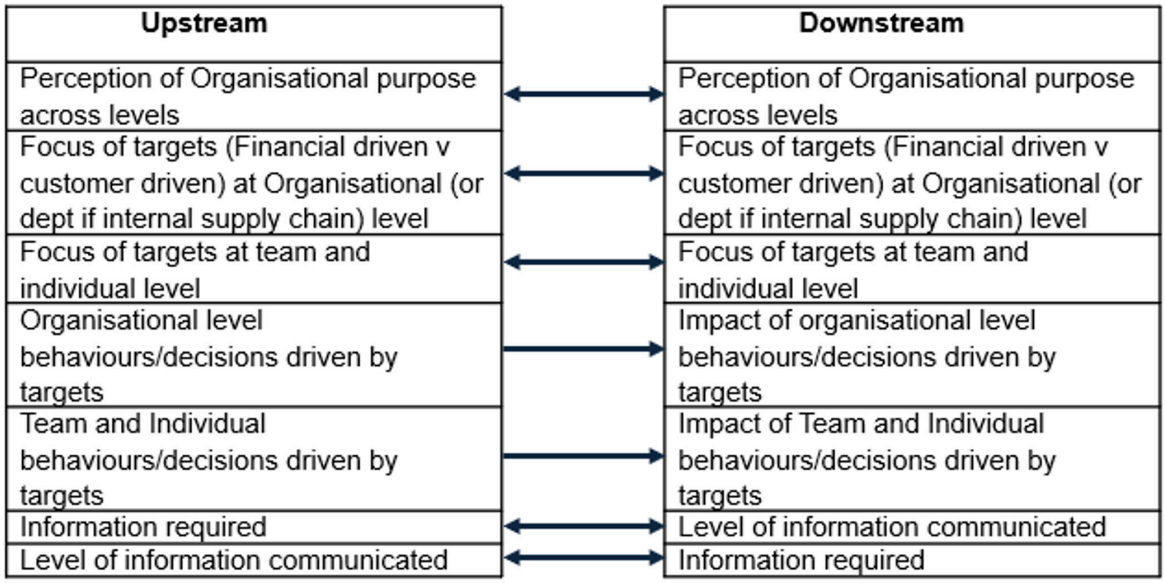

Fig 1 – Key IIA Features

Model Verification

The Delphi method proved effective with both rounds of the survey achieving a high level of consensus and therefore verification of the model. There were many positive comments, and in addition constructive criticism for enhancing the model. The learning from round 1 (through analysis of qualitative questions in survey 1) enabled the model to be enhanced, with the modifications reviewed by the Delphi panel in round 2 (survey 2). The resulting high level of consensus further verified the model concepts and related enhancements.

Model Validation

Partial testing of the model was undertaken within the case organisation, in particular testing of the IIA (Interdepartmental Impact Audit) which was derived through evolvement and convergence of key theories identified from the literature.

Application of the IIA element of the model identified the existence of functional barriers (Christopher, 2016; Seddon, 2003) and negative behaviours that would have a negative impact on supply chain performance. Such results highlight the potential for limiting supply chain integration and holistic thinking, further highlighted by a lack of knowledge of performance measures outside of the functional areas. This was in addition to the use of arbitrary targets, and the lack of understanding of information needs for efficient working upstream and downstream of a function. These results highlight the value of the IIA and validate the associated concepts used in the design of the model, including the iterative structure and strategic management for thinking more holistically, vis a vis, systems thinking.

Leveraging the Model Concepts

Since the original model development, the authors close association with organisations within the mineral products and construction sector enabled fact finding stages of action research to be undertaken. Using the principles of the IIA, the fact-finding stages identified factors as inhibiters for maximizing performance in areas of environmental sustainability. Key findings include:

- Achieving circularity in supply chain operations can have a negative impact on Co2 reduction
- Potential for Co2 targets and circularity targets to be viewed and measured in isolation – not viewed as a system
- In one organisation using lower Co2 raw material has a significant negative impact on financial performance due to using 3rd party suppliers
- Corporate pressure for volume targets and high financial returns prioritise the sale of products with much higher Co2 emissions
- Ambitious targets for using more recycled material could induce more use of raw materials (e.g. due to premature waste production)

Using the IIA principles, the identification of these factors highlights the difficulties in balancing financial, operational and sustainability related targets (Silva and Gomes, 2025; Rahman, 2024; Allwood, 2014; Molinaro and Sarkis, 2026). This further validates the concepts of the IIA and highlights potential opportunities for adapting the conceptual model for application within different sectors/contexts.

Conclusion and Discussion

The rationale for the study was based on the need for supply chain related organisations to continually improve performance due to the challenges of the external environment.

The convergence of theories and research in the fields of business improvement methods, supply chain integration and systems thinking enabled the design and subsequent testing of a conceptual model with unique attributes, including the IIA. From the results it can be concluded that the model works both conceptually and practically (the tested aspects), enabling the identification of performance improvement opportunities and weaknesses of integration between departments (or functions) within a vertically integrated supply chain.

Further to this, it can be concluded that leveraging the model concepts gives opportunity for understanding potential conflicts of performance in relation to environmental sustainability (i.e. Co2 reduction v circularity performance). This presents opportunity for case organisations to review current methods/structure/strategy for viewing the elements (or functions) of the supply chain more holistically (as a system), leading to higher levels of integration (between functions/departments).

Contribution

The research discussed in this paper has a theoretical contribution to the fields of supply chain management, systems thinking and environmental sustainability. From a practical perspective, the model offers organisations an approach for identifying performance improvement within their supply chain, and therefore value to the customers and wider society (e.g., through efficiencies leading to carbon reduction or improved circularity).

Future research directions

There is opportunity to extend the fact-finding steps of action research to a more intensive study within case organisations for further understanding current barriers and limiting factors for achieving performance in areas of environmental sustainability. In addition, through further research the model could be further leveraged into areas of future relevance, for example, areas related to implementing AI and digital readiness within vertically integrated supply chains.

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LEARNING SUPPLY CHAIN SUSTAINABILITY AND RESILIENCE CONCEPTS THROUGH SIMULATION GAMES

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Introduction

The concept of a supply chain system is challenging to teach due to their structure, complexity and dynamic nature. Supply chains consist of multiple organisations working together to deliver products and/or services to customers. They are characterised by several interdependencies, multiple relationships, a large set of processes, systems and being part of global networks that span multiple locations. Together, these characteristics create significant challenges when attempting to present and explain supply chain concepts in a learning environment.

Supply chain management is often difficult for students to grasp through traditional teaching methods alone, therefore, the use of supply chain simulation games offers considerable benefits. Simulations provide students with opportunities to explore how decisions made within one organisation can affect the performance of other organisations across the supply chain and the impact it has on these. They also enable learners to engage with a range of scenarios and operational challenges, thereby enhancing their understanding of supply chain and associated concepts such as resilience and sustainability. Using simulations, students can explore theoretical knowledge in practical settings (Drumhiller, et al. 2021) by replicating real-life scenarios.

This paper sets to bring further insight into the development of simulation games that incorporate concepts of resilience and sustainability to supply chain management and modelling.

Literature Review

Supply chains in the modern business environment face several challenges due to various disruptive events. Resilience is the ability of a system to withstand these disruptive events by maintaining the function of structure of the system disruption (Fahimnia et al., 2018; Azadi et al., 2022). Further, resilience includes the capability of the system to adapt quickly to disruption and bounce back to its original state (Wieland and Durach, 2021; Saffari et al., 2023) and also it refers to a system's capacity to adapt to a better state because of the experience it has gained from the disruptive event (Vergara et al., 2023). The new adapted state is viewed to reduce the negative impact and risk by preventing future disruptions. Therefore, it can be considered that supply chain resilience is the ability of the system to predict disruptive events and withstand unforeseeable disruptions by maintaining its basic function while efficiently returning to its original performance or adapting to a more desirable state that reduces the risk of future disruptions.

There is also an increasing body of literature that brings together concepts of sustainability in the supply chain management field (Amin et al., 2026). Often, sustainable supply chain management considers the three dimensions such as the economic, environmental and social dimensions, when presenting sustainability concepts to learners. Whereas the efficiency and effectiveness of both upstream and downstream members make up a supply chain sustainability's economic component. The ability of the supply chain members to effectively use resources, and decrease waste, consumption, and the environmental impact of their activities is referred to as the environmental component. The social dimension pertains to the steps taken by supply chain members to ensure a respectable workplace and the social welfare of their workers while also minimising the detrimental impact of their actions on the local communities. Hence sustainable supply chain management has the objective of maximising profitability while, minimising negative environmental and ecological impact while also improving social well-being (Vergara et al., 2023).

Development of games in business education

Simulations games have brought many benefits when incorporated into the business and management curriculum (McGrath et al., 2020). Tipi (2025a) brings forward a framework for tutors to adopt in developing their own simulation games allowing for a better integration of the teaching content with other materials already developed for the module or learning programme.

However simulation games are being discussed within this material as of beneficial within a classroom environment, they are not only valuable within this setting, but they can also be of benefit as training material in industry, for manager to explore concepts in a simulated environment (van der Zee et al., 2012).

In general, simulation games could be geared more towards learners who prefer access to learning content as part of a group, being part of a "game" with multiple players, however it is also to recognise that not all learners prefer this type of learning environment. Other may prefer to "be alone", when learning new concepts, and perhaps have the opportunity to repeat running a scenario multiple time. There are setting for a simulation game that will allow for this approach, specifically in an online asynchronous environment of learning (Tipi, 2021). This paper seats to present a simulation game that could be considered in both of these situations.

Methodology

This study adopts a two-stage simulation-based research approach to examine how resilience and sustainability concepts in supply chain management can be captured through, and taught with, simulation games. Building on the conceptual supply chain design proposed by Tipi (2025b, p. 50) and the five-stage modelling framework developed for simulation-based teaching and learning (Tipi, 2025a), the first stage develops a discrete-event simulation model of a manufacturer-centred supply chain and identifies a set of key performance measures (KPM) at each stage of the chain. The second stage introduces two disruptive event scenarios, used to evaluate the resilience and sustainability implications of the decisions captured within the simulated environment.

Modelling framework

The development of the simulation follows the five-stage framework set out by Tipi (2025b) and applied to simulation-based teaching by Tipi (2025a): (1) evaluate current learning needs; (2) develop the simulation model; (3) analyse the model against the intended learning objectives; (4) implement the model within the teaching and learning platform; and (5) carry out a post-implementation review informed by student feedback (Figure 1).

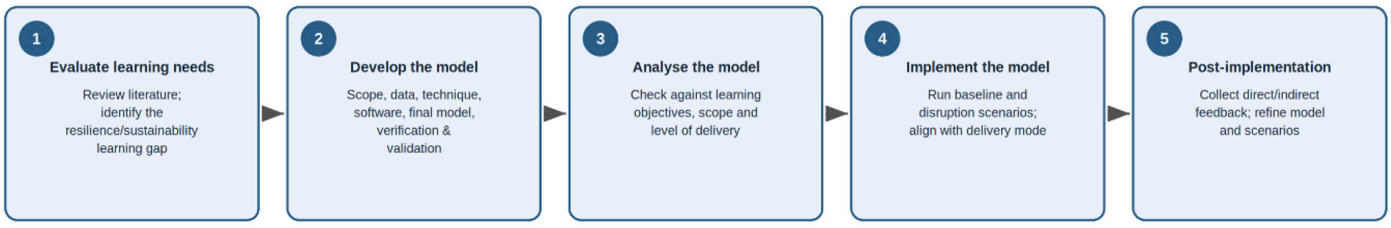

Figure: 1 Five-stage modelling framework applied to this study (adapted from Tipi, 2021b, 2025a)

Stage 1 was addressed through the review of existing supply chain simulations and games reported in the literature, which highlighted a gap in models that allow learners to observe, in a single environment, how a disruptive event affects resilience and sustainability performance jointly rather than in isolation. Stages 2 to 5 are described in the remainder of this section.

Simulation model development

Following the modelling stages set out in Tipi (2025b), a manufacturer-centred supply chain is developed using a pen manufacturing case as the illustrative product and industry context (Figure 2). The chain is structured across four groups of activity and fourteen individual nodes: raw material extraction (rubber/wood, petroleum and chemicals, metal ore and mining), component manufacturing (plastic resin and pellets, rubber grips and packaging, ink and dye formulation, and metal stamping of tips, springs and clips), the pen manufacturer's assembly operation (injection moulding, the assembly line, and quality control and packaging), and distribution and sales (a central warehouse and distribution centre and a retail/e-commerce channel), together with the end customer and a reverse logistics flow. The model deliberately retains the interconnections between these nodes rather than collapsing them into a single generic stage. Each component manufacturing node draws on a specific combination of raw materials, quality control and packaging issues, a production plan to the distribution centre and, through a dotted inventory-replenishment loop, signals back to each component manufacturing node individually, and the distribution centre and retailer exchange demand forecasts, orders, returned goods and defective-return information in addition to the forward flow of physical product (Figure 2).

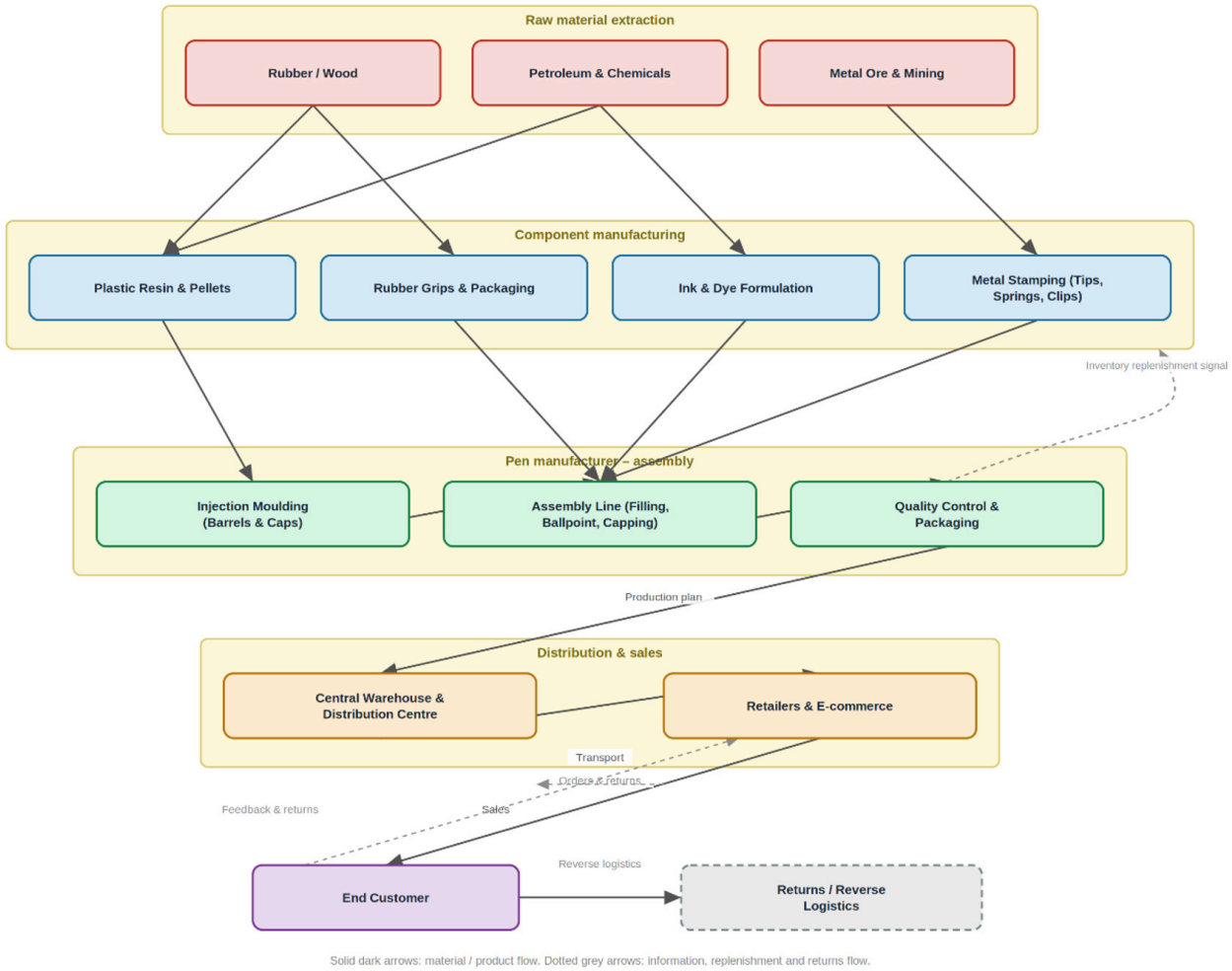

Figure 2: Pen manufacturing supply chain structure used in the simulation model (baseline)

The model is developed using Simul8, a discrete-event simulation software package, consistent with simulation material previously developed for teaching and learning supply chain concepts (Tipi, 2025b). Each stage of the chain is represented as a network of processing, queuing, inventory and transport activities. Material flows from raw material suppliers through component manufacturing, assembly, distribution and retail to the end customer, with matching order and information flows, and a reverse flow of returns, moving back through the chain. Input data for processing times, order quantities, transport times and customer demand are defined using statistical distributions derived from typical manufacturing operating conditions, allowing the model to reflect the variability observed in practice.

A set of KPM is defined and captured as an output at key stages of the chain, structured around the two concepts explored in this study and limited to the measures that are subsequently reported and compared across scenarios (Table 1). Resilience-related measures focus on the ability of the chain to maintain and recover performance following a disruptive event, namely average lead time, order fulfilment rate and recovery time. Sustainability-related measures focus on the resource and environmental implications of operating decisions, namely transport distance and associated emissions, inventory holding level and the rate of product returns. Including a reverse logistics stage in the model also allows returns, an aspect frequently omitted from teaching-oriented supply chain simulations, to be captured as a joint resilience and sustainability indicator: a rise in returns following a disruption, signals both a loss of service quality and an increase in wasted material and rework.

Supply chain stage	Resilience-related KPM	Sustainability-related KPM
Component manufacturing / pen manufacturer (assembly)	Average lead time	–
Distribution centre	–	Transport distance / emissions
Retailers	Order fulfilment rate; Recovery time	Inventory holding level
End customer / reverse logistics	–	Returns / defective-return rate

Table 1: Key performance measures identified at each supply chain stage

Scenario design

To address the second stage of the research approach, two disruptive event scenarios are constructed in addition to a baseline (undisrupted) scenario, allowing a comparative analysis of the KPM identified under normal and disrupted operating conditions.

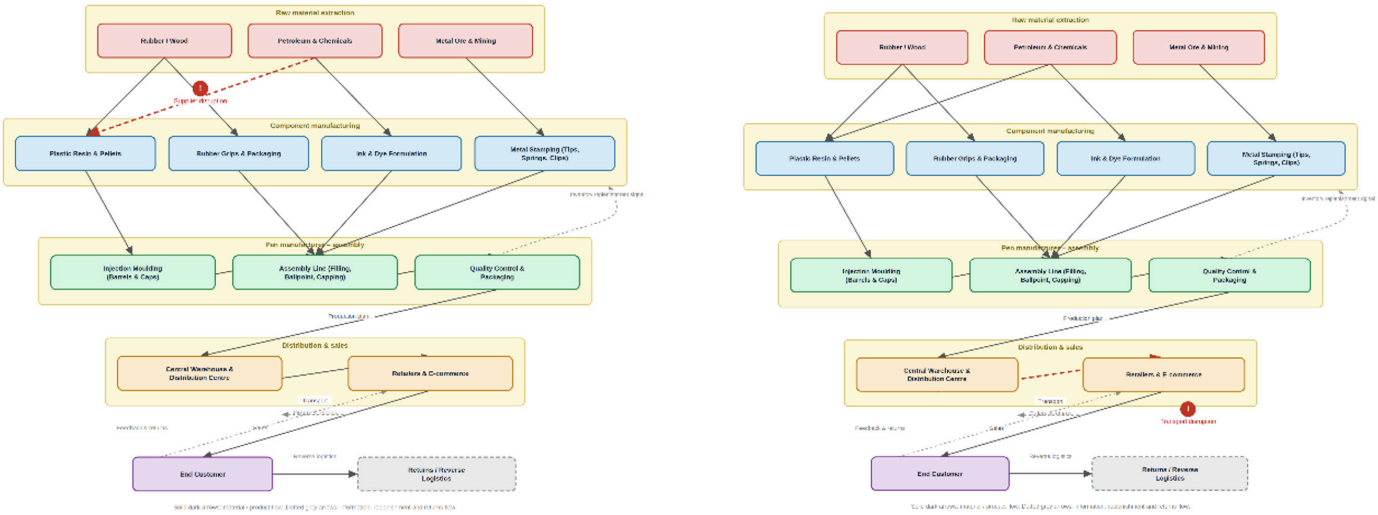

Figure 3: Scenario (a) and Scenario (b): supplier disruption (a) and transportation disruption (b) applied to the original supply chain model

The baseline scenario represents the supply chain operating under standard demand and supply conditions, with no disruptive events introduced, and is used as the reference point for comparison. Scenario (a) - supplier disruption - introduces a reduction in capacity and an extension of lead time at the raw material supply stage, representing an upstream disruption such as a shortage of plastic resin or metal stock feeding component manufacturing (Figure 3). Scenario (b) - transportation disruption - introduces a delay to the transport lead time between the distribution centre and retailers, representing a disruption such as a route closure or a carrier capacity constraint (Figure 3). In both scenarios, the disruption is introduced after an initial warm-up period, and its duration and severity are set to be broadly comparable across the two events, so that the effects of a supply-side and a transport-side disruption can be compared on an equivalent basis.

The underlying model logic, warm-up period and simulation run length are held constant across all three scenarios, with only the disruption-related input parameters varied, ensuring that differences in the recorded KPM can be attributed to the disruptive event rather than to changes in model structure. Consistent with recommended practice for discrete-event simulation experimentation, the model is run for multiple replications under each scenario to reduce the effect of random variation and to obtain a stable estimate of each KPM. The mean value of each KPM is then compared across the baseline, Scenario (a) and Scenario (b), to identify the extent to which each disruption affects resilience and sustainability performance, and to highlight where trade-offs occur between the two objectives.

Verification, validation and experimental design

Verification and validation form the final step of the six-step model development process (Tipi, 2025b) and are treated as an explicit part of Stage 2 of the modelling framework. Verification is carried out through structured walkthroughs of the model logic and through extreme-condition testing, for example setting supplier capacity or transport availability to zero to confirm that the model responds as expected (no throughput, growing backlog) before disruption scenarios of a more moderate severity are introduced. Validation considers whether the baseline model behaviour, including typical lead times, fulfilment rates and inventory patterns, is consistent with what would be expected of a manufacturing supply chain of this type, drawing on the operating parameters used in comparable published simulations (Tipi, 2025b; Chilmon and Tipi, 2020). For the experimental design, a warm-up period is used to remove the influence of initial model conditions on the recorded KPM, and each scenario is run for multiple replications, with the number of replications set with reference to the variability observed in pilot runs, so that the width of the resulting confidence interval around each KPM is acceptable for comparison purposes.

Embedding the simulation within the learning design

Consistent with the use of the simulation for teaching and learning rather than purely for analysis, the model development also takes account of Stages 4 and 5 of the framework, implementation and post-implementation. Running the baseline scenario first allows learners to engage in a concrete experience of operating the supply chain under normal conditions, in line with the starting point of Kolb's experiential learning cycle (Tipi, 2025a). Learners then engage with Scenario (a) and Scenario (b), either individually or in teams, and are asked to record and interpret the resulting KPM before comparing their observations in a facilitated discussion. This mirrors the direct and indirect feedback mechanisms described by Tipi (2025a): indirect feedback is gathered from the pattern of engagement with the simulation and the quality of the KPM interpretation submitted by learners, while direct feedback is collected through a short post-session survey on the clarity of the scenarios and the usefulness of the KPM in understanding the trade-offs involved. This feedback forms the basis of the post-implementation stage of the framework, informing any refinement of the scenarios or the KPM set in subsequent iterations of the simulation.

Findings

Baseline performance

Under the baseline conditions the model returns a stable pattern of performance across the supply chain, with lead times, fulfilment rates and inventory positions consistent with the operating parameters set for the pen manufacturing supply chain (Table 2). These results are used as the reference point against which the two disruptive scenarios are compared.

Effect of the disruptive scenarios

KPM	Baseline	Scenario (a) – Supplier disruption	Scenario (b) – Transport disruption
Order fulfilment rate (%)	96	84	89
Average lead time (days)	4.2	7.1	6.3
Recovery time (days)	–	9	5
Inventory holding level (units)	320	470	260
Transport distance / emissions (index, baseline = 100)	100	92	118
Returns / defective-return rate (%)	3.1	4.6	3.4

Table 2: Selected KPM under baseline and disruptive scenarios

The results indicate that both disruption scenarios reduce order fulfilment and extend average lead time relative to the baseline, confirming the expected resilience impact of an upstream and a downstream disruption respectively. The supplier disruption (Scenario (a)) produces the larger reduction in fulfilment rate and the longer recovery time, reflecting the difficulty of substituting raw material supply once a shortage occurs at the component manufacturing stage, whereas the transportation disruption (Scenario (b)) recovers more quickly once the disrupted route between the distribution centre and retailers is resolved. Scenario (a) also produces a higher rate of returns and defective products, consistent with quality control pressures when component manufacturers substitute materials or suppliers under time pressure.

The two scenarios diverge, however, in their sustainability implications. In Scenario (a), the reduction in raw material availability is partly compensated by an increase in inventory holding at the pen manufacturer and distribution centre, raising average inventory levels while marginally reducing recorded transport distance, as fewer full loads move through the chain during the disruption period. In Scenario (b), maintaining service levels at retailers in the face of the transport disruption is achieved in part through rerouting and more frequent, smaller deliveries from the distribution centre, which increases the recorded transport distance and associated emissions measure relative to the baseline, despite inventory levels falling as stock is drawn down more quickly. This illustrates a trade-off between the two concepts under investigation: actions that preserve resilience, such as holding additional buffer stock or increasing delivery frequency, can carry sustainability costs, and the direction and scale of this trade-off differs depending on where in the chain the disruption occurs.

Challenges in capturing resilience and sustainability through a single set of KPM

A further finding relates to the difficulty of expressing resilience and sustainability using a common or directly comparable metric. Resilience-related measures in this study are naturally expressed in time-based or percentage terms, such as recovery time and fulfilment rate, while sustainability-related measures combine physical quantities, such as distance, material use and returns, with an estimated environmental measure. Comparing performance across the two disrupted scenarios therefore required the KPM to be considered stage-by-stage and side-by-side, rather than combined into a single composite score, since a change that improves one measure, for example faster recovery through additional stock, does not translate into a proportional change in another, for example emissions or returns. This is consistent with the wider literature noting that trade-off analysis across resilience and sustainability objectives is not straightforward and depends on the specific KPM selected for evaluation (Chilmon and Tipi, 2020).

Conclusion

Implications for simulation-based learning

Beyond the KPM results themselves, running the two scenarios in sequence within a single supply chain model, rather than as separate simulations, appears well suited to the type of reflective discussion associated with Kolb's learning cycle. Once learners have observed and recorded the KPM under Scenario (a) and Scenario (b), the facilitated discussion stage can draw directly on Table 2 to prompt comparison, for example asking learners to identify which scenario they consider more damaging overall, and to justify this using specific KPM rather than general impressions. This is consistent with the open case study approach to assessment described in earlier work (Tipi, 2014), where learners are asked to interpret model output against a set of criteria rather than to reproduce a fixed answer. It also suggests that a deliberate discussion of how KPM are chosen, and of their limitations, forms as important a part of the learning activity as the simulation output itself, since learners who understand why resilience and sustainability cannot be reduced to a single score are better placed to evaluate real supply chain trade-offs in practice.

The findings derived from the simulated manufacturer centred supply chain, structured around a simplified Tier 1 supplier configuration, offer several critical insights into the interplay between resilience and sustainability in operations management. By comparing a baseline against two distinct disruptive scenarios this study demonstrates that the location of a disruption fundamentally alters both the nature of the resilience challenge and its associated sustainability consequences. These results directly address the abstract's central aim: to design a methodology that enables learners to observe these complex trade offs within a single, controlled simulation environment.

A central methodological finding, consistent with the study's emphasis on challenges in capturing these two concepts, is the inherent incommensurability of resilience and sustainability metrics. Resilience related KPMs in this simplified framework are naturally expressed in temporal (lead times), volumetric (throughput), or percentage terms (fulfilment rate). Sustainability related KPMs, however, combine physical quantities (transport distance, inventory units, and waste) with derived environmental estimates such as emissions indices. These measures do not share a common unit, which precludes the construction of a single composite "resilience sustainability" score. Comparing Scenario (a) and Scenario (b) therefore required a side by side, tier by tier evaluation rather than a single ranking. This reinforces Tipi's (2025b) assertion that trade off analysis remains central to supply chain analytics; forcing these disparate objectives into a single optimisation formula would obscure the very tensions that managers must navigate in practice.

Limitations and future research

While the simplified structure aids pedagogical clarity, it introduces certain limitations. The current design treats disruptive events as exogenous shocks with fixed durations and severities. In real supply chains, managers employ adaptive strategies such as dynamic supplier switching, inventory pooling, or demand shaping, that would alter the propagation of the disruption. Future iterations of the simulation could embed these decision points as interactive variables, allowing learners to adjust sourcing ratios or transport modes mid simulation and observe real time impacts on both resilience and sustainability. Additionally, the current KPM set does not explicitly capture the social dimension of sustainability (e.g., labour conditions at supplier sites or community impact of transport rerouting). As sustainability frameworks evolve towards a full Environmental, Social, and Governance (ESG) perspective, future research could explore how such qualitative aspects might be translated into simulation parameters or incorporated as supplementary discussion prompts.

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CONSUMER RETURN BEHAVIOUR AS A SOURCE OF SUPPLY RISK IN CIRCULAR ELECTRONICS SYSTEMS

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Abstract

Circular economy (CE) strategies are increasingly viewed as mechanisms for improving supply chain resilience by securing secondary material flows and reducing dependence on primary resources (Silva et al., 2023; Gaudenzi et al., 2023). In consumer electronics, however, reverse supply chains depend on voluntary consumer decisions, creating behavioural uncertainty in supply availability. This study conceptualizes consumer return behaviour as a source of behavioural supply risk and examines return intention and channel choice as mechanisms of supply generation and supply allocation.

Drawing on the Theory of Planned Behavior (Ajzen, 1991), the study analyses survey data from 461 respondents. Results reveal extensive device hibernation, with approximately 86% of respondents retaining end-of-use mobile phones at home rather than releasing them into recovery channels. However, only 16.1% of respondents indicated that they would continue retaining the device if considering disposal today, suggesting the existence of substantial latent supply. Reliability analysis indicated satisfactory internal consistency for Perceived Behavioural Control (= .811) and Trust (= .836). Regression analysis showed that attitude was the only significant predictor of return intention, while Perceived Behavioural Control and Trust were not significant predictors ($R^2 = .019$).

The findings suggest that uncertainty in circular supply chains is shaped not only by whether consumers release devices but also by how they allocate them across competing channels. The study contributes by introducing behavioural supply risk, conceptualising device hibernation as latent supply, and identifying channel choice as a mechanism of supply allocation.

1. Introduction

Circular economy (CE) strategies are increasingly recognised as mechanisms for improving sustainability and supply chain resilience by enabling the recovery and reuse of secondary resources (Silva et al., 2023; Gaudenzi et al., 2023). In consumer electronics, circular supply chains can reduce dependence on primary materials through the recovery of end-of-use devices for reuse, refurbishment, and recycling (Althaf & Babbitt, 2021).

Unlike forward supply chains, however, reverse supply chains depend on voluntary consumer decisions. Consumers determine whether products are returned and which channels they enter, creating uncertainty in the quantity and accessibility of secondary supply (Bressanelli et al., 2019). This challenge is amplified by device hibernation, whereby unused electronic devices remain stored in households rather than entering recovery systems (Wilson et al., 2017; Ylä-Mella et al., 2015).

Supply chain resilience research has traditionally focused on disruption-based risks such as supplier failures, transportation interruptions, and demand uncertainty (Tukamuhabwa et al., 2015; Hohenstein et al., 2015). Although recent studies have increasingly emphasised network complexity and systemic uncertainty (Scholten et al., 2020; Wieland & Durach, 2021), resilience research largely assumes that supply originates from organisational actors whose behaviour can be coordinated through governance and contractual arrangements. Circular supply chains challenge this assumption because access to secondary resources depends on the behaviour of consumers.

Importantly, uncertainty arises not only from whether consumers release devices but also from how they allocate them across competing recovery channels, which vary in their accessibility to circular recovery networks (Wieser & Tröger, 2018)

To address this challenge, this paper introduces the concept of behavioural supply risk, which captures supply uncertainty arising from consumer decisions in reverse supply chains. In particular, attention is directed towards two behavioural mechanisms: supply generation, referring to whether end-of-use devices are released, and supply allocation, referring to the channels through which released devices are distributed.

Using survey data from 461 consumers, the paper addresses the following research question:

How do consumer return intention and return channel choice influence the reliability of reverse supply flows in circular electronics supply chains?

The paper contributes to supply chain resilience and circular economy research by extending attention beyond disruption-based explanations of supply uncertainty and highlighting the role of consumers in shaping the availability and accessibility of secondary resources. In doing so, it introduces behavioural supply risk as a source of uncertainty in circular supply chains and conceptualises hibernated devices as a form of latent supply.

2. Literature Review

2.1 Behavioural Supply Risk in Circular Supply Chains

Supply chain resilience (SCR) is commonly defined as the ability of supply networks to anticipate, respond to, and recover from disruptions while maintaining performance (Pettit et al., 2010; Tukamuhabwa et al., 2015). Traditional resilience research has primarily focused on disruption-based risks such as supplier failures, transportation interruptions, natural disasters, and demand volatility (Hohenstein et al., 2015). More recent work has broadened this perspective by emphasising network complexity, interdependencies, and systemic uncertainty (Scholten et al., 2020; Wieland & Durach, 2021).

Despite these advances, resilience research continues to focus predominantly on supply originating from organisational actors connected through formal governance and contractual relationships (Katsaliaki et al., 2022). As a result, uncertainty is typically conceptualised as arising from disruptions that affect existing supply relationships rather than from the behaviour of actors who decide whether supply becomes available in the first place.

This assumption becomes problematic in circular supply chains. Unlike conventional supply networks, circular systems rely on reverse flows generated by consumers who are not contractually obligated to return products and whose decisions remain largely outside organisational control (Bressanelli et al., 2019). Consequently, uncertainty may arise not only from disruption events but also from variability in consumer behaviour.

Within this context, behavioural supply risk refers to supply uncertainty arising from consumer decisions that affect the availability and accessibility of secondary resources. Unlike traditional supply risks, which emerge from disruptions affecting established supply relationships, behavioural supply risk originates from the decentralised decisions of consumers who control access to end-of-use products. Consumers can therefore be viewed as distributed suppliers because they collectively determine whether products remain stored, are released into circulation, and which recovery pathways they enter. As a result, consumer behaviour directly shapes the quantity, timing, and accessibility of secondary supply available to circular recovery systems (Bressanelli et al., 2019; Wilson et al., 2017; Knight et al., 2022). From a resilience perspective, behavioural supply risk represents a distinct source of uncertainty that precedes and influences the formation of secondary supply before products enter formal recovery networks (Scholten et al., 2020; Wieland & Durach, 2021).

2.2 Supply Generation and Supply Allocation

The Theory of Planned Behavior (TPB) has been widely applied to explain recycling, reuse, and product return behaviour (Ajzen, 1991). Previous research has identified attitudes, trust, and perceived behavioural control as important determinants of participation in circular economy activities (Islam et al., 2021; Shevchenko et al., 2023). In the context of consumer electronics, concerns regarding convenience, data security, and trust in recovery organisations have also been linked to disposal decisions and device retention (Atlason et al., 2017; Tan et al., 2018; Abdelmeguid & Corsini, 2026).

While prior research has improved understanding of return participation, less attention has been devoted to what happens after products are released. End-of-use devices may enter trade-in, refurbishment, resale, gifting, donation, recycling, or storage pathways, which differ in their accessibility to circular recovery systems.

From a supply-chain perspective, consumer behaviour influences reverse flows through two distinct mechanisms. The first is supply generation, which concerns whether products are released or retained. The second is supply allocation, which concerns where released products are directed. Together, these mechanisms determine both the quantity and accessibility of secondary supply entering circular systems (Bressanelli et al., 2019; Wilson et al., 2017; Ylä Mella et al., 2015).

This distinction suggests that the reliability of reverse supply flows depends on more than consumer participation alone. Product release determines whether secondary supply becomes available, whereas channel choice influences whether that supply remains accessible to formal circular recovery systems. End-of-use devices may be directed towards reuse, resale, gifting, refurbishment, or recycling pathways, each with different implications for resource recovery and supply visibility (Wieser & Tröger, 2018; Ratay & Mohnen, 2022; Wilson et al., 2017). In circular supply chains, the quantity and accessibility of secondary resources therefore depend on both supply generation and supply allocation processes (Scholten et al., 2020; Wieland & Durach, 2021).

3. Methodology

3.1 Survey Development

This study adopts a quantitative research design to examine the behavioural drivers of consumer return intention and channel choice in circular electronics supply chains. The survey instrument was developed from prior literature on circular economy behaviour, electronic waste recovery, and product disposition decisions, and refined through a focus group, expert review, and pilot testing (Islam et al., 2021; Atlason et al., 2017; Tan et al., 2018).

Measurement items were operationalised using Likert-type scales. Perceived Behavioural Control (PBC) captured convenience and effort associated with returning a device. Trust reflected perceptions of organisational reliability, transparency, customer support, and secure handling of personal data. Attitude measured respondents' evaluations of returning or selling a device rather than retaining it at home.

3.2 Data Collection and Analysis

Data were collected through an online survey administered using the Qualtrics platform. Participation was voluntary and respondents were required to provide informed consent before completing the questionnaire.

The initial dataset contained 710 responses. To ensure data quality, several cleaning procedures were applied. Pilot responses collected before the official launch date were removed, along with incomplete questionnaires, non-consenting respondents, and individuals not meeting the screening criteria. Two attention-check questions were used to identify inattentive responses. Completion times were also examined, and responses completed in less than 168 seconds or more than 1,260 seconds were excluded, following recommended survey data screening practices (Hair et al., 2022). Following these procedures, the final analytical sample consisted of 461 valid observations. Reliability was assessed using Cronbach's alpha, with values above .70 indicating satisfactory internal consistency (Hair et al., 2010). Perceived Behavioural Control achieved a reliability coefficient of = .811, while Trust achieved = .836.

Data analysis consisted of four stages. First, descriptive statistics were used to examine patterns of device retention and disposal channels. Second, reliability analysis was conducted for the multi-item constructs. Third, correlation analysis was used to explore relationships among Perceived Behavioural Control, Trust, Attitude, and Return Intention. Finally, Ordinary Least Squares (OLS) regression was performed to examine the effects of Perceived Behavioural Control, Trust, and Attitude on Return Intention, following established multivariate analysis procedures (Hair et al., 2010).

4. Results

4.1 Sample and Device Hibernation

The initial dataset contained 710 survey responses. Following data-cleaning procedures, including the removal of pilot responses, incomplete questionnaires, non-consenting participants, duration outliers, and respondents failing attention checks, the final analytical sample consisted of 461 respondents.

Descriptive analysis revealed extensive device hibernation among respondents. Approximately 86% of respondents reported retaining their end-of-use mobile phone at home after it had ceased to function as their primary device. Only a relatively small proportion of devices had entered trade-in programmes, resale channels, donation pathways, or recycling systems.

This finding indicates a substantial gap between potential and realised secondary supply. Although devices remain physically available within society, they are largely inaccessible to formal circular recovery systems. Device hibernation therefore represents a form of latent supply, where potentially recoverable products remain unavailable to reuse, refurbishment, or recycling activities.

4.2 Supply Allocation Across Channels

The findings indicate that consumer behaviour affects reverse supply flows through two sequential mechanisms. First, consumers determine whether devices are released into circulation. Second, consumers determine how released devices are allocated across competing channels.

Among the devices that were released, 17.5% entered trade-in programmes, 19.0% were sold through resale channels, 34.9% were donated or gifted, and 9.5% entered recycling systems. These results indicate that released devices do not enter a single recovery pathway but are dispersed across multiple competing channels. While trade-in programmes and recycling schemes provide relatively direct access to products and materials for recovery organisations, devices entering resale, donation, and gifting channels become less visible to formal recovery networks.

The distribution of released devices across multiple pathways highlights the role of supply allocation in reverse supply chains. Even when consumers choose to release products, channel choice influences the extent to which secondary supply remains accessible to formal circular recovery systems. Consequently, reverse supply reliability depends not only on the volume of products returned but also on the channels through which those products are allocated. In the present sample, 39.7% of released devices entered formal recovery channels, whereas 52.4% were directed to informal pathways, demonstrating that channel choice can substantially affect the accessibility of secondary resources. The remaining 7.9% consisted of devices that were reported as lost, stolen, disposed of in household waste, or allocated to miscellaneous pathways.

4.3 Latent Supply Activation and Return Drivers

Responses to the hypothetical return scenario provide additional insight into the potential activation of latent supply. When asked which option they would realistically consider if they were to sell or return the device today, only 16.1% of respondents indicated that they would continue keeping the phone at home. In contrast, 62.9% selected a formal recovery pathway, including trade-in programmes, sales to refurbishers, or recycling systems. A further 21.0% selected informal pathways such as online resale, donation, or transfer to family and friends.

These findings contrast sharply with the observed device hibernation rate of 86.3% and suggest that a substantial proportion of currently inactive devices may be recoverable under appropriate conditions. From a supply chain perspective, this highlights the existence of latent supply that could potentially be mobilised through effective channel design and consumer engagement strategies.

Responses to the survey suggest that consumers evaluate return and disposal options using a combination of practical, economic, and trust-related considerations. Factors relating to convenience, effort, time requirements, secure handling of personal data, organisational trustworthiness, and expected financial value emerged as important considerations when evaluating return options.

The strongest concern related to secure deletion of personal data, with 79.6% of respondents rating this factor as important or very important when assessing trust in a recovery organisation. Similarly, 70.3% of respondents considered a well-known and trustworthy company important or very important, while 66.8% emphasised the importance of fast and reliable payment after returning a device. In addition, 58.6% of respondents indicated that a clear explanation of what happens to a returned phone was important or very important.

These findings suggest that behavioural barriers to device release extend beyond environmental attitudes alone and may reflect concerns relating to effort, trust, transparency, and perceived value. Taken together, the results provide additional insight into the persistence of device hibernation. Although many respondents indicated willingness to release devices under hypothetical return scenarios, participation appears to depend on the availability of recovery channels that are convenient, trustworthy, transparent, and capable of addressing data security concerns.

4.4 Reliability and Correlation Analysis

Reliability analysis demonstrated satisfactory internal consistency for both multi-item constructs. Perceived Behavioural Control achieved a Cronbach's alpha value of .811, while Trust achieved a Cronbach's alpha value of .836.

Correlation analysis revealed a strong positive relationship between Perceived Behavioural Control and Trust ($r = .685$). Relationships between the behavioural constructs and Return Intention were comparatively weak, suggesting that factors influencing device return decisions may be more complex than those captured by conventional behavioural constructs alone.

Construct	Cronbach's Alpha
Perceived Behavioural Control	.811
Trust	.836
Table 1. Reliability Results	

4.5 Regression Analysis

Ordinary Least Squares (OLS) regression was conducted to examine the effects of Perceived Behavioural Control, Trust, and Attitude on Return Intention.

The model explained a limited proportion of variance in Return Intention ($R^2 = .019$), indicating that approximately 1.9% of observed variation in respondents' intentions to release devices was captured by the model.

Predictor	B	p
Perceived Behavioural Control	0.031	.397
Trust	-0.048	.183
Attitude	-0.050	.012

Table 2. Regression Results

Among the predictors, Attitude emerged as the only statistically significant variable. Neither Perceived Behavioural Control nor Trust demonstrated significant effects on Return Intention.

Overall, the results indicate that traditional behavioural variables provide limited explanatory power for explaining participation in reverse supply systems. While attitudes appear to influence device release decisions, much of the variation in return behaviour remains unexplained by the present model.

5. Discussion

The study also supports the conceptualisation of consumers as distributed suppliers. In circular systems, consumers collectively influence the availability of secondary resources because they control access to end-of-use products. Rather than acting solely as end users, consumers become suppliers of products, components, and materials that may potentially re-enter circular recovery systems. This perspective extends existing circular supply chain research by highlighting that supply availability is shaped not only by organisational decisions but also by decentralised consumer behaviour (Knight et al., 2022).

The findings further demonstrate that supply uncertainty does not end once a consumer decides to release a device. Instead, uncertainty also emerges through supply allocation processes. Released devices may enter formal recovery systems, resale markets, donation pathways, gifting arrangements, or recycling schemes. Consequently, supply availability depends not only on whether products are released but also on where they are directed once released. Consistent with previous research on recovery pathways and disposition decisions (Ratay & Mohnen, 2022; Shevchenko et al., 2023), the results indicate that channel choice can significantly affect the accessibility of secondary resources.

The behavioural model demonstrated limited explanatory power ($R^2 = .019$). Although previous studies have identified Perceived Behavioural Control and Trust as important determinants of circular behaviour (Islam et al., 2021; Shevchenko et al., 2023), neither variable significantly influenced Return Intention in the present study. Instead, descriptive findings suggest that concerns related to data security, trustworthiness, transparency, and financial value may play a more important role in device release decisions than traditional behavioural models alone capture.

The findings have important managerial implications. Organisations should view households not only as sources of demand but also as repositories of secondary supply. Improving circular supply chain resilience therefore requires activating latent supply through trusted recovery systems, secure data-erasure services, transparent communication, and attractive recovery channels. Because consumers allocate devices across multiple competing pathways, organisations must compete not only to recover products but also to gain access to secondary resources.

Future research could examine behavioural supply risk across different product categories, investigate how latent supply evolves over time, and explore interactions between behavioural, operational, and disruption-based risks. Particular attention should be given to understanding the gap between observed behaviour and stated willingness to participate in recovery systems, as this may reveal important mechanisms underlying latent supply activation.

6. Conclusion

This study examined how consumer return behaviour influences reverse supply flows in circular electronics supply chains. The findings show that behavioural supply risk emerges through two mechanisms: supply generation and supply allocation.

Approximately 86.3% of respondents retained end-of-use mobile phones at home, while released devices were distributed across multiple competing channels. The results further suggest the existence of substantial latent supply, as only 16.1% of respondents indicated that they would continue retaining the device if considering disposal today.

The study contributes by introducing behavioural supply risk, conceptualising hibernated devices as latent supply, identifying consumers as distributed suppliers, and highlighting channel choice as a mechanism of supply allocation. These findings suggest that improving circular supply chain resilience requires not only product recovery capabilities but also effective mechanisms for activating and accessing secondary supply.

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USING SYSTEM DYNAMICS TO ANALYSE MANUFACTURING SUPPLY CHAIN RESILIENCE AND ITS IMPACT ON HUMAN RESOURCE MANAGEMENT PRACTICE

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Abstract

Manufacturing supply chains are exposed to compounding disruptions arising from geopolitical uncertainty, climate-related shocks, labour shortages, and digital vulnerabilities. While the resilience literature has matured considerably, the workforce is still too often treated as a passive resource rather than an active mechanism through which resilience is built, degraded, and renewed. This paper develops and tests a system dynamics model that links manufacturing supply chain resilience (SCR) to human resource management practices (HRMP), aiming to understand how integrated resilience HR policies affect productivity, safety, and workforce stability over time. The model connects four resilience domains (capability, preparedness, flexibility and technology) with four HRMP dimensions: talent management and workforce capacity (TMGWC), risk management culture (RMC), workplace flexibility and engagement (WFE) and communication and technology (COTEC). Empirical data from manufacturing cells are used to calibrate training intensity, scheduling flexibility, digital tracking, and safety practices, and the model is validated through behavioural tests, including tests under extreme conditions, sensitivity analyses, and out-of-sample checks. Simulated scenarios show that combining resilience investments with HRMP initiatives improves recovery time, reduces absenteeism and overtime, and raises motivation, but may also generate unintended work intensification and uneven burden across shifts. The model was calibrated using manufacturing cell data and uses causal loop and stock-and-flow structures to represent the feedback relationships linking training intensity, scheduling flexibility, digital tracking, and safety practices to recovery time, absenteeism, overtime, motivation, and production continuity. The analysis shows that resilience investments yield benefits only when coordinated with workforce development and safety-oriented HR practices. Flexible scheduling and digital visibility support continuity, but their gains are diminished when intensified workloads erode motivation and increase absenteeism. Training improves preparedness and recovery, yet its returns depend on the timing of implementation and adequate recovery capacity. The paper contributes a dynamic and operationally grounded view of resilience in which people, technology, and process adaptation co-evolve. It also offers managers a staged implementation framework for diagnosis, policy design, scenario testing, and iterative refinement. The study contributes a reproducible modelling and validation process for manufacturing SCR that explicitly incorporates workforce dynamics and highlights both beneficial and adverse consequences of resilience strategies

Keywords: system dynamics, supply chain resilience, human resource management practice, manufacturing operations, modelling and simulation

1. Introduction

Manufacturing supply chains have become more fragile because efficiency-centred globalisation, lean inventories and multi-tier sourcing have reduced slack while increasing interdependence. This fragility is not only technical. It is also social, because production continuity depends on workers who interpret risk signals, operate digital systems, improvise around bottlenecks, comply with safety routines and restore output after disruption. A supply chain does not recover on its own. It recovers through coordinated human judgement and operational discipline. This framing is consistent with foundational resilience work that links global sourcing, lean operating systems and increasing supply chain complexity to heightened vulnerability (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009; Tukamuhabwa et al., 2015; Ahmadi, Hesaraki and Morsch, 2025; Zheng et al., 2025).

A persistent weakness in the literature is that people are often positioned outside the causal core of resilience. Structural levers such as redundancy, flexibility, visibility, and supplier diversification are important, but they do not explain whether the workforce is capable, motivated, and available enough to enact recovery. This omission matters because common responses, especially overtime and rapid redeployment, can restore output in the short term while creating fatigue, absenteeism and declining motivation later. Resilience is therefore overstated when only output indicators are measured (Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Ren, 2026; Ahmed et al., 2025; Pellegrino & Gaudenzi, 2025).

This paper asks three questions. First, how do supply chain resilience capabilities interact dynamically with HRM practices in manufacturing? Second, which feedback loops explain both the benefits and unintended workforce consequences of resilience interventions? Third, how can managers sequence training, scheduling, digital visibility and safety interventions to improve recovery without weakening workforce sustainability? The study contributes by placing HRM practice within the model boundary and by showing how resilience gains depend on delayed feedback among capability, work pressure, trust, and attendance.

2. Literature review

Supply chain resilience has developed from a narrow concern with risk mitigation into a strategic capability concerned with preparedness, response, recovery and adaptation. The literature increasingly recognises that resilience is not a single buffer but a bundle of capabilities, including visibility, redundancy, collaboration, flexibility and learning. However, the field remains uneven in how it specifies the human mechanisms through which these capabilities become operational behaviour. This is a serious conceptual limitation in manufacturing, where tightly coupled systems make small workforce disruptions capable of producing substantial production losses. Systematic reviews show that the field has moved from definitions and conceptual frameworks toward more explicit measurement, simulation and strategy selection, yet the evidence base remains fragmented across methods and sectors (Hohenstein et al., 2015; Tukamuhabwa et al., 2015; Hosseini, Ivanov and Dolgui, 2019; Narassima et al., 2024; Adu & Dorasamy, 2025).

HRM research helps address this limitation by showing that skills, engagement, leadership, communication, safety culture, and fair work design shape organisational capability. Training builds cross-functional competence and risk awareness. Flexible scheduling supports redeployment and attendance stability. Communication allows employees to interpret digital visibility as coordination support rather than surveillance. Recent evidence also connects high involvement HRM, strategic HR practice, artificial intelligence and human capital development with agility and resilience, which supports treating HRM as a resilience mechanism rather than a background function (Tobora et al,.2025; Li and Huo, 2023; Al-Banna, Yaqot and Menezes, 2024; Yamin et al., 2024; Esan, Ajayi and Olawale, 2024; Ahmed et al., 2025).

System dynamics is appropriate because the problem involves stocks, flows, non-linear feedback and delays. Training may temporarily reduce available production hours but increase future recovery competence. Over time, it may sustain initial throughput while later eroding motivation and attendance. Digital tracking may reduce information delays but may also weaken trust if implemented without voice and transparency. These examples show why resilience should be evaluated as a time path rather than a static performance score (Forrester, 1994; Sterman, 2001; Li, Ren and Wang, 2016; Bussieweke, Mula and Campuzano-Bolarin, 2025; Jiang, Pang and Zhang, 2025).

3. Case study, data and model specification

The case concerns a manufacturing cell embedded in a wider supply chain and exposed to demand disturbance, material delay and staffing variability. The cell was selected because resilience outcomes are observable at the operational level, while HRMP mechanisms, including training, scheduling, communication, and safety practices, can be linked to production behaviour. The unit of analysis is therefore not a whole firm but a production system in which workforce capability and operational recovery interact directly. Positioning the manufacturing cell as the focal unit also aligns with quantitative resilience research, which recommends modelling disruption response at a level where stocks, flows, delays, and operational performance can be observed rather than inferred only at the aggregate enterprise level (Hosseini, Ivanov and Dolgui, 2019; Dey et al., 2024; Narassima et al., 2024).

The model boundary includes production throughput, backlog, effective capacity, workforce capability, motivation, absenteeism pressure, overtime pressure, safety discipline, digital visibility and recovery status. Four resilience domains are connected to four HRMP bundles: capability to talent management and workforce capacity (TMGWC); preparedness to risk management culture (RMC); flexibility to workplace flexibility and engagement (WFE); and technology to communication and technology (COTEC). Figure 1 summarises the framework for M-SCM- R HRM-P. This boundary is deliberately critical: it excludes broader financial and supplier-network dynamics, except where they enter the cell as demand and material-availability shocks, because the purpose is to examine the workforce mechanisms usually hidden within aggregate resilience claims. Recent studies further support this socio-technical boundary by linking resilience to flexibility, endurance, soft organisational factors and digital coordination (Bag et al., 2025; Ahmed et al., 2025; Pellegrino and Gaudenzi, 2025).

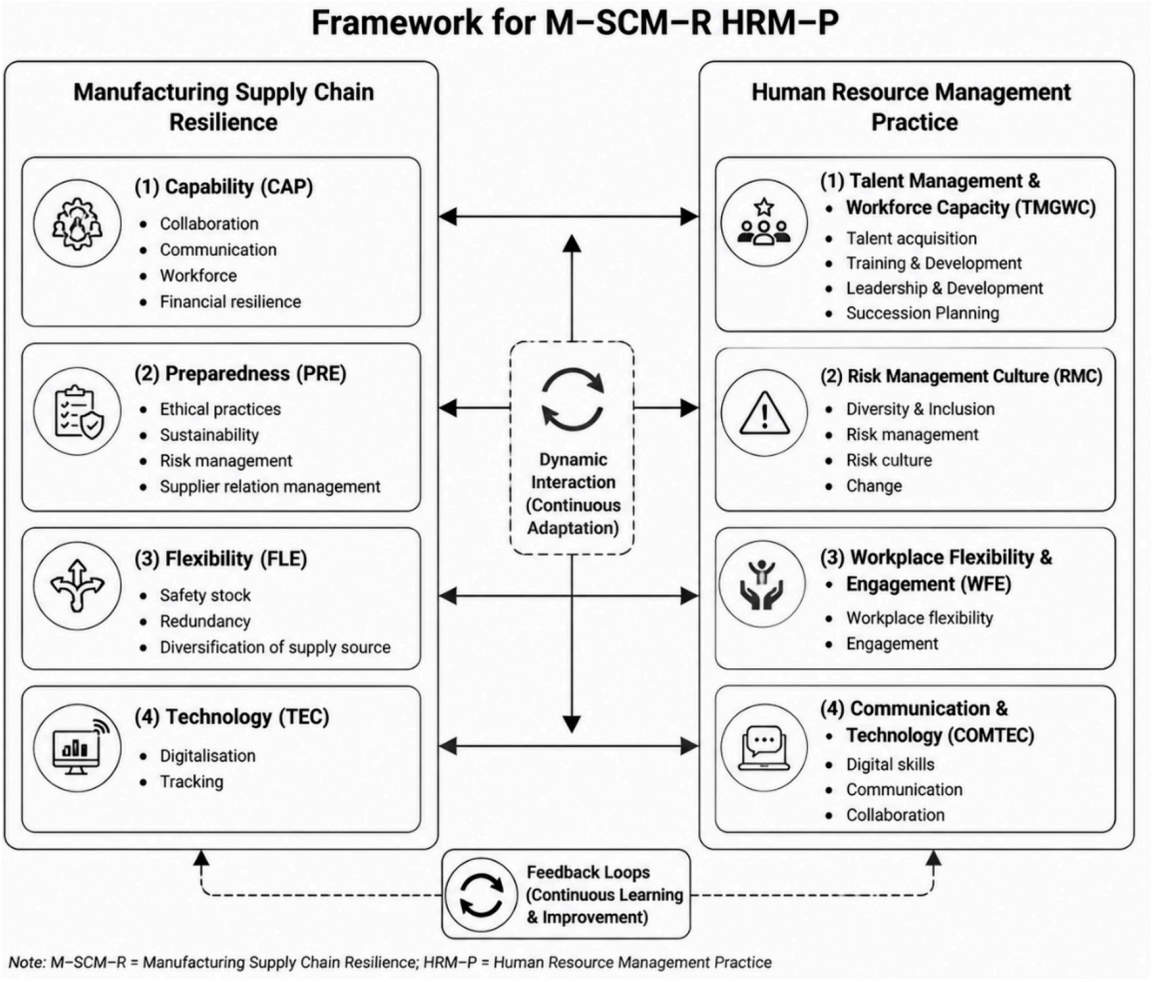

Figure 1: Manufacturing supply chain resilience and HRM practice framework

Model calibration uses operational and HRM indicators available at cell level. Where direct measurement is difficult, especially for motivation, trust, and safety culture, the model uses triangulated proxies from survey scores, absence patterns, incident reports, and supervisory assessment. This is a weaker validation base than direct measurement, but it is preferable to treat these constructs as unobserved managerial assumptions.

Variable	Source	Measure	Frequency	Model role
Production output	Cell records	Units completed	Weekly	Throughput and continuity
Downtime	Maintenance logs	Lost hours	Weekly	Disruption severity
Training intensity	HR records	Hours per employee	Monthly	Capability inflow
Overtime	Payroll records	Extra hours	Weekly	Work pressure
Absenteeism	Attendance records	Absence rate	Weekly	Capacity loss
Safety incidents	EHS logs	Incident count	Monthly	Safety erosion
Communication quality	Pulse survey	Index score	Monthly	Trust and coordination

Table 1: Data appendix and calibration variables

Model element	Operational equation or decision rule	Interpretation
Workforce capability	Capability rises through training and learning, then falls through skill decay.	Capability accumulates but is delayed and can decay
Effective capacity	Effective capacity equals base capacity multiplied by availability, capability and motivation factors	Capacity is social and technical, not only headcount
Backlog	Backlog(t+1) equals backlog plus demand shock minus completed output	Backlog transmits disruption pressure
Overtime pressure	Overtime rises when backlog exceeds normal capacity and falls when backlog is cleared	Short-term stabiliser with long-term cost
Motivation	Motivation rises with engagement and recognition and falls with sustained overtime and unfair scheduling	Explains delayed side effects
Absenteeism pressure	Absence pressure rises with fatigue and safety stress and falls through recovery support	Turns work pressure into future capacity loss
Recovery status	Recovery improves with effective capacity, preparedness and visibility and slows under absence and incidents	Links HRM to resilience outcome

Table 2: Core stock and flow logic

4. Simulation results and validation evidence

The model was tested under four policy settings: baseline practice, training only, training plus scheduling flexibility, and an integrated policy combining training, fair flexibility, digital visibility and safety-oriented communication. The baseline preserves existing staffing and escalation habits. Training only raises capability but temporarily diverts labour from production. Training and flexibility enable redeployment and reduce overtime concentration. The integrated policy adds digital visibility and explicit communication protocols so that tracking is used for coordination rather than surveillance. (Tukamuhabwa et al., 2015; Kamalahmadi and Parast, 2016; Bag et al., 2025; Berger et al., 2025).

Figure 2 shows that the integrated policy performs best because capability and coordination improve while overtime pressure is moderated. Training alone improves preparedness but has a slower recovery effect when the cell lacks scheduling slack. The baseline appears acceptable early in the disruption because overtime masks capacity loss, but performance deteriorates as fatigue and absence accumulate. The central result is that output continuity can conceal degradation of resilience.

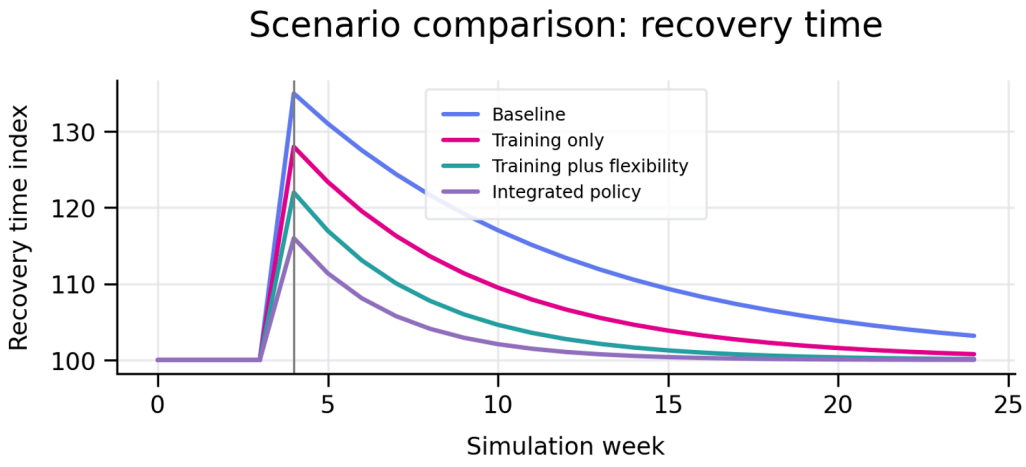

Figure 2: Normalised recovery time trajectories under policy scenarios

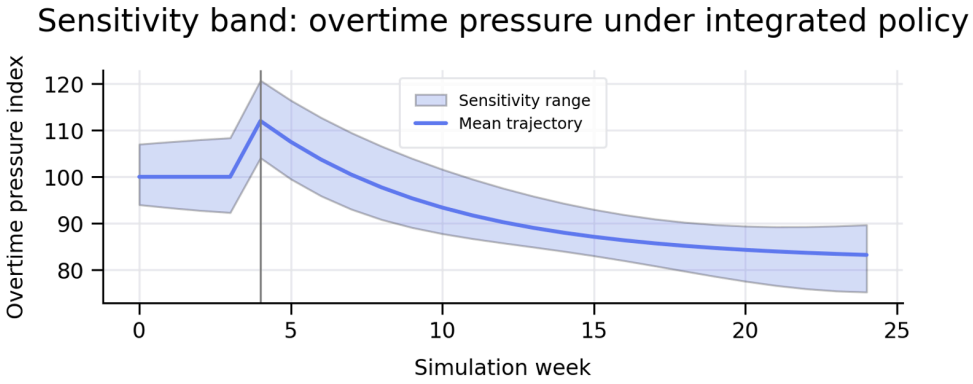

Figure 3: Sensitivity band for overtime pressure under the integrated policy

Scenario	Recovery time	Overtime pressure	Motivation	Absenteeism risk
Baseline	Reference level	Highest after week 8	Declines steadily	Rises through recovery
Training only	Moderate improvement	Short-term increase	Small delayed gain	Moderate risk
Training plus flexibility	Clear improvement	Lower and shorter	Stabilises earlier	Lower risk
Integrated policy	Strongest improvement	Controlled range	Recovers above baseline	Lowest relative risk

Table 3: Key performance indicators from the normalised scenario runs

Validation used four tests. Behavioural fit was assessed by checking whether the baseline reproduced the expected reference mode: disruption raises backlog, backlog raises overtime, sustained overtime erodes motivation, and absence then constrains recovery. Extreme condition tests confirmed that zero training prevents capability accumulation, very high absence collapses effective capacity, and full digital visibility without communication does not automatically improve recovery. Sensitivity analysis varied training effectiveness, overtime fatigue elasticity, communication quality and scheduling fairness. Higher communication quality narrows the overtime pressure band because managers respond earlier and distribute recovery work more evenly. Held-back operational observations were used where available. The validation is therefore behavioural and structural rather than a claim of universal numerical prediction.

5. Discussion

The study contributes to supply chain resilience theory by treating workforce capability, motivation and attendance as endogenous resilience resources. This matters because resilience policies can generate contradictory effects. Training improves preparedness but creates an opportunity cost when released time is scarce. Flexible scheduling protects capacity but can damage trust if it is perceived as unfair. Digital visibility improves coordination but may become surveillance if workers are excluded from interpretation and decision-making. These contingencies move the argument beyond general advocacy for resilience toward causal specificity. The argument therefore extends established views of resilience as readiness, response, and recovery by specifying the workforce stocks and feedback loops through which those capabilities are either strengthened or depleted (Ponomarov and Holcomb, 2009; Hohenstein et al., 2015; Maheshwari, Kaur and Renwick, 2024; Samuels, 2025).

The findings challenge the managerial assumption that recovery speed is the best resilience indicator. Rapid recovery achieved through chronic overtime may be operationally impressive but socially fragile. It transfers risk from the supply chain to the workforce and stores it as fatigue, absence, incidents and disengagement. A stronger resilience dashboard should therefore include recovery time, backlog, overtime concentration, absence, safety incidents, motivation and communication

quality. Without these indicators, managers may reward policies that defer rather than solve failure. This point is consistent with quantitative resilience research showing that resilience cannot be assessed solely by end-state performance, as the path, recovery rate, and capacity degradation also matter (Hosseini, Ivanov and Dolgui, 2019).

For practice, the model supports a four-stage pathway. Managers should diagnose baseline operational and HR indicators before disruption. They should design joined-up interventions so that training, scheduling, digital systems and safety routines reinforce each other. They should use scenario analysis to test policies under different shock sizes and timing assumptions. Finally, they should refine policies iteratively as behavioural data reveal delayed harms. The core managerial lesson is that resilience is built through sequencing and governance, not through isolated investment in buffers or technology.

6. Limitations and future research

The study is calibrated around a focal manufacturing cell, so the findings should not be generalised uncritically to process industries, service supply chains or multi-site networks. Some constructs, especially motivation, trust and risk culture, are only partially observable and require triangulation.

The model also simplifies supplier behaviour, labour market constraints and financial trade-offs. These limitations do not invalidate the model, but they define the conditions under which its claims should be read.

Future research should extend the model to supplier tiers, labour market availability and cyber disruption. Comparative studies could test whether preparedness, flexibility and technology change in relative importance across production regimes. Hybrid simulation could combine system dynamics with discrete event modelling to represent shop floor heterogeneity. Research should also examine the ethics of workforce analytics, because digital visibility strengthens resilience only if governed through transparency, voice and accountability.

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7. Conclusion

This paper develops a system dynamics explanation of manufacturing supply chain resilience and its impact on HRM practice. The central argument is that resilience is not only a property of networks, inventories or information systems. It is also an outcome of workforce capability, fair flexibility, safety discipline and trustworthy communication. Integrated HRM and resilience policies reduce recovery time and stabilise attendance more effectively than isolated interventions. However, the model also shows that resilience can be weakened by the very policies intended to strengthen it when those policies rely on work intensification, poorly governed digital tracking or delayed capability investment. A resilient manufacturing supply chain must therefore be judged by both operational recovery and workforce sustainability.

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DATA ECOSYSTEM IMPACTS ON FOOD PRODUCTION – A CASE STUDY.

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Introduction

Information sharing and data utilisation have been a critical part of the food supply chain. Juan Ding et al. (2014) found that sharing quality information between supply chain stakeholders positively affects food quality, which is an important indicator of the food supply chain performance. The extant literature further highlighted that the timeliness and the frequency of information being shared can improve the synchronisation of key processes in planning and control of the food supply chain (e.g., sourcing, processing, monitoring shelf life, etc), leading to better efficiency and lower cost for the whole food supply chain (Christensen et al., 2023). At the same time, food supply chain firms with strong data-driven capabilities and know-how regarding data utilisation are more likely to achieve better performance, align internal and external supply chain processes effectively, and transform certain operations (demand forecasting, inventory management, supply management, etc) (Irfan et al., 2019).

Given the key role of data and information sharing in the food supply chain, it is imperative to study emerging phenomena in this space and their potential implications to food supply chain management. This research aims to explore the novel concept of data ecosystem and its effects on the food production node of the food supply chain.

Data ecosystem is an innovative concept that emphasises the continuous co-creation and collaboration between all stakeholders of the system for the purpose of generating data with the best possible value for all members of the system. The data ecosystem network can be understood as a complex socio-technical collection of autonomous stakeholders who participate regularly in the creation, management, exploitation, and even competition of a shared data source (Oliveira et al., 2019). Unlike a traditional approach to a data system or platform, where the data is often subjected to a unidirectional relationship; data ecosystem embeds frequent feedback, interactions, and co-creation activities between all stakeholders (e.g., data generator, data controller, data consumer, and so on), maximising the usefulness of data.

While the data ecosystem is seldom studied in the supply chain management domain, some examples exist in the literature, such as using an open platform for container booking in maritime logistics (Zeng et al., 2020) or an open database for food safety analysis (LeBanc et al., 2015). Thus, this study contributes to the ongoing conversation in the literature by exploring a use case of data ecosystem in the food supply chain.

Methodology

A single case study is the method of choice for this study. The case is about a data ecosystem named the Observatory. Stemmed from an European project – ECO-READY, the Observatory is a digital platform that aims to address food security issues in Europe by providing data and knowledge regarding climate change and biodiversity drivers of food security. Embeded in the Observatory system is a network of 10 entities. These 10 entities operate in the European food system. The majority of the 10 entities are food producers (farms of different sizes), and some are involved with food processing and distribution. The entities maintain a two-way interaction with the digital platform, assuming the roles of both data consumers and data generators. A process of co-creation is in place to facilitate the collaboration within the 10 entities, and between the entities and the Observatory, generating a continuous flow of data between all stakeholders (stored and shared by the Observatory), and feedback to improve the overall system (in terms of data selection, data quality, and so on). Figure 1 depicts the general structure of the Observatory network.

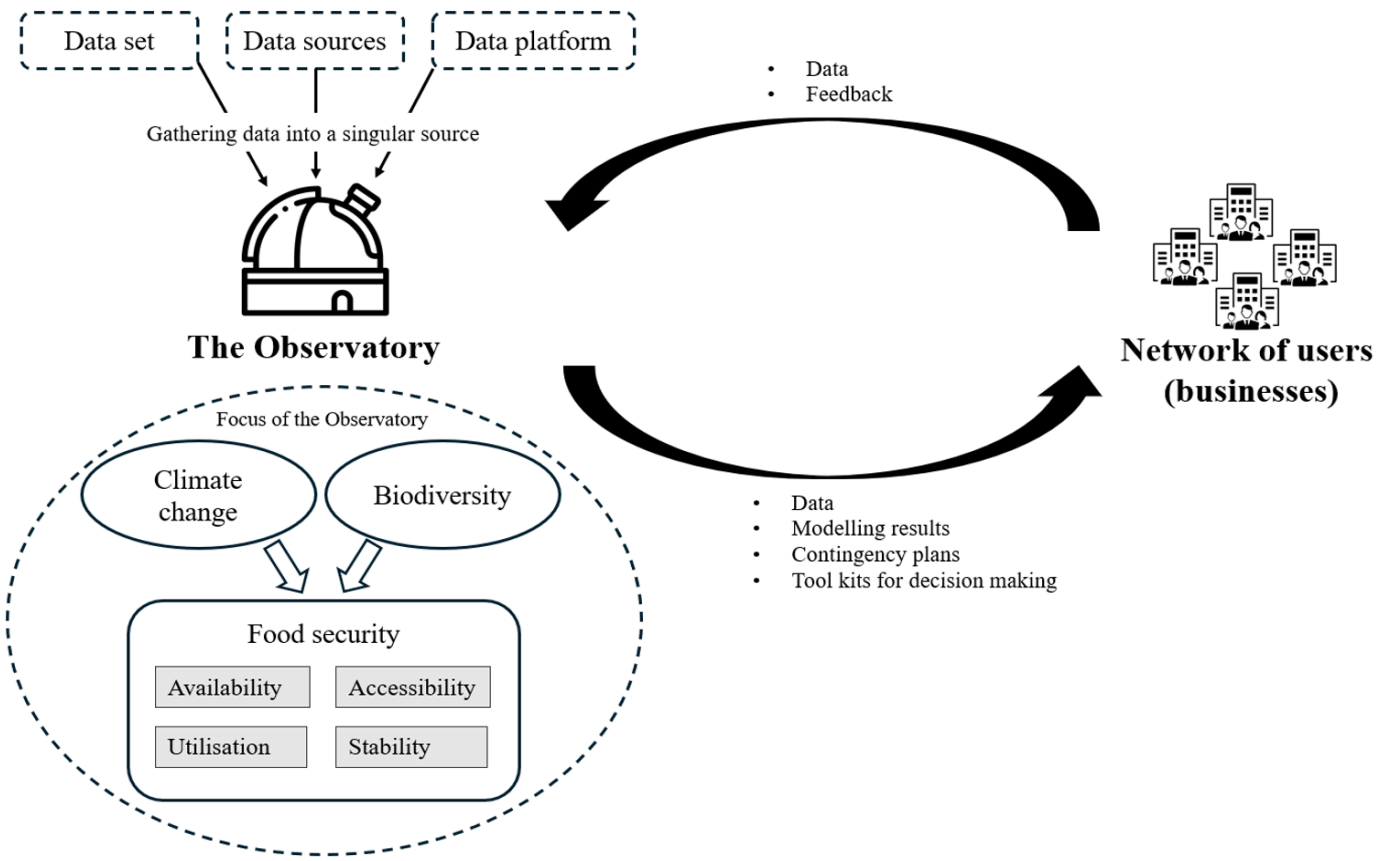

Figure 1. A schematic description of the Observatory structure and functions

When designing the study, we argued that uniqueness and revelation were the underpinning factors that inclined us to opt for a single-case-study methodology. An unique case refers to the study of a phenomenon which is normally difficult to observe, and a revelatory case refers to a rare occurrence (Ying, 2009). In this case, we investigate the use of the Observatory at one of the entities embedded in the Observatory's network. Data ecosystem emerged from the Open Data movement, which mainly focuses on making data from public institutions and research freely accessible to the common citizens. Hence, the majority of the data ecosystem development has been in the public domain. An industry-centric data ecosystem, such as the Observatory, is not common; therefore we argue that the access to the empirical data collected in this case, and the case itself, are unique, warranting the single case study design.

The entity to which the Observatory's offerings were applied is located in Southern Europe. This entity was referred to as E1 from this point onward in this paper. E1 specialises in growing crops, with co-operations with small and large farms in the local area and experimental fields. E1's products mainly enter the short food supply chain, which serves the nearby communities via local farmer markets and shops. Occasionally, E1 and partners can enter contractual agreements to grow and sell their produce to supermarket chains. To gather data regarding the use and impacts of the Observatory at E1, the authors conducted interviews (online and in person), and exchanged information with key personnel at E1 via emails. Notes of the meeting and transcripts were generated, and the analysis was supported by the use of NVivo software.

Findings

Insights from the empirical data depict a detailed understanding of the interaction between E1 and the Observatory consortium, and how the data and knowledge offered by the Observatory are utilised for enhancing various aspects of the operation at E1. Figure 2 summarised how the Obsevatory is utilised for E1.

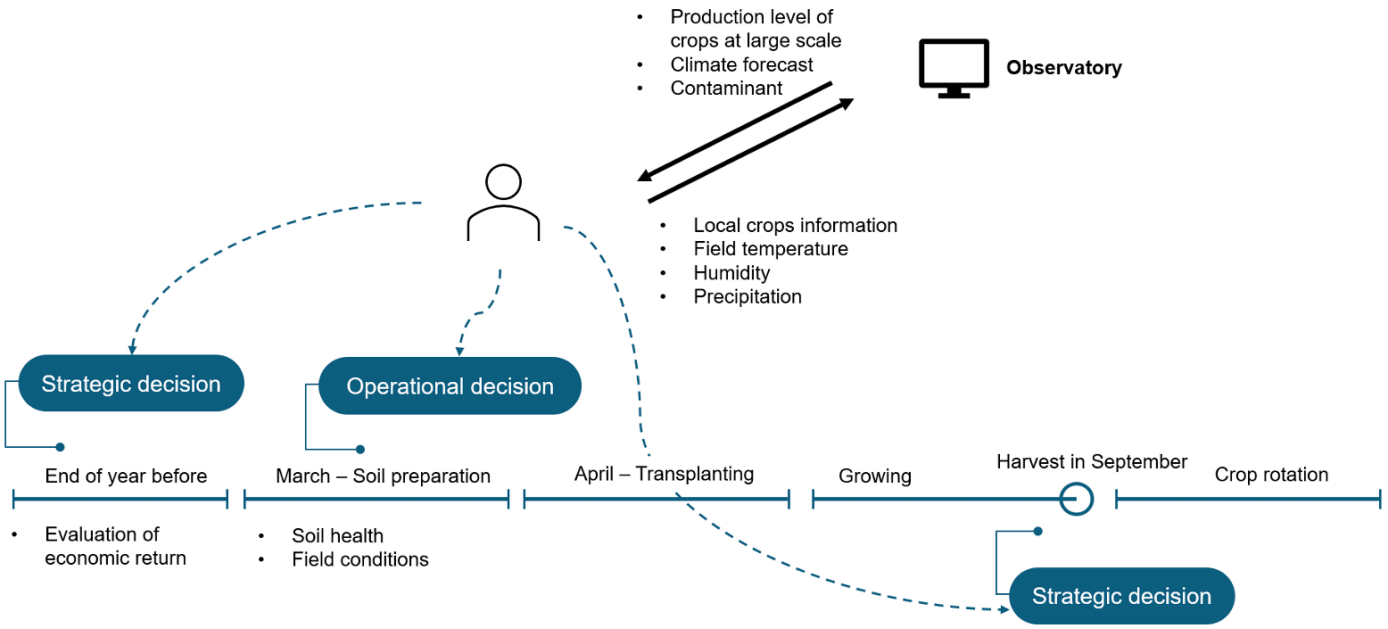

Figure 2. The integration of the Observatory.

First, a production cycle of tomatoes is presented in Figure 2. It should be noted that E1 is capable of producing various types of crops in two categories: cereal and vegetable. At the time of the study, tomatoes were chosen by the firm, and the production of tomatoes has been going on for E1 for several years. A tomato production cycle, in the case of E1, typically started in March. The firm began the process by preparing the soil and selecting the cultivars. There are mainly two methods of planting tomatoes – seed sowing and transplanting, the latter of which was the method of choice for E1. Transplanting happened in April, and the final produce is harvested and sold in September. When tomato season is completed, E1 would engage in crop-rotation activities, planting winter crops on the fields until the next tomato season. At the same time, post-harvest was the time for E1 to start their planning process for the next season of tomato, thus in Figure 2, there is an evaluation activity before the start of this year's season.

E1, as part of the 10-entity network embedded in the structure of the Observatory, went through a process of co-creation with the consortium running the digital platform to finalise what data to include in the platform, data format, means of sharing data, and data generation capabilities. The foundation of a data ecosystem was created through this process. At the time of the study, the Observatory went live, and a bidirectional flow of information can be observed between E1 (which acts as both data generator and data consumer) and the platform. E1 provides information about the crops they produce and various data regarding the conditions of their fields (temperature, humidity, precipitation level), whereas the Observatory offers information about crops at a larger scale (e.g., national level of crop production, price), climate forecast, and soil information (i.e, soil contaminant level).

The information and knowledge provided by the Observatory were utilised by E1 in making production decisions at strategic and operational levels. Before the cropping season, E1 management needs to make a decision on what crops to grow. As noted previously, E1 expertise, coupled with the specific weather and soil conditions of the fields, allows them to select one crop from a range of options for the season, if there is enough time in advance. The most important factor for this decision is the potential economic returns from growing such crop, which are mostly based on the historical data of production level in the region and market price. To this end, the Observatory broadened the information for E1, providing data on crop production and price at the regional, national, and European levels. In March, tomato was selected as the crop for the season. At this point, E1 engaged in the preparation of soil and various factors for their operation, such as irrigation planning. By sharing comprehensive monitoring data of the fields with the Observatory, modelling results and forecasts insights regarding the impact of climate change on production in the specific region were returned. These insights were incorporated into E1's preparation process. Among these insights, the forecast of precipitation was highly valued by E1, as water supply

had been an issue with growing tomatoes in recent years. Thus, having this prediction helped E1 in liaising with local water provider to plan their irrigation throughout the season. Other information such as the current contaminant level of soil at the sites, was also shared with E1. Finally, when the main season of tomatoes was completed, E1 entered another shorter cycle of production for winter crops, in which the process of making strategic decisions of what crop to plant started again.

Two major insights were observed from the case of E1 engaging with the Observatory. First, the Observatory increased the availability and accessibility of information for decision-making. While some of the data (production level, historic price) were already available, it was also time-consuming to search and gather information. One E1 executive viewed "the Observatory is a one-stop-shop for information, we can get everything we need in one place". Furthermore, due to the broad range of data included in the Observatory, E1 now had access to information that they might not have considered before. For instance, they previously just considered the crop production at the regional level, and now they could view the same information at national and continental levels, and compare with other organisations within the same network, to make a more rigorous prediction regarding the economic viability of growing tomatoes for this year. Second, being in the Observatory network enabled E1 to explore collaboration opportunities that were not available previously. Currently, E1 was in contact with other organisation within the network, located in a different country, to share best practices and plans.

Conclusion

This study contributes to the growing literature regarding data ecosystem application in the business domain. Via a single case study, the study explored and reported the actual use of a data ecosystem for a production node of the food supply chain, with detailed mechanisms by which the data ecosystem can impact operation. Due to the infancy stage of data ecosystem phenomenon, the authors opted for a single case study method, utilising the available data that we could access. Findings from the case study suggested that the approach of managing and sharing data with a data ecosystem could be beneficial to food producers. A data ecosystem focused on continuous improvement of the data being stored and shared between the network of participants, generating the most value of data for all stakeholders. For the organisation in the case, the approach of data ecosystem allowed them to obtain data that was most useful for their cropping activities, and gain valuable insights to support their decision-making at strategic and operational levels.

A limitation of this study is the generalisation of the results, as a single case study was reported. Another limitation of the study is that the use of the platform is currently confined to only selected number of organisations, most of which are food producers. The solution needs to scale into wider use across the food supply chain for further insights into the impacts of a data ecosystem at the supply chain level to be uncovered.

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RESIDUAL VALUE AS A DRIVER FOR ROAD FREIGHT TRANSPORT DECARBONISATION

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Purpose

The UK is committed to decarbonising freight transport, with electric heavy goods vehicles (eHGVs) central to this transition. Finance is a key driver of adoption, particularly residual value (the worth a vehicle retains through successive ownership/use), which supports a circular freight ecosystem aligned with the net zero CO^2 emissions target by 2050. A major challenge is the lack of insight into eHGV residual value, a pressing gap as the UK phases out the sale of new non-zero-emission HGVs by 2040. Under such tight timelines, limited understanding of residual value may discourage investment and adoption due to increased acquisition and disposal risks. To address this gap, the research examines residual value in the diesel HGV market and uses these insights to inform emerging expectations for electric vehicles.

Research Approach

This study used an interpretive grounded approach to investigate a topical and rapidly evolving phenomenon. An exploratory lens supported early fact-finding and data gathering, with academic and industry experts involved to ensure validity and practical relevance. Semi-structured interviews were conducted with key stakeholders, including manufacturers, fleet operators, and a distributor. Data were analysed through Interpretive Description, supported by cross-checks between interviewers to ensure the accuracy of findings.

Findings and Originality

The findings establish a foundation for understanding eHGV residual value by drawing on diesel HGVs as the most immediate and relevant precedent. This step is essential for clarifying the finance dimension, which remains one of the most uncertain yet vital factors in electric vehicle adoption. Because the research was shaped directly by industry needs, the study is uniquely positioned to be empirically focused yet firmly grounded in scholarship. It offers a balanced integration of practical insight and theoretical understanding.

Research Impact

The study contributes directly to the limited literature on residual value within transport decarbonisation, helping address a gap that has received little attention to date. It identifies key factors that shape the residual value of diesel HGVs and opens new avenues for examining how they influence the transition to eHGVs. By integrating scholarly research that is informed by industry-driven evidence, this study advances understanding in an emerging and important area of sustainable freight transportation and logistics.

Practical Impact

In a sector operating on narrow profit margins, understanding financial mechanisms, especially those tied to residual value, supports the development of viable financing options, insurance products, and secondary-market opportunities. These insights support net-zero ambitions, competitive positioning, and longer-term ownership strategies while providing greater clarity on financially viable pathways towards freight decarbonisation.

Keywords

Residual value, financing models, electric heavy goods vehicles (eHGVs), road freight transport decarbonisation, secondary market.

Introduction

The UK domestic transport sector was the largest contributor to greenhouse gas emissions in 2023, accounting for 29% of the national total of 385 $MtCO^2e$; within this sector, heavy goods vehicles (HGVs) generated 16% of transport-related emissions (DfT, 2025). To address this, the UK Government has committed to ending sales of new non-zero-emission HGVs by 2040, with a 2035 phase-out for vehicles weighing up to 26 tonnes, as part of its net-zero target for 2050 (DfT, 2021). Research into the HGV sector is therefore critical, particularly as existing studies have focused largely on passenger cars, with limited attention to heavy vehicles (Cerquitelli et al., 2020). Shariati (2024, p. 1) highlighted that "[w]hilst much research to date has concentrated on light vehicles these challenges are more extreme for Heavy Goods Electric Vehicles (HGEVs)". More recently, Jha et al. (2025) reported that the optimal pathway for the long-haul road freight sector is uncertain. These observations indicate that the HGV sector and its decarbonisation remain underexplored and thus require investigation. Several studies examine technological pathways for transport decarbonisation. Li et al. (2022) evaluated four technologies—liquefied natural gas (LNG), biomethane, electricity, and hydrogen—using a PEST-SWOT framework, while Ainalis et al. (2023) compared electric road systems with hydrogen for long-haul freight. Among these options, electrification is widely regarded as the most viable pathway (Li et al., 2022; Ainalis et al., 2023; Wang et al., 2024). Supporting this view, Gifford (2026) reported that battery-electric vehicles (BEVs) are expected to dominate the HGV market from 2030 and account for nearly 90% of new commercial vehicle sales by 2050. While technological aspects are well documented, financial considerations remain underexamined. de Saxe et al. (2023) emphasised the need for a full assessment of transport decarbonisation costs, while Jha et al. (2025) argued that parameters for measuring emission pathways are not comprehensive. Similarly, Wang et al. (2024) found that techno-economic barriers and financial risks continue to discourage fleet operators from replacing diesel-powered internal combustion engine vehicles (ICEVs) with low- and zero-emission alternatives. These challenges highlight the importance of finance as an enabler of eHGV adoption. Examining residual value is thus essential because it influences financial decisions, investment confidence, and economic viability thereof. This research gap has implications for both academic understanding and industry decision-making and motivates this study.

Literature Review

The literature review examines key topics related to the role of residual value in advancing transport decarbonisation. These include an overview of the HGV market, vehicle ownership approaches, residual value and its key drivers, culminating in a synthesis that informs the development of the research question.

Heavy Goods Vehicle Market

The HGV sector is "hard to abate" because its long-haul duty cycle and heavy payload requirements demand energy-dense power sources (Li et al., 2022). According to RHA (2026), the UK road freight sector comprises more than 625,000 HGVs, over 58,000 freight transport enterprises, and approximately 684,000 HGV drivers, contributing around £13.5 billion annually to the UK economy. In the UK, HGVs are defined as goods vehicles with a gross vehicle weight exceeding 7.5 tonnes and range from rigid trucks to 44-tonne articulated tractor–semitrailer combinations (DfT, 2003). Demand for new HGVs continues to increase, with more than 46,000 new trucks registered in 2023, including a 15% rise in rigid truck registrations and a 12% increase in articulated truck registrations (SMMT, 2024). The latter category is dominated by 6×2 tractor units, which are widely used in 44-tonne tractor–semitrailer combinations and are therefore adopted as the representative HGV examined in this study, consistent with de Saxe et al. (2023). HGVs typically remain in service for several years before entering the used vehicle market, often passing through multiple owners. Many used trucks exported from the UK are destined for Namibia, Tanzania, and Zimbabwe (Volza, 2025). While the small medium enterprises (SMEs) form the backbone of the freight transport sector, the fleet landscape is dominated by large operators, defined as firms employing more than 250 employees and annual turnover exceeding £50 million (Allen et al., 2023).

Common Vehicle Ownership Approaches

Li et al. (2022) reported that BEVs are significantly more expensive than diesel equivalents and other alternatives, including LNG, biomethane, and hydrogen. Given this substantial capital investment, understanding ownership approaches in the HGV sector is vital. BVRLA (2020, as cited in Green Finance Institute, n.d) identifies five methods of acquiring HGVs. First, outright purchase is the most common, accounting for 46% of acquisitions, whereby operators purchase vehicles using cash

reserves or business loans and assume full responsibility for ownership and maintenance. Second, contract hire or operating leases with maintenance account for 25% of acquisitions and typically involve fixed-term agreements via monthly payment of around 5 years, after which vehicles are returned to the leasing provider. Third, flexi leasing or rental arrangements represent 15% of acquisitions and usually span six to twelve months, enabling operators to meet temporary or seasonal demand. Fourth, other leasing arrangements without maintenance account for 9% of acquisitions with maintenance responsibilities retained by the operator. Fifth, fleet management accounts for the remaining 5% where specialist third-party providers manage vehicle fleets.

Residual Value and Key Drivers

Residual value is defined as the "estimated worth of a vehicle at the end of a predefined period, typically in the context of leasing and financing contracts" (Yapicioglu et al., 2026, p. 43351). Accurate estimation is essential to avoid over- or undervaluation, as it affects leasing, resale, insurance, fleet management, and brand positioning (Yapicioglu et al., 2026). Understanding residual value is thus critical for assessing lifetime cost-effectiveness (Guo and Zhou, 2019). Gobbi (2011, p. 768) observed that "low PRV is associated with second-class recovery options (recycling and energy recovery) and that high PRV is associated with first-class recovery options (reconditioning and remarketing)", highlighting its role in recovery decisions and strategies. However, estimating residual value remains challenging (Cerquitelli et al., 2020), justifying this study. The following subsections review key drivers of residual value.

Battery Health. From a financing perspective, the battery can be viewed as a distinct asset class as it represents a substantial proportion of vehicle cost (Li and Chen, 2020). They identified battery degradation as a major driver of BEV depreciation and note that battery reliability is commonly assessed using state of charge (SoC) and state of health (SoH). SoH measures the ratio of remaining to nominal battery capacity under standard conditions and serves as a performance indicator. Battery degradation should be considered when assessing residual value because performance declines with repeated charge–discharge cycles (Cao and Yang, 2019). This deterioration contributes to depreciation and is measured by the capacity retention rate, defined as the ratio of remaining to rated battery capacity (Cao and Yang, 2019). Put differently, assured battery SoH could support a secondary eHGV market. Even if the vehicle is not reused, the battery retains value for storage or other applications.

Total Cost of Ownership (TCO). TCO is another important driver, encompassing factors such as upfront vehicle cost, lifetime fuel cost, maintenance and repair cost, and competitive payback periods (Ainalis et al., 2020). Wang et al. (2024) identified capital expenditure (CAPEX), operating expenditure (OPEX), and other factors—including the discount rate, vehicle lifetime, scrappage value, purchase subsidy, and inflation rate—as fundamental inputs for TCO assessment. Wang et al. (2024) projected that BEVs could achieve TCO parity with ICEVs if battery costs declined by approximately 56%, from £160/kWh to £70/kWh, although their analysis excluded charging infrastructure costs.

Operational Performance. Several operational characteristics influence eHGV attractiveness and adoption, such as driving range, payload capacity, refuelling or charging time, service life, carbon reduction potential, vehicle age, cost-effectiveness, energy efficiency, vehicle replacement attractiveness, commercial readiness (e.g. infrastructure and vehicle availability), and broader environmental and social impacts (Ainalis et al., 2020; Li and Chen, 2020).

Government Intervention. Another important driver is government intervention (Ainalis et al., 2023), such as through policies associated with infrastructure payback periods, wholesale electricity prices, and zero-emission vehicle (ZEV) uptake rates. Such interventions can support the transition to zero-emission freight transport while enabling HM Treasury to offset declining diesel excise duty revenues through energy-related taxation.

Market Competition. Emerging eHGV manufacturers are becoming increasingly prominent. For example, several major Chinese electric truck manufacturers are planning to enter the European market in 2026 with battery-electric trucks priced up to 30% below the European average, leveraging China's scale and lower-cost battery supply chains (Carey and Mannes, 2026). Similarly, a Chinese manufacturer has recently announced a new battery-electric truck for the European market, claiming payback periods as short as 2.5 years—approximately half that of comparable diesel vehicles (Polos, 2025). The anticipated declining vehicle costs and shorter payback periods could significantly improve the commercial attractiveness of eHGVs.

Formulation of Research Question

The literature review above highlights that, while electrification pathways for HGV decarbonisation are established, financial dimensions remain underexplored. Residual value, in particular, emerges as a critical yet insufficiently understood factor influencing leasing models, lifecycle cost-effectiveness, and recovery options. The review indicates that uncertainties surrounding residual value, including battery performance, second-life applications, and evolving financing structures, directly affect market confidence and investment decisions. Furthermore, factors such as operational cost structures, government intervention, and market competition introduce complexity to valuation considerations. Despite these interdependencies, existing studies have not sufficiently examined how residual value influences the development and uptake of eHGVs. This gap is particularly significant given the importance of leasing within the sector. It is also especially timely given increasing pressure to transition towards zero-emission freight within the context of the UK's planned transition away from new non-zero-emission HGV sales by 2040 (DfT, 2021). This study also responds to the call by de Saxe et al. (2023) for "a full assessment of the cost implication" of UK road freight decarbonisation pathways. In this context, residual value represents a critical, yet underrepresented, component of decarbonisation viability. Accordingly, the following research question is proposed: How does residual value influence the development of eHGV uptake in the UK? Addressing this question will identify future research priorities on eHGV residual value, supporting uptake and decarbonisation objectives.

Research Design

Following the formulation of the research question, a case study methodology was adopted to explore the emerging topic. This interpretivist approach is consistent with Ellram (1996) and Yin (2018), who argue that case study research enables deeper insights into the phenomenon under investigation. This aligns with the aim of the study, which seeks to examine the role of residual value in advancing decarbonisation. Rather than relying on deductive logic to test assumptions, this research adopts an inductive approach to generate insights directly from real-world contexts. This methodology is intended to produce knowledge that closely reflects reality, with outputs that address real challenges. In this scoping study, the initial stage focuses on understanding the existing diesel truck market through the perspectives of practitioners from diverse backgrounds within the freight transport industry. Data were collected via semi-structured interviews. Consistent with Creswell and Guetterman (2019), participants were selected through purposive sampling to gather expert opinions and perspectives. The sample comprised representatives from fleet operators of different sizes, an original equipment manufacturer (OEM), and a distributor, capturing perspectives from key stakeholders involved in HGV ownership, resale, and value recovery. Meetings between the researchers and key stakeholders were also conducted to support the analytical analysis. This approach enables the incorporation of multiple perspectives, facilitating cross-validation of insights. Interview recordings were transcribed and analysed alongside analytical memos. Drawing on Thorne's (2025) Interpretive Description approach, data were analysed through iterative reading of the transcripts, revisiting recordings, and reviewing analytical memos. Findings were developed by examining recurring topics, areas of emphasis, and differing stakeholder perspectives. In line with Yin (2018), the findings were interpreted through pattern matching and the use of multiple perspectives, enabling the examination of key insights. Secondary sources, including policy documents, market research, and news media were used to support interpretation and enhance study validity, in line with Ellram (1996).

Findings and Discussion

This section presents key insights emerging from the fieldwork. Discussion is integrated in the findings to ensure analytical coherence.

Data Context

To generate sector-relevant insights, key stakeholder groups were identified, including three fleet operators of different sizes (SMEs and large operators), one OEM, and one distributor. In addition, eight meetings were conducted with the research team, comprising both academic and industry experts, providing practical grounding. Two additional meetings were undertaken with a stakeholder group to obtain targeted insights into residual value mechanisms. Fieldwork was conducted between July and November 2025.

Segment-Specific Vehicle Ownership Strategies

The findings reveal two broad categories of HGV buyers and suggest that eHGV procurement broadly follows established HGV purchasing patterns. First, operators that favour outright vehicle purchase over leasing, typically accompanied by longer operating periods and less emphasis on residual value. In many cases, residual value is realised through the recovery (Gobbi, 2011) and resale of serviceable spare parts. The findings further suggest that OEMs' established structures, supported by extensive dealer networks, access to capital, and well-defined disposal routes, are primarily geared towards new vehicle sales rather than the marketing of used vehicles. New trucks are typically specified and customised to meet operator requirements. Participants also indicated that vehicles are commonly acquired with the expectation of potentially being resold once within the UK market. As a result, 6x2 tractor units with larger cabs and more general specifications are perceived to be more marketable. Some operators prefer to retain risks in-house by financing vehicles and maintaining internal servicing capabilities. For these firms, operating vehicles throughout their service life of 10 years or more is often considered the most economically viable option. Second, 3PL operators commonly adopt leasing for contract-specific, fixed-price operations. It was reported 5-year contracts often involve leasing a fleet with full maintenance and servicing support, thereby reducing operational risk. Under such arrangements, the leasing provider assumes residual value risk and imposes contractual requirements relating to vehicle use, including mileage limits and vehicle condition standards.

Residual Value Considerations

The findings indicate that operators have increasingly extended asset lifecycles in recent years, effectively "sweating the asset". Participants associated this trend with tighter margins (Ainalis et al., 2023), improved maintenance practices, and declining residual values. OEMs typically offer 5-year contracts, with residual values structured to achieve diesel-equivalent lease rates, contingent on grant funding availability and favourable interest rates. The findings further suggest that, although current grant schemes can reduce acquisition costs, eHGVs remain substantially more expensive than a diesel equivalent, with purchase prices of approximately £250,000 compared with £90,000 for diesel vehicles. Participants viewed this cost differential as key to assessing eHGV viability. The findings also reveal differing perspectives on residual value. One participant viewed residual value anxiety as a symptom of overpriced vehicles, arguing that government-backed residual value guarantees may inadvertently incentivise inflated pricing. This challenges the commonly held view that further government incentives are required to support the transition to zero-emission vehicles. Nonetheless, participants identified limited warranties as a major determinant of residual value, typically specified for around 8 years. However, the findings indicate that battery longevity is perceived to be constrained more by cumulative energy use than by age or a fixed mileage limit, consistent with Cao and Yang (2019). While batteries may be capable of supporting around 4,000 charge cycles and operational mileage approaching 2 million kilometres under predictable operating conditions, residual value was considered to depend on when battery SoH declines to the point of affecting vehicle performance and usability.

The Contested Need for a Secondary Market

The findings reveal that the first-life operational period of 44-tonne 6x2 diesel tractor units in the UK varies considerably across operators and business models. One participant indicated that large 3PL providers often replace vehicles after 3–5 years to align with contract and lease cycles, whereas smaller haulage firms tend to retain them for 10 years or more, subject to mileage, maintenance, and other operational requirements, and constraints. At present, a secondary market for eHGVs does not exist, and participants expressed differing views on its future necessity. While some stakeholders advocate its development, others question its relevance. On one hand, there is a perception that widespread acceptance of eHGVs requires a secondary market. The findings also indicate that OEMs have been challenged by financing stakeholders regarding the absence of residual value mechanisms, such as guaranteed buybacks, particularly if a secondary market is to be developed. Conversely, some participants reject the idea for a secondary market. They argue that eHGVs may remain in service significantly longer than diesel vehicles, owing to higher upfront costs, battery life, and chassis durability. Under this scenario, a battery replacement or refurbishment after approximately 8–10 years could enable operation for a further 8–10 years. However, participants acknowledged that this pathway remains speculative, as no eHGV fleets have yet reached such ages and the economic viability of mid-life battery replacement remains unproven at scale. Consequently, participants anticipated that fewer vehicles may enter second-hand markets. Even where a secondary market exists, the "rapid depreciation" of BEVs may reduce its attractiveness, as reported by Li and Chen (2020) in the Chinese market.

Battery-Driven Residual Value

The findings highlight the centrality of the battery in eHGVs, positioning it as a key determinant of residual value, second-hand market confidence, and insurance pricing. One participant indicated that insurance providers often write off battery value within 3 years due to limited understanding of battery chemistry, while restricted access to battery data was considered a key barrier. The separation of the battery from the chassis was also discussed as a potential future model. This is consistent with Li and Chen (2020) who found that power batteries exhibit higher residual value retention than vehicles. However, another participant noted that this would require legal reform, standardisation of battery management systems across OEMs, and confidence in battery data, which is currently lacking. For example, under battery-as-a-service models, existing legal frameworks do not accommodate split ownership structures in which the vehicle and battery are financed separately. By contrast, participants observed that some operators, particularly those with in-house maintenance capabilities, can extend chassis life to 15–16 years, thereby reducing residual value risk. The findings also reveal that a substantial proportion of eHGV cost is attributable to the battery, which can retain value at the end of a 10-year lifecycle. This supports alternative recovery pathways (Gobbi, 2011). Some operators anticipate using older eHGVs for spare parts while selling batteries into second-life applications outside freight transport. Others are exploring battery refurbishment or modular replacement and view extended battery guarantees as necessary to match the anticipated vehicle lifespan, assumed at 10 years. As battery technology advances (Li and Chen, 2020), participants suggested refurbishment may become increasingly feasible. One participant further noted that some battery assemblers have already developed mechanisms to replace defective cell strings within battery packs to maintain performance. Consequently, participants suggested that the conventional 10-year vehicle lifespan is being reconsidered, with potential extensions to 15 years, thereby affecting TCO. During early adoption, operators are expected to retain vehicles longer due to high upfront costs and the absence of a secondary market. At end-of-life, residual value is retained through battery reuse and component recovery.

Economics and Commercial Viability

Participants reported that new diesel 6x2 tractor units are customised to operator requirements. While commercial pricing remains confidential, diesel units are approximately £90,000, compared to around £250,000 for electric equivalents. The findings indicate that dealers have traditionally generated profit primarily through maintenance and servicing rather than vehicle sales. With eHGVs, one participant suggested that this model may require revision given reduced servicing requirements. Consequently, dealers may rely more on vehicle sales margins. Participants identified operational overheads for eHGVs as highly sensitive to electricity pricing, with costs varying considerably by charging location and infrastructure. It was reported that depot-based charging can be available at around 20p/kWh, while purpose-built eHGV charging hubs may charge approximately 40p/kWh. Mixed-use public charging sites can reach around 60p/kWh, with premium forecourts charging at around 80p/kWh. The findings suggest that this wide range in electricity costs plays a critical role in eHGV operating economics. This variability introduces significant uncertainty in operating costs, particularly for smaller operators engaged in unscheduled or long-haul operations. The findings also suggest that TCO sensitivity to residual value is relatively limited. This may be because battery efficiency degradation has only a minimal impact on TCO (Wang et al., 2024). However, reduced servicing needs may require adjustments to dealer pricing strategies.

Competitive Pressures and Market Dynamics

The findings reveal that margin pressures are expected to intensify with the entry of emerging competitors. Participants suggested that established European manufacturers face challenges in matching the lower-cost offerings of principally Chinese manufacturers, consistent with Carey and Mannes (2026). This advantage is driven by differences in labour costs, material sourcing, subsidies, and supply chain efficiencies. Dealers are likely to rely on established relationships, while manufacturers may seek efficiency, economies of scale, and automation to remain competitive. Although relationships remain important, purchasing decisions are driven by financial considerations, suggesting conditional loyalty among operators.

Conclusions

This study examined the role of residual value in supporting eHGV uptake in the UK. In doing so, it responds to calls for greater attention to the finance and economic dimensions of freight decarbonisation. The findings demonstrate that residual value is a key financial consideration influencing ownership decisions, financing arrangements, leasing models, insurance practices, and broader investment confidence in zero-emission freight transport. Residual value is increasingly associated with battery value rather than vehicle value alone. The battery emerged as a critical determinant of residual value through its influence on warranty provisions, second-life applications, insurance assessments, and long-term ownership strategies. The findings reveal contrasting perspectives regarding the need for a secondary eHGV market. While some stakeholders consider a functioning second-hand market essential for reducing investment risk and supporting market confidence, others anticipate longer vehicle lifespans, battery refurbishment, and component reuse, potentially reducing the importance of resale pathways. Furthermore, residual value considerations vary across buyer segments and operating models. Vehicle acquisition costs, electricity prices, maintenance requirements, and increasing competition from lower-cost manufacturers continue to shape the commercial attractiveness of eHGVs. Collectively, these factors influence residual value expectations and the market adoption. This study contributes to knowledge by extending discussions of freight decarbonisation beyond technological and infrastructure considerations to encompass the financial mechanisms that underpin investment decisions. It provides an empirically grounded understanding of residual value in the UK HGV context and highlights the interconnected roles of batteries, ownership models, secondary markets, and economics in supporting the transition to eHGVs. From a practical perspective, the findings offer insights for policymakers, OEMs, leasing providers, insurers, and fleet operators. Improving battery performance transparency, developing robust residual value assessment methods, and exploring innovative financing and ownership models may help reduce uncertainty surrounding eHGV adoption and strengthen market confidence. The study is not without limitations. The findings are based on a relatively small sample of stakeholders and reflect perspectives from a market in an early stage of eHGV adoption. Consequently, long-term battery replacement economics, vehicle lifespans beyond 10 years, and the emergence of secondary markets, remain uncertain. Future research could examine how residual value evolves over time, particularly in relation to battery performance, second-life applications, financing innovation, and residual value forecasting. Longitudinal studies would be particularly valuable in testing the stakeholder expectations identified in this research and generating further insights to support the decarbonisation of freight transport.

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DIGITAL BUSINESS MODEL INNOVATION FOR INLAND WATERWAYS

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ABSTRACT - Work in Progress

Purpose

Inland waterways (IWW) remain an underutilized component of the European transport system. Digital innovations and autonomous solutions have been highlighted as key avenues for strengthening the competitiveness of inland waterway transport (IWT). This paper examines digital business model innovation aimed at advancing the IWT sector.

Design/methodology/approach

This study was conducted through interviews and workshops with entrepreneurs developing digital solutions for the transport sector in general, and for the IWT sector in particular. The empirical material was analysed using business model innovation as analytical framework.

Findings

The paper identifies barriers and enabling factors associated with digital business model innovation in the IWT sector. Contextual conditions such as low digital maturity, regulatory inflexibility, and limited customer interest, together with entrepreneurial challenges including rapid technological development, uncertain financing, and fragmented data, have constrained progress.

Research limitations

The paper explores digital business model innovation from a North European perspective.

Practical implications

By identifying the key factors behind digital business model innovation, this paper highlights potential areas of interest for entrepreneurs and incumbents in the sector.

Societal implications

The IWT sector offers significant potential sustainability benefits, but adoption remains slow, and operations are increasingly threatened by factors such as climate change. Digital innovations may enhance IWT attractiveness by improving both reliability and efficiency.

Original/value

The paper looks at the underdeveloped digitalization of the IWT sector.

Keywords: Inland waterway transport; digitalization; business model innovation; shipping.

1. Introduction

Inland waterways transport (IWT) and short-sea-shipping are underutilized components of the European transport system (Eurostat, 2026). Both the EU and the Swedish government have set targets to increase the share of freight transported on waterways. Research and policy documents suggest that the untapped potential of IWT could be better realized if modal shift is facilitated through technological and organizational innovations. In particular, digital innovations and autonomous solutions have been highlighted as key avenues for strengthening IWT competitiveness (Al Amien, 2024).The commercial struggles of IWT-based solutions have underscored the importance of suitable market strategies and business models (Rogerson et al., 2019; Williamsson et al., 2020). Despite the importance of commercialization for the success of IWT the topic of business model innovation for IWT-based remains underexplored. It is unclear how business model innovation in general, and digital business model innovation in particular, can facilitate modal shift to water and which challenges impede commercialization. Hence, this study aims to identify barriers associated with digital business model innovation targeting the IWT sector in the immature but developing Swedish IWT market.

By examining digital business model innovation aimed at advancing the IWT sector the paper present findings that are of interest to practitioners, policy makers and researchers concerned with the role of the business models in enabling modal shift from land to water.

2. Previous research

2.1. Digital business model innovation

The business model describes how a product or service is produced, delivered, and presented to the customer in a way that creates customer and company value (Magretta, 2002). Creating a financially viable business model is essential for commercial success of companies operating in competitive markets, but identifying an attractive model can be challenging, particularly when it must absorb the costs of a new technological innovation (Teece, 2010).

It has been theorized that the general barriers that stand in the way of the development and implementation of new business models are either related to the acquisition and management of resources, or with the cognitive disposition of the individual and the organizational context in which it operates (Chesbrough, 2010). The primary barriers to business model innovation are thus obstruction of resource utilization and confusion in terms of what the organization should do. Subsequent reviews have identified barriers and facilitating factors associated with specific contexts or domains of business model innovation. For example, the loci of barriers and enablers can be found in the macro-setting in which the company operates, at the business level through organizational design and culture, and at the micro-level in employee and managerial factors such as attention and cognition (Foss & Saebi, 2016).

Furthermore, research on sustainable business model innovation has identified specific challenges in shifting from unsustainable practices to more environmentally and socially responsible ways of producing and delivering customer value. In the field of sustainable consumer goods it has been suggested that there are three categories of barriers that stand in the way of, or facilitate, progress in business model innovation: institutional (i.e. organizational rules, norms and beliefs that influence behavior), strategic (i.e. long-term goals and the process of establishing them) and operational (the organizational and operational design) (Bocken & Geradts, 2020). Barriers also arise across the business model innovation phases: initiation, ideation, integration, and implementation (Bachmann et al., 2025). Barriers to business model innovation are thus associated with all general areas of the business landscape and are also acknowledged to exist at every stage of the innovation process. Consequently, these barriers affect the commercialization of specific technological innovations such as digitalization and the introduction of IWT solutions.

2.2. Digital business model innovation in the freight transport sector

The potential of digital technologies to enhance value creation has been widely recognized since the advent of the computer. Notably, the dot com bubble brought the business model to the fore, highlighting its relevance for financially unsustainable ventures in the IT sector (Magretta, 2002). Digital business model innovation has evolved into a sub field of business model research. As a concept, it refers to purposeful and dynamic changes to business model elements that are non trivial in nature

and connected to the transformation of resources or processes into digital formats (Böttcher et al., 2022; Trischler & Li-Ying, 2022). Digital business model innovation thus also deals with the analysis and implications of technological development in specific subfields such as the Internet-of-Things (Tesch, 2019) and artificial intelligence (Aagaard et al., 2019). Digital business model innovation has been identified as a means of advancing environmental sustainability (Böttcher et al., 2023), and ongoing technological development is reinforcing its role as a core driver of competitive advantage (Böttcher et al., 2022).

Research on the Swedish IWT sector has identified business models and market development as key challenges (Rogerson et al., 2019). In relation to business model innovation specifically directed toward the IWT container segment considerable challenges are associated with price and service quality, stakeholder cooperation, and regulation (Williamsson et al., 2020). Similarly, research exploring modal shift in the North-Sea region identified different approaches for innovating IWT-solutions based on market characteristics and the need for iterative and long-term stakeholder oriented innovation processes (Santén et al., 2021). These results are supported by other research conducted n the Swedish logistics sector. A review of five cases involving digitalization and electrification showed that the interconnected nature of freight supply chains create a situation in which successful business model innovation is dependent on communication between key actors (Williamsson & Moen, 2022). Likewise, research on stakeholder interaction with key supply chain actors indicate that norms and behavior preferred by property managers and administrators may guide business model innovation among freight service providers (Brettmo & Williamsson, 2020). Consequently, research thus adds communication as a third central barrier to business model innovation besides obstruction and confusion (Williamsson & Moen, 2022). Combining these results, digital business model innovation for IWT concerns outcomes and work methods linked to the digitalization of assets and processes. The innovation process is expected to encounter obstacles associated with the external business setting, the organization per se, and individuals within the organization. Furthermore, organisations engaging with digital business model innovation for IWT are likely to face barriers throughout each phase of the innovation process, indicating that each phase may involve distinct challenges.

3. Methodology

This paper reports on ongoing research and examines a longitudinal case study of digital business model innovation aimed at shifting goods transport from land to water. The case study focused on developing alternatives for freight customers that would potentially use inland waterways and short sea shipping. The research was conducted within two projects funded by the Swedish Energy Agency and the European Union's Interreg NSR programme. Primary data were collected through interviews, meetings, and workshops with the founder of the initiative central to the study, as well as with representatives from several organizations active in the Swedish logistics sector. Secondary data include promotional materials, internal documents, early stage prototype evaluations, and publicly available reports. The primary data collection spanned three and a half years.

Because of confidentiality considerations, it was decided not to rely on recordings for data collection. Interviews were conducted both in person and through digital tools such as Microsoft Teams. The interviews were semi-structured to allow for the respondent to elaborate on topics and to give the researchers the freedom of answering suitable follow-up questions (Alvesson, 2011). The meetings and workshops were conducted together with one or several industry partners and at least two research partners. In these settings, one research partner acted as the lead while the others took notes and asked follow up questions to clarify statements or gather additional information. During workshops and meetings related to business model innovation, the research partners presented tools, theories, and models that participants could use to explore potential solutions to the issues at hand. As a result, the research partners were active participants in the business model development process, and this active involvement was required by the funding bodies. The research presented in this paper is thus a type of action research (Maestrini et al., 2016), conducted with the broader goal of supporting modal shift from road to water. The empirical material was analysed using a framework based on the literature on business model innovation presented in the previous section.

4. Results

The research was initiated in December 2022 and concluded in June 2026. During this period, the entrepreneur evaluated multiple service designs and business model variants targeting the IWT sector. The process was complex and marked by several setbacks, leading to complete redesigns of the business model and changes in the constellation of partners involved in the entrepreneurial process.

The barriers associated with digital business model innovation in the IWT sector are grouped into two broad categories: contextual barriers and venture specific barriers. The latter category is used because the case company is small, making the distinction between organizational and micro level factors less meaningful, as these categories are difficult to separate in small entrepreneurial firms.

4.1. Contextual barriers

4.1.1. Market and competition outlook

During the development process, it was identified that competition primarily came from rail and truck based alternatives, whose main advantages were convenience, established procurement procedures, and flexibility. These alternatives also benefited from a considerable moat, as customers' existing frames of reference, including KPIs and specialized terminology, were grounded in practices developed for land based freight solutions. Business systems and other logistics related system architectures therefore placed a burden on IWT solutions either to adopt the land based framing on transport, or to suffer developmental costs for creating unique solutions and establishing a distinct framing for sea based transport.

To achieve the latter, inspiration was drawn from international markets with broader uptake and more successful IWT sectors, such as the Netherlands, Belgium, and Germany. The entrepreneur subsequently used the power of examples in communications with customers and stakeholders, highlighting projects and trials that had demonstrated positive outcomes. It was also assessed that digital maturity in the sector was low, which made it difficult to arrange door-to-door solutions capable of identifying potential routes and coordinating waterway transport with local truck-based delivery services.

In the Swedish market, there was a dearth of competitors. Only a handful of companies worked with the development and implementation of solutions for IWT and in specific segments such as containers the competition was only present intermittently. The lack of competition meant that it was difficult to gauge the potential of the product, and that it was difficult to identify a suitable business model.

The lack of competition and market development in Sweden was mainly attributed to limited customer interest and poor support from the national government. Historically, Sweden had a considerable merchant navy and a vibrant IWT sector but after the second world war and the death of the shipbuilding industry in the 1970 the interest in commercial waterway solutions for inland transport almost evaporated.

4.1.2. Geopolitics and the policy landscape

Geopolitical events such as the aftershocks of the COVID-19 pandemic, the 2022 Russian invasion of Ukraine and the supply-chain shocks, affected the development of the venture negatively. Direct effects were mainly associated with an increased uncertainty and thus a rising business risk. This type of risk also hit the potential customers who suffered financially and were not as interested in testing new products when they had considerable challenges in existing business segments. During the process of identifying potential customers and assessing market potential, the entrepreneur encountered reluctance and outright negative responses, often motivated by concerns about current viability and future-proofing of IWT.

From the regulatory side the financial support for the innovation projects was seen as crucial for moving forward during the process. Without it the capacity of the entrepreneur to carry the project costs would have been considerably lower. However, both the financing and the regulatory view on IWT was described as inflexible. This reasoning reflects a mismatch between the entrepreneurial process and funding agencies' expectations about how innovation should unfold: agencies favour a clear long term goal and small, iterative changes, whereas the venture required organisational reconfigurations and shifts in market segments, design elements, and target customers. During the developmental process it also became clear to the entrepreneur that authorities had a lacking attention to the potential for digital innovations. Although Swedish transport authorities publicly acknowledge and prioritize digitalization in other logistics contexts, such as the procurement of road transports or construction logistics, they did not support the development of digital IWT solutions in the way one would expect from agencies with those stated priorities.

Authorities responsible for sea-based solutions were primarily preoccupied with regulatory issues related to piloting, port management, and supply-chain stability, which left limited attention for the sector's innovative potential. Although authorities had identified IWT and SSS as priority segments and the government appointed officials to support their development, the broader policy emphasis appeared to favour rail and road over waterborne transport. This perception was supported by budgetary priorities and by the authorities' inability to resolve long-standing problems that have hindered the IWT sector for decades. Examples of challenges for the IWT sector were a lack of pilots, difficulties administrating piloting exemptions, uncertainties about funding for waterways maintenance and poor planning of major maintenance projects for key waterways. These issues signalled to actors within the sector, and also to customers with some awareness of IWT, that the uncertainty surrounding IWT and SSS made them appear risky and of limited potential. A telling example occurred when a governmental report overestimated the costs of water based solutions and portrayed a sustained modal shift to waterways as unlikely. Consequently, public support for water based solutions was widely perceived as largely symbolic.

4.2. Venture related barriers

Challenges for the venture and the entrepreneurial process are linked to the difficulty for a small development team to grasp and evaluate technological progression in a rapidly developing technological field, uncertainty about the availability of different financing sources, fragmented data sources, and relative uncertainty about methodology for assessing segment viability.

4.2.1. Developing a minimum viable product

Working with product development meant that it was important to find alternative solutions that would add value in ways that would compel customers to not only try but also continue using IWT. Being a new and largely untested solution in the Swedish context this meant that IWT in many scenarios struggled with cost-disadvantages, making it important to find the specific customers and freight segments where cost could become a competitive advantage. Moreover, as the Swedish freight market had a segment of environmentally conscious freight customers and regulatory and funding sources highlighted the importance of sustainable solutions it also became important to try to identify and work with the environmental profile of IWT in order to show its relevance for a future transport system with increasingly stricter environmental requirements.

When it comes to data management it was quickly realized that the data required to develop a market facilitating service was dispersed across numerous systems and held by different actors, creating a need to manually collect, verify, and manage information on issues such as port locations, pricing components, and quay properties. Consequently, gathering and curating this data was a considerable challenge and therefore also constitutes a potential moat against future competition.

Financing also proved challenging. While several potential investors, such as shipowners and shipping companies, stood to benefit from increased volumes transported via IWT, neither they nor other potential financing sources were familiar with the sector. Therefore, investors had to be educated in the same way as potential customers. Additionally, there were cases with stakeholders that had dual interests. A telling example was a coalition of actors who owned and operated a freight service provider that offered rail-based solutions while also operating ports. Ports often had fee structures that penalized IWT compared with truck transport.

4.2.2. Estimating market size and identifying customers

Estimating the total addressable market for the IWT service was challenging throughout the project. When determining which services to include in the customer value proposition, the evaluation of options and the assessment of different customer segments relied on bottom-up discounted cash-flow (DCF) calculations and comparative analyses to triangulate the price at which potential customers would be willing to commit to a modal shift. While quantitative aspects were considered important it also became clear that many qualitative aspects associated with customer knowledge and attention to logistics issues could create considerable traction for IWT services among freight buyers. It was therefore noted that the innovation process incorporate the customer's level of knowledge and the role of the company representative within the organization, with senior managers being of primary interest due to their organisational mandate. Accordingly, early in the process it became necessary to identify potential goods flows and freight buyers who might be willing to shift to IWT. These prospects were approached through traditional sales efforts, with repeated contacts used to confirm interest and secure letters of intent as an initial commitment. Later in the innovation process, sufficient customer insight had been gathered to shift focus toward recruiting customers via digital channels, direct marketing, and public events.

5. Discussion

This paper set out to identify barriers associated with digital business model innovation for the IWT sector. The research was executed through a three-and-a-half-year long case study in which the researchers followed an entrepreneurial development process of digital IWT services targeting the Swedish IWT sector. The findings are structured in line with previous research on barriers to business model innovation while recognizing the distinct situation of the organization being studied.

A key insight is the misalignment between the digital innovation process and the institutional environment. Although Swedish authorities emphasize digitalization in freight transport, they offer limited practical support for digital IWT solutions. This institutional inertia is regrettable considering decades of declining waterway activity and regulation shaped by legacy modes.

The findings underscore the importance of communication and framing. Customers and regulators rely on concepts and terminology designed for other transport modes. Both customers and regulators are also characterized by a conservative view on technological development and the potential for reaping benefits for IWT through digitalization. Entrepreneurs promoting digital IWT solutions must thus navigate entrenched cognitive structures and carefully engage in communication with multiple stakeholders before new value propositions can be evaluated (Chesbrough, 2010; Williamsson & Moen, 2022). From a venture perspective, the case study also highlights the difficulty of innovating while managing developments on several fronts. Rapid technological change and geopolitical disruptions increase pressure on the venture at the same time as it must secure financing and build an understanding of customer needs and capabilities.

6. Conclusion

This paper contributes to the understanding of digital business model innovation in the IWT sector by identifying key barriers that constrain progress in immature markets. The findings show that digital business model innovation for IWT is shaped by a combination of contextual barriers such as low digital maturity, regulatory inflexibility, limited customer interest, and a lack of comparative water-based alternatives. The results demonstrate that digital business model innovation in IWT is more than a technological endeavor. Much of the entrepreneurial work takes instead the form of traditional sales work and stakeholder interactions aimed at raising awareness of, and knowledge about, IWT. The dominance of land based freight solutions also creates cognitive and procedural lock ins that hinder the adoption of water based alternatives. At the same time, the lack of coordinated regulatory support and the immaturity of the Swedish IWT market reduce the incentives for experimentation and investment. Confirming previous studies, the results show that a successful innovation process requires an alignment of interests across institutions, customers, and the venture in order for the innovation to gain traction (Santén et al., 2021).

For practitioners, the findings highlight the need to invest in communication, customer education, and stakeholder engagement as core components of digital business model innovation. For policymakers, the results underscore the importance of aligning regulatory frameworks, funding structures, and digitalization strategies with modal shift ambitions. For researchers, the study suggests that digital business model innovation in emerging transport modes requires further exploration, particularly regarding how institutional contexts shape innovation trajectories.

Overall, the paper shows that while digital business model innovation may strengthen the competitiveness of IWT, realizing this potential requires overcoming a complex constellation of barriers that often lie outside the entrepreneur's control.

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SUSTAINABILITY TRILEMMA TENSION IN HEALTHCARE SUPPLY CHAINS.

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ABSTRACT

Purpose. Healthcare supply chains (HSC) face competing economic, social, and environmental sustainability priorities. This study investigates how these challenges interact and proposes the Healthcare Sustainability Trilemma to explain the resulting trade-offs.

Research Approach. A systematic literature review and integrative synthesis were conducted to identify recurring sustainability challenges and examine their interrelationships.

Findings and Originality. The findings show that interventions targeting one sustainability dimension often create tensions with the others. The study introduces the Healthcare Sustainability Trilemma as a novel conceptual model to understand structural trade-offs.

Research Impact. The study extends healthcare supply chain sustainability literature by advancing a trilemma perspective beyond the conventional Triple Bottom Line.

Practical Impact. The proposed framework supports healthcare managers and policymakers in recognising and balancing competing sustainability priorities during supply chain decision-making.

Keywords: Healthcare Supply Chain; Sustainability; Healthcare Sustainability Trilemma; Triple Bottom Line; Systematic Literature Review

INTRODUCTION

The United Nations' 2030 Agenda for Sustainable Development presents a comprehensive roadmap for global progress, urging institutions to pursue economic vitality, social equity, and environmental stewardship in tandem. The Triple Bottom Line (TBL) offers a strategic lens through which organisations can harmonise these three pillars, transforming abstract goals into actionable strategies (Azmat et al., 2023). Rather than representing independent objectives, economic, social, and environmental priorities are mutually dependent, requiring organisations to balance financial performance, societal value, and environmental responsibility to achieve long-term resilience and sustainable development (Purvis et al., 2018).

Healthcare supply chains (HSCs) are among the most complex systems, spanning multiple stakeholders and international networks that supply pharmaceuticals, medical devices, and other critical healthcare products. Healthcare supply chains (HSC) face simultaneous economic pressures to control costs, social responsibilities to ensure equitable access and ethical practices, and environmental expectations to minimise waste, emissions, and resource consumption. Overemphasising one dimension can undermine the others; for example, cost reduction may compromise patient access (Sustainable Healthcare: Balancing Patient Care and Environmental Impact, 2025), while prioritising speed or equity without environmental or financial considerations may reduce long-term sustainability (Ruiz-Orjuela et al., 2025).

Despite growing interest in sustainable supply chains, healthcare research continues to examine economic, social, and environmental sustainability largely in isolation (Gimenez et al., 2012)(Elabed et al., 2024). This fragmented perspective overlooks the interactions and trade-offs that characterise healthcare supply chains (HSC), where affordability, patient outcomes, and environmental responsibility are inherently interconnected. Consequently, there remains limited understanding of how these dimensions collectively shape sustainability decision-making (Vergunst et al., 2020).

To address this gap, the study adopts a Triple Bottom Line trilemma perspective to examine how economic, social, and environmental objectives interact within healthcare supply chains (HSC). Rather than treating these dimensions as independent goals, the study argues that improvements in one may generate unintended consequences for the others. (Ruiz-Orjuela (2025).

The research was conducted in two phases. Phase 1 employed a systematic literature review to identify and classify sustainability challenges according to the economic, social, and environmental dimensions of the Triple Bottom Line. Phase 2 used an integrative review to examine how these challenges interact, revealing the sustainability tensions and trade-offs that characterise HSC.

Accordingly, this study addresses the following research question:

RQ1: How do the economic, social, and environmental dimensions of the Triple Bottom Line interact to generate sustainability tensions in healthcare supply chains (HSC)?

This study contributes to research on HSC sustainability by introducing the Healthcare Sustainability Trilemma as a conceptual model to understand sustainability trade-offs. Unlike previous studies that examine economic, social, and environmental sustainability as parallel objectives, this research conceptualises sustainability as the outcome of persistent interactions between these dimensions, providing a foundation for future empirical investigation and decision-making.

2. METHODOLOGY

This study employed a two-phase literature review to investigate sustainability tensions in HSC. Phase 1 employed a systematic literature review to identify and classify sustainability challenges across the economic, social, and environmental dimensions of the Triple Bottom Line (TBL). Phase 2 employed an integrative literature review (ILR) to examine how these dimensions interact, generating trade-offs and sustainability tensions.

2.1 PHASE 1 SYSTEMATIC LITERATURE REVIEW

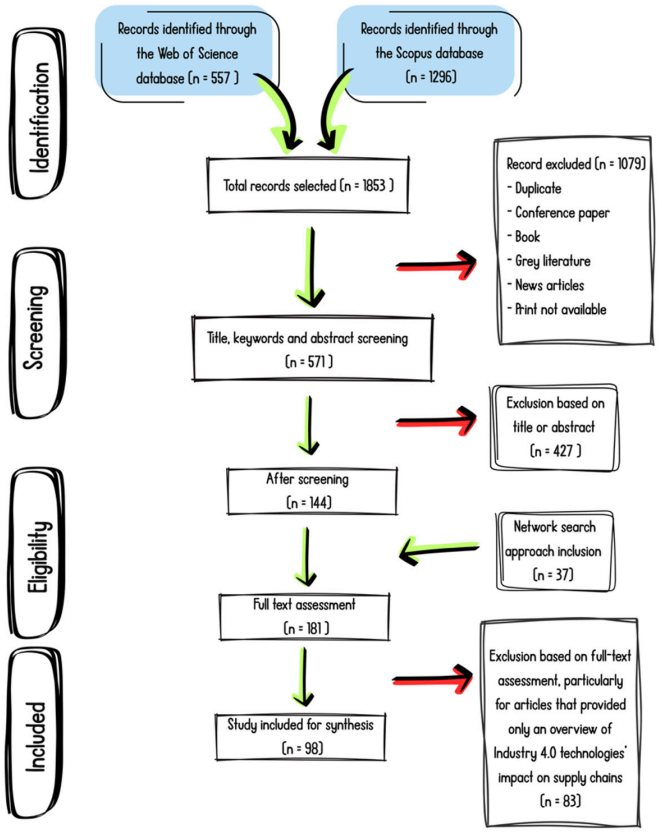

Figure 1. PRISMA flow diagram depicting the methodological framework adopted for this systematic literature review.

A systematic literature review (SLR) was conducted to identify and classify sustainability challenges reported within HSC. The review followed predefined inclusion and exclusion criteria to ensure methodological rigour and transparency. Only peer-reviewed journal articles published in English and indexed in Web of Science and Scopus were considered. Studies focusing on HSC and sustainability were included, while conference papers, book chapters, editorials, and studies unrelated to healthcare supply chains were excluded (Figure 1).

The literature search employed Boolean keyword combinations relating to healthcare supply chains, sustainability, and the Triple Bottom Line (TBL). Following duplicate removal and title, abstract, and full-text screening, 98 peer-reviewed articles were retained for analysis. The screening process was undertaken collaboratively by the research team to ensure consistency and consensus. NVivo 14 was subsequently used to code the literature according to the economic, social, and environmental dimensions of the Triple Bottom Line, enabling the identification of recurring sustainability challenges, interactions, and trade-offs across HSC.

The extracted data were analysed using NVivo 14 to classify sustainability challenges across the three Triple Bottom Line dimensions and identify recurring patterns and gaps within the HSC literature.

3.2 Phase 2: Integrative Literature Review

Building on Phase 1, a second-phase integrative literature review (ILR) was conducted to deepen the theoretical understanding of the interactions between the economic, social, and environmental dimensions of sustainability.

Thirty-one studies providing conceptual, empirical, and system-level insights into healthcare sustainability were selected for the narrative review. From this collection, 18 studies were purposively selected for integrative analysis. The selected studies were analysed using NVivo 14 through iterative thematic synthesis. Coding focused on identifying (i) economic, social, and environmental sustainability dimensions, (ii) interactions and trade-offs between these dimensions, and (iii) recurring patterns of sustainability tension across HSC. The synthesis informed the conceptualisation of the Healthcare Sustainability Trilemma (Table 1).

Table 1. Analytical steps undertaken during the integrative literature review

Analytical Step	Contributing Studies	Number of Studies	Explanation
Step 1: System-level problem framing and boundary definition	Sherman, 2020; Nature Sustainability, 2022; Zurynski et al., 2022; Dolcini et al., 2025; Hussain et al., 2018; Elabed et al., 2024; Jia et al., 2025	7	These studies explicitly frame healthcare sustainability within a system-level perspective, highlighting supply chains as integral to broader healthcare operations.
Step 2: Theoretical anchoring and conceptual positioning	Khokhar et al., 2022; Żak, 2015; Biswas et al., 2018; Ahi & Searcy, 2015; Isil & Hernke, 2017; Neri et al., 2021	6	These studies provide the conceptual foundation using TBL theory or critique its application, linking theory to healthcare supply chains.
Step 3: Thematic categorisation of sustainability dimensions	Wahab et al., 2023; Miller et al., 2021; Verlinden et al., 2024; Ashworth et al., 2025; Fahimnia et al., 2025; Alfina et al., 2024; Alfina et al., 2025	7	Studies that identify economic, social, and environmental sustainability dimensions, categorising challenges and practices across TBL pillars.
Step 4: Identification of interactions, trade-offs, and tensions	Esfahbodi et al., 2016; Fahimnia et al., 2025; Hussain et al., 2018; Jia et al., 2025; Verlinden et al., 2024; Alfina et al., 2025	6	Studies analysing trade-offs between economic, social, and environmental objectives, highlighting tensions rather than synergies.
Step 5: Integrative synthesis into conceptual or operational models	Jia et al., 2025; Elabed et al., 2024; Alfina et al., 2024; Sherman, 2020	4	Studies that develop or propose integrated frameworks, conceptual models, or operational approaches for sustainable healthcare supply chains.

4. RESULTS AND DISCUSSION

4.1 SUSTAINABILITY TRILEMMA AND PARADOXICAL TRADE-OFFS

The integrative literature review demonstrates that sustainability in HSC is characterised by persistent interactions between economic, social, and environmental objectives, resulting in recurring trade-offs rather than mutually reinforcing outcomes. Table 2 summarises the eighteen studies included in the integrative synthesis, showing that sustainability tensions occur consistently across different healthcare contexts, although they are rarely conceptualised explicitly. Collectively, these studies indicate that sustainability trade-offs are structural characteristics of HSC rather than isolated operational challenges.

Table 2. Table 2. Integrative synthesis of studies examining sustainability interactions and trade-offs in healthcare supply chains.

No.	Study	Why included in integrative synthesis	Type of tension identified	Level of analysis	How trade-offs are treated in the study
1	Jia et al. (2025)	System-level healthcare SC framework; TBL-based; implicit multi-dimensional tensions	E–S: cost containment vs patient safety & access; E–Env: efficiency vs environmental obligations; Tri: affordability–resilience–environment	Healthcare supply chains	Trade-offs are treated as coordination and alignment challenges, with sustainability dimensions modelled in parallel rather than in conflict
2	Hussain et al. (2018)	Social sustainability drivers/barriers revealing economic–social tensions	E–S: cost pressures vs social accountability & workforce wellbeing	Healthcare supply chain and organisational	Trade-offs are discussed through reported barriers and motivators, showing how cost pressure, competition, and limited resources constrain social sustainability initiatives
3	Elabed et al. (2024)	System-wide healthcare SC innovation framework	Implicit E–Env: innovation costs vs environmental gains; Implicit E–S: affordability vs diffusion of sustainable practices	Healthcare supply chain system	Trade-offs are largely absent, with innovation and diffusion framed as mechanisms for simultaneous improvement across dimensions
4	Alfina et al. (2024)	Circular SCOR in healthcare; operational TBL tensions	E–Env: efficiency & KPI optimisation vs circular resource use; E–S operational efficiency vs equity/access	Healthcare supply chain operations	Trade-offs appear through process metrics and KPIs, where efficiency and compliance targets dominate while social outcomes are marginal.
5	Alfina et al. (2025)	Dynamic Barrier Management; efficiency–equity/environment tensions	E–Env: performance optimisation vs environmental responsibility; E–S: efficiency vs equitable delivery	Healthcare supply chains	Trade-offs are reflected in barrier management priorities, where performance improvement and digitalisation are emphasised over equity and access
6	Sherman et al. (2020)	Healthcare sustainability science; system boundaries and LCA	E–Env: cost/resource constraints vs system-wide emissions reduction	Healthcare system including supply chains	Trade-offs are not framed explicitly; environmental impact reduction is treated as a technical measurement and system design challenge
7	Nature Sustainability (2022)	System framing of healthcare sustainability incl. supply chains	E–Env: decarbonisation vs cost/operational feasibility; S–Env: care quality vs environmental harm	Healthcare system	Trade-offs are discussed normatively, emphasising ethical responsibility while acknowledging financial and operational constraints

8	Zurynski et al. (2022)	System boundary inconsistencies; fragmentation across healthcare systems	Tri (structural): fragmented system boundaries creating misaligned economic, social, and environmental outcomes	Healthcare systems	Trade-offs are treated as boundary inconsistencies, where actions at one system level generate unintended consequences at another
9	Dolcini et al. (2025)	Environmental sustainability beyond hospital boundaries	E–Env: hospital cost constraints vs upstream environmental impacts	Hospital systems and supply chains	Trade-offs are discussed through boundary limitation critiques, highlighting the exclusion of upstream impacts due to operational constraints
10	Tushar et al. (2023)	System-oriented sustainability drivers (managerial–policy–environmental)	E–Env: managerial efficiency vs environmental investments; E–S (implicit): performance vs workforce/social priorities	Hospital level	Trade-offs are embedded in causal prioritisation, where operational efficiency drivers exert stronger influence than environmental factors
11	Verlinden et al. (2024)	LCA-based pharmaceutical SC trade-offs	E–Env: carbon reduction vs resource efficiency; S–Env (latent): sourcing shifts vs social/regulatory risk	Pharmaceutical supply chain	Trade-offs are quantified using life cycle assessment, explicitly comparing emissions reductions against increased abiotic and nuclear resource use
12	Esfahbodi et al. (2016)	Cost–environment trade-offs in supply chains	E–Env: environmental performance vs cost efficiency	Supply chains	Trade-offs are explicitly modelled, demonstrating inverse relationships between cost efficiency and environmental performance
13	Fahimnia et al. (2025)	Sustainability paradoxes and persistent trade-offs	Tri: paradoxical trade-offs across cost, environmental protection, and social responsibility	Supply chains	Trade-offs are explicitly conceptualised as paradoxes, arguing that competing objectives persist and cannot be fully resolved
14	Berniak-Woźny et al. (2023)	Sustainability as multidimensional system challenge	Tri: sustainability as structurally conflicting system objectives	Sustainability systems	Trade-offs are treated as systemic and structural, arising from incompatible sustainability objectives in complex systems
16	Milojević et al. (2024)	Integrated sustainability approaches; limits of siloed thinking	Tri: failure of siloed approaches to reconcile economic, social, environmental goals	System level sustainability	Trade-offs are discussed through critique of pillar-based approaches, arguing that isolated optimisation obscures interactions
17	Aboueid et al. (2023)	Organisational constraints shaping sustainability trade-offs	E–Env: environmental initiatives vs organisational resource constraints; E–S (implicit): service pressures	Healthcare organisations	Trade-offs are described through implementation barriers, including limited time, funding, leadership capacity, and infrastructure
18	Sánchez-Flores et al. (2020)	Environmental impacts of SC decisions within broader systems	E–Env: logistics efficiency vs emissions and waste	Supply chains	Trade-offs emerge through performance comparisons, where efficiency gains coincide with increased environmental burdens
19	Khokhar et al. (2022)	TBL as multidimensional sustainability lens for SCs	Tri (conceptual): incompatibility of isolated TBL optimisation	Supply chain sustainability theory	Trade-offs are treated conceptually, highlighting tensions created by independent optimisation of triple bottom line dimensions

E–S = Economic–Social, E–Env = Economic–Environmental, S–Env = Social–Environmental, Tri = Tri-dimensional

Economic–environmental interactions represent the most consistently reported sustainability tension. Across the reviewed studies, initiatives designed to improve operational efficiency, resilience, and cost performance frequently increase environmental impacts, while environmental interventions often require additional financial investment or operational compromise. However, these relationships are generally interpreted as optimisation or implementation challenges rather than as structural interactions between sustainability dimensions. Economic–social interactions follow a similar pattern. Measures intended to improve efficiency, affordability, and organisational performance frequently constrain patient safety, workforce wellbeing, equitable access, and service resilience. Most studies attribute these outcomes to implementation barriers or resource constraints, overlooking their broader sustainability implications.

Although several studies adopt system-level perspectives, sustainability interactions are generally interpreted in terms of coordination, innovation, or performance improvement rather than as competing objectives. Only a small number of recent contributions explicitly conceptualise these interactions as persistent sustainability paradoxes or trilemmas, arguing that economic viability, social responsibility, and environmental stewardship cannot always be simultaneously optimised. These studies provide the strongest theoretical foundation for reinterpreting healthcare supply chain sustainability through a trilemma perspective (Figure 2).

Overall, the integrative synthesis suggests that sustainability challenges should not be viewed as independent economic, social, or environmental issues but as interconnected phenomena arising from continual interactions across the Triple Bottom Line. This analytical perspective provides the foundation for examining how addressing the sustainability challenges identified through the systematic literature review may generate new cross-dimensional sustainability tensions, ultimately giving rise to the Healthcare Sustainability Trilemma (Figure 2).

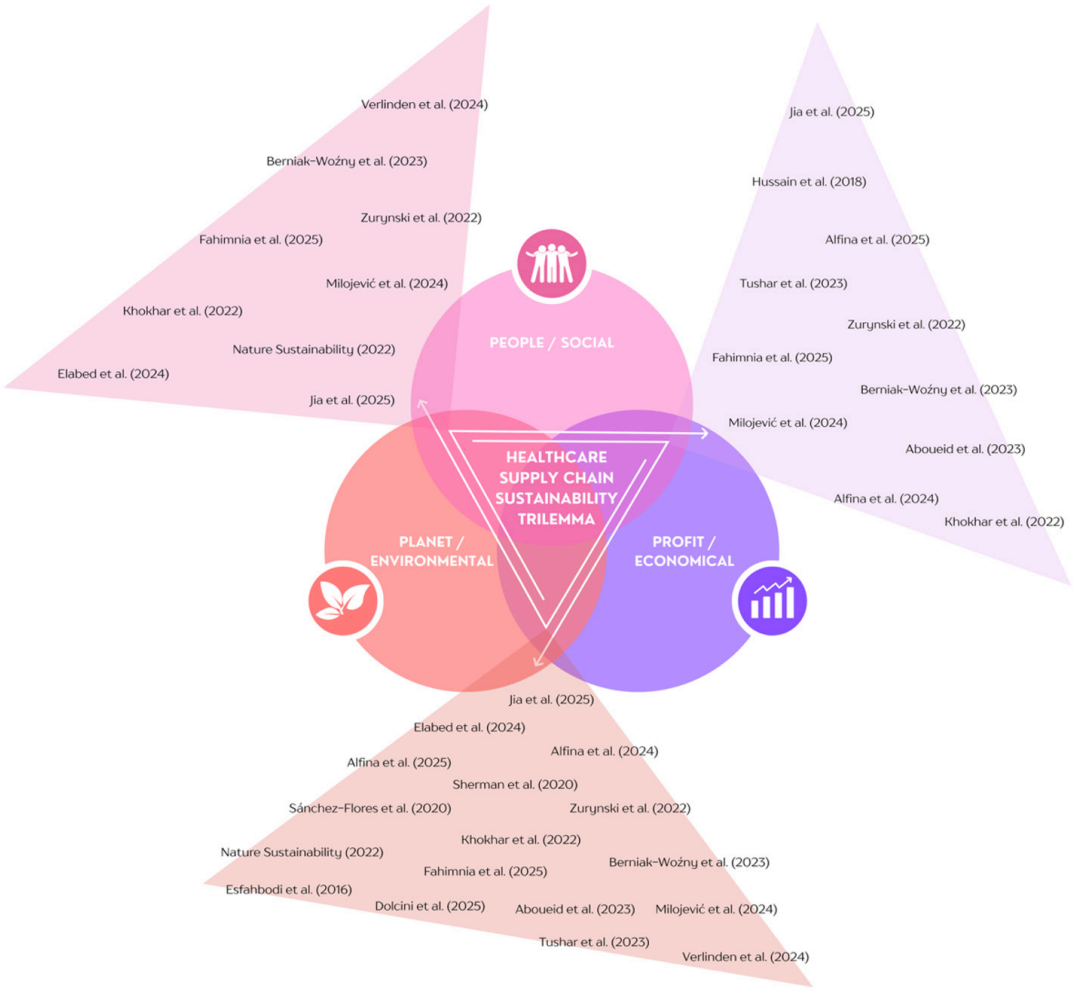

Figure 2. Healthcare Sustainability Trilemma showing cross-dimensional sustainability tensions. References identify supporting studies from the integrative review.

4.2 Sustainability Challenges Generating the Healthcare Sustainability Trilemma

4.2.1 Economic sustainability challenges

The systematic literature review identified five recurring challenges associated with the economic dimension of sustainability within healthcare supply chains: cost pressures and limited budgets, inventory inefficiencies, fragmented information systems, supply chain coordination failures, and technology and compliance investment costs (Table 3). Building upon the analytical perspective established in Section 4.1, Table 3 summarises the sustainability tensions that emerge when organisations seek to address these challenges.

Table 3 indicates that addressing cost pressures and inventory inefficiencies improves financial efficiency and resource utilisation but may constrain investment in patient safety, organisational resilience, and service continuity (Hussain et al., 2018; Miller et al., 2021; Wahab et al., 2023; Zurynski et al., 2022). Likewise, interventions targeting fragmented information systems, supply chain coordination, and digital integration enhance visibility and operational performance but require additional governance, compliance, and financial resources, creating broader organisational and environmental pressures (Ahi & Searcy, 2015; Milojevi et al., 2024; Jia et al., 2025; Miller et al., 2021; ak, 2015). These findings indicate that addressing economic sustainability challenges often extends beyond financial performance, necessitating trade-offs among social and environmental priorities.

Table 3. Economic sustainability challenges and resulting sustainability tensions

Economic intervention	Potential sustainability tension when addressed	Indicative references
Cost containment	Improves financial performance but limits investment in patient safety and environmental initiatives.	Hussain et al. (2018); Miller et al. (2021); Wahab et al. (2023)
Lean inventory	Reduces waste and costs but increases stock-out risks and weakens resilience.	Zurynski et al. (2022); Miller et al. (2021)
Digital integration	Improves visibility but increases governance complexity and reduces organisational flexibility.	Ahi & Searcy (2015); Milojević et al. (2024); Jia et al. (2025)
Supply chain coordination	Improves efficiency but requires greater compliance and constrains patient-centred decision-making.	Miller et al. (2021); Jia et al. (2025); Żak (2015)
Digital and compliance investment	Enhances transparency but increases financial and organisational burdens.	Hussain et al. (2018); Jia et al. (2025)

4.2.2 Social sustainability challenges

The five social sustainability challenges identified through the systematic literature review are presented in Table 4 alongside the sustainability tensions that arise when healthcare organisations seek to address them. Patient safety and quality assurance represent the clearest example: improving healthcare outcomes requires additional monitoring, redundancy, and resource utilisation, thereby increasing operational costs, waste generation, and energy consumption (Sherman, 2020; Miller et al., 2021). Similarly, interventions addressing counterfeit medicines, transparency, ethical procurement, and pharmacoepidemiological surveillance strengthen governance and public trust but require greater compliance, digital infrastructure, and organisational resources (Hussain et al., 2018; Zurynski et al., 2022; Jia et al., 2025; Nature Sustainability, 2022; Milojevi et al., 2024; Wahab et al., 2023). Collectively, the findings indicate that addressing social sustainability challenges consistently requires additional economic and environmental resources, demonstrating the cross-dimensional nature of sustainability decision-making in healthcare supply chains.

Table 4. Social sustainability paradoxes in healthcare supply chains

Social intervention	Potential sustainability tension when addressed	Indicative references
Patient safety and quality assurance	Improves patient outcomes through monitoring and quality assurance but increases operational costs, waste generation, and energy consumption.	Sherman (2020); Miller et al. (2021)
Counterfeit prevention and medicine authentication	Strengthens patient safety and trust but increases compliance costs, administrative complexity, and may restrict medicine access in resource-constrained settings.	Hussain et al. (2018); Zurynski et al. (2022); Jia et al. (2025)
Transparency and accountability	Improves governance and information sharing but increases administrative workload, digital infrastructure requirements, and energy consumption.	Nature Sustainability (2022); Milojević et al. (2024)
Ethical procurement and human rights protection	Strengthens responsible sourcing and accountability but increases procurement costs and limits supplier flexibility and clinical autonomy.	Wahab et al. (2023); Miller et al. (2021)
Pharmacoepidemiological surveillance and medicine access regulation	Enhances population safety and regulatory oversight but requires additional infrastructure and data management while potentially reducing equitable access.	Miller et al. (2021); Zurynski et al. (2022)

4.2.3 Environmental sustainability challenges

Table 5 illustrates how the four environmental sustainability challenges identified through the systematic literature review contribute to the Healthcare Sustainability Trilemma. Although aimed at improving environmental performance, addressing transport intensity, cold-chain dependence, product wastage, and circular pharmaceutical systems frequently generates broader economic and social trade-offs.

Table 5 indicates that addressing transport intensity and cold-chain dependence improves environmental performance and product integrity but may reduce delivery responsiveness while increasing energy consumption, greenhouse gas emissions, and operational costs (Dolcini et al., 2025; Wahab et al., 2023; Sherman, 2020; Miller et al., 2021; Nature Sustainability, 2022). Likewise, interventions addressing product wastage and resource utilisation through circular pharmaceutical systems improve waste management and resource efficiency but require additional coordination, regulatory oversight, and operational resources (Zurynski et al., 2022; Jia et al., 2025; Dolcini et al., 2025). This analysis demonstrates that efforts to improve environmental sustainability extend beyond emission reduction, requiring careful balancing of operational, economic, and patient-centred priorities.

Table 5. Environmental sustainability interventions and resulting sustainability tensions

Environmental sustainability intervention	Resulting sustainability tension	Indicative references
Transport optimisation and route consolidation	Reduces transport emissions but may increase delivery times and reduce responsiveness for time-critical healthcare products.	Dolcini et al. (2025); Wahab et al. (2023)
Cold-chain management	Preserves medicine quality and patient safety but substantially increases energy consumption, greenhouse gas emissions, and operational costs.	Sherman (2020); Miller et al. (2021); Nature Sustainability (2022)
Product wastage reduction and reverse logistics	Improves waste management and product recovery but increases transportation, coordination, compliance, and processing requirements.	Zurynski et al. (2022); Dolcini et al. (2025)
Circular pharmaceutical systems	Improves resource efficiency and reuse but creates additional regulatory, safety, and operational requirements that may affect supply chain resilience.	Jia et al. (2025); Nature Sustainability (2022); Dolcini et al. (2025)

CONCLUSION

This study examined sustainability challenges within healthcare supply chains through a systematic literature review and integrative synthesis. The findings demonstrate that economic, social, and environmental objectives are inherently interconnected, leading to the development of the Healthcare Sustainability Trilemma as a conceptual framework for understanding the trade-offs that shape sustainability decision-making.

Theoretically, the study advances research on healthcare supply chain sustainability by introducing the Healthcare Sustainability Trilemma as a framework for understanding structural sustainability tensions. Practically, it provides healthcare decision-makers with a structured perspective for recognising and balancing competing sustainability priorities when designing and managing healthcare supply chains. Future research should empirically validate the proposed framework across different healthcare settings.

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SIMULATING THE CONFIGURATION OF BATTERY SWAPPING STATIONS FOR LAST-MILE E-VANS

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1 Introduction

Road freight decarbonisation remains a challenge because freight transport contributes substantially to transport-related greenhouse gas emissions and depends heavily on fossil fuels (Department for Transport, 2023; Meyer, 2020). In urban areas, e-commerce growth has increased last-mile logistics activity, making e-van adoption important for sustainable urban freight systems (Bosona, 2020; Temporelli et al., 2022). However, e-vans require reliable charging infrastructure to maintain daily delivery operations (Napoli et al., 2021).

E-van adoption faces obstacles relating to charging infrastructure, as recharging facilities directly affect operational efficiency (Kin et al., 2021). Battery swapping stations (BSSs) can be regarded as a potential charging solution, as they swap depleted batteries with fully charged ones rather than keeping vehicles parked for plug-in charging (Xinyi et al., 2014; Wu, 2021). However, for logistics businesses and potential BSS operators, the key planning challenge is how to configure a station with sufficient battery swapping bays (BSBs) and battery inventory to provide timely service without creating idle capacity and unnecessary cost. Therefore, this paper investigates BSS configuration as an operational trade-off between service level, resource utilisation and cost. It develops a simulation-based model to evaluate how different combinations of BSB capacity and battery inventory affect BSS performance under different e-van demand scenarios, and to identify recommended configurations for early-stage planning.

2 Literature review

Existing research has examined BSSs as charging infrastructure across different electric vehicle contexts (Feng and Lu, 2021). Wang et al. (2025) compared battery swapping and fast charging for electric heavy-duty trucks and showed that BSSs can reduce vehicle downtime and improve transport efficiency, although this requires additional battery reserves. Qiang et al. (2023) studied electric taxis and developed a cost-oriented optimisation model considering battery state of charge, waiting cost and BSS congestion. Roudbari et al. (2025) examined electric buses by integrating BSS siting, battery storage capacity, charging scheduling and grid impacts. These studies show that BSSs involve complex service, capacity and operational decisions. However, they mainly focus on heavy-duty trucks, taxis and buses, with limited attention to BSS configuration for e-vans in urban last-mile delivery.

Configuration planning is also an important direction in BSS operation research. Xinyi et al. (2014) optimised battery pack and charger numbers within a BSS using facility cost, station scale and service availability constraints. Guo et al. (2025) developed a mixed-integer linear programming model to determine BSS locations and battery inventory under uncertain commercial electric vehicle demand. An et al. (2020) used a two-stage stochastic programming model to address BSS location, demand allocation, battery quantity and swapping robot requirements for electric buses. Overall, existing BSS configuration studies consider issues such as demand, battery quantity, charging facilities, and cost. However, fewer studies jointly examine BSB capacity and battery inventory as configuration variables under different daily e-van demand levels. Methodologically, many studies adopt optimisation-based frameworks, while fewer examine BSS configuration as an operations management problem involving capacity, inventory, service performance and cost trade-offs. In this paper, simulation is used to model e-van BSS operations under alternative configurations and demand scenarios, generating performance outputs used to calculate performance indicators for service-feasibility screening and weighted ranking.

Accordingly, this paper addresses this gap by jointly examining BSB capacity and battery inventory for an e-van BSS under different daily demand levels. Using indicators related to demand fulfilment, system operation and economic performance, the study compares alternative configurations and provides decision support for logistics businesses considering BSS investment and potential BSS operators estimating station resource requirements.

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3 Methodology

3.1 Problem setting and model design

This study developed a MATLAB-based simulation model to evaluate BSS configuration for urban last-mile delivery e-vans. The model simulates the main BSS operation process, including random e-van arrivals, battery swapping service, vehicle waiting and the circulation of batteries between depleted and fully charged states.

Table 1 summarises the key simulation and cost assumptions used to define the modelling environment. These assumptions provide a consistent basis for comparing alternative configurations, rather than representing a detailed engineering design of a specific BSS.

Category	Assumption
Case context	Single UK urban BSS serving last-mile e-vans
Reference e-van	Mercedes-Benz eVito-type e-van, 60 kWh battery
Operating window	8 hours per day
Swapping time	10 minutes per e-van
Layout basis	Footprint based on swapping area, distribution and waiting areas
Cost basis	Annualised CAPEX and OPEX per completed swap
CAPEX items	Batteries, charging bays, swapping machine, electrical infrastructure, civil works and application-related costs
OPEX items	Land rent, maintenance and information system subscription

Table 1: Key simulation and cost assumptions

Using these assumptions, the model compares different BSS configurations under daily battery swapping demand levels ranging from 10 to 50 e-vans per day. Two core decision variables are considered: the number of BSBs and battery inventory. BSBs determine the station's immediate service capacity, while battery inventory determines the availability of fully charged batteries for arriving e-vans. A swap can only start when both a BSB and a fully charged battery are available; otherwise, the arriving e-van waits. The simulation outputs operational and economic indicators, which are then used to compare and rank alternative configurations.

3.2 Performance indicators and evaluation approach

To evaluate BSS configuration performance, this study adopts a multi-indicator framework covering demand fulfilment, system operation and economic performance. Previous BSS planning and operation studies have considered service availability, swapping capacity, battery availability and cost-related performance (Xinyi et al., 2014; Wu, 2021; An et al., 2020). Based on these considerations, five indicators are used: actual number of e-vans serviced, average waiting time per e-van, average work in progress (WIP), service efficiency and average cost per swap. Their roles are summarised in Table 2.

Indicator	Dimension	Role in evaluation
Actual number of e-vans serviced	Demand fulfilment	Measures the number of e-vans successfully served over the simulation period
Service efficiency	Demand fulfilment	Measures the proportion of daily demand successfully served
Average waiting time per e-van	System operation	Measures delay before swapping starts
Average WIP	System operation	Measures the average number of e-vans in the BSS system, including waiting and swapping, to indicate congestion
Average cost per swap	Economic performance	Annualised CAPEX and OPEX divided by completed swaps during the simulation period

Table 2: Performance indicators used for BSS configuration evaluation

A two-stage evaluation method is used to determine recommended configurations. In the first stage, service feasibility is screened using two thresholds: average waiting time per e-van of 5 minutes or less and service efficiency of 95% or greater. These thresholds are used as strict service-screening assumptions for comparing alternatives in a rapid battery swapping context, rather than as universal industry standards. This step removes configurations that appear cost-effective but cannot provide an acceptable service level.

In the second stage, feasible configurations are normalised and ranked using weighted scoring. Weighted scoring compares alternatives by assigning weights to criteria according to their relative importance (Belton and Stewart, 2002). Indicator values are first normalised according to their direction. For a positive indicator, the normalised value is calculated as:

$$\text{Equation 1: } z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

For a negative indicator, the normalised value is calculated as:

$$\text{Equation 2: } z_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$$

where *xij* is the original value of configuration i on indicator j, max*(xj)* and min*(xj)* are the maximum and minimum values of indicator *j* among feasible configurations under the same demand level. The weighted score is then calculated as:

$$\text{Equation 3: } S_i = \sum_{j=1}^{m} w_j z_{ij}$$

where *Si* is the overall score of configuration *i, wj* is the weight assigned to indicator *j*, and m is the number of indicators included in the second-stage ranking. Service efficiency is excluded from the second-stage weighted ranking, because under each fixed demand scenario, it provides the same demand-fulfilment information as the actual number of e-vans serviced after normalisation. To avoid double-counting this dimension, the weighted ranking retains the actual number of e-vans serviced and excludes service efficiency. Average waiting time is also retained because feasible configurations may still differ in user delay after the service threshold has been met.

The weighting scheme reflects an economic-priority evaluation after service feasibility has been ensured. Average cost per swap is assigned the highest weight (0.40) to support cost-driven BSS planning before infrastructure investment. The remaining indicators retain demand support and operational stability considerations: actual number of e-vans serviced (0.25), average WIP (0.20), and average waiting time per e-van (0.15). Therefore, the final score represents the weighted performance of each feasible configuration, with a higher score indicating a better balance between service provision, system operation, and cost-efficiency. Figure 1 summarises this process from simulation outputs to service feasibility screening, indicator normalisation, weighted scoring and final ranking.

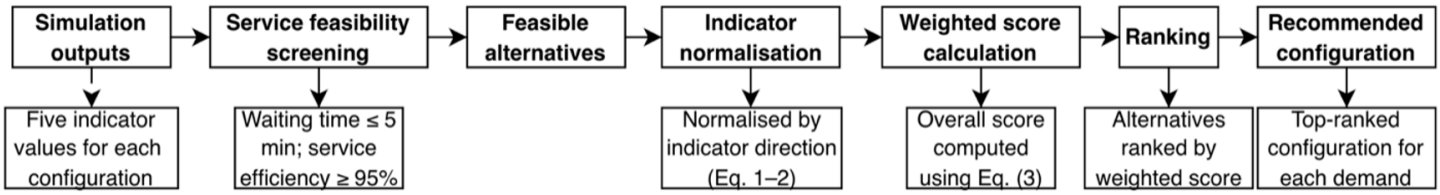

Figure 1: Two-stage screening and ranking process for BSS configuration evaluation

3.3 Experimental design

The simulation experiment compares BSS configurations under five daily demand scenarios: 10, 20, 30, 40, and 50 e-vans per day. These scenarios represent potential scales of e-vans battery swapping demand, ranging from small fleets or public transportation use to higher-demand urban logistics applications. For each demand level, alternative configurations are developed by combining different numbers of BSBs with various battery inventory levels.

Rather than testing every mathematically possible configuration, this study uses a demand-based configuration testing approach. This is consistent with simulation experimentation, where scenarios are designed to compare decision-relevant alternatives rather than every possible combination (Law, 2015). Under lower demand levels, very high-capacity configurations are excluded because they provide limited decision value. As demand increases, the tested range expands to include more BSB and battery inventory levels. Table 3 shows the alternative configurations ultimately simulated in the experiment.

Daily demand (e-vans/day)	BSBs tested	Battery range	Alternatives
10	1 – 2	2 – 20	38
20	1 – 2	2 – 30	58
30	1 – 3	2 – 35	102
40	2 – 4	2 – 40	117
50	2 – 5	2 – 45	176

Table 3: Experimental alternative configurations

Because e-van arrivals are random, multiple simulation runs are performed for each alternative, and average output values are used for comparison. The model period is set to one year, and indicator results are normalised according to their positive or negative direction before the two-stage evaluation.

4 Results and discussion

4.1 Preliminary analysis of performance patterns

Before applying the two-stage screening and ranking method, the simulation results are analysed to show how BSB numbers and battery inventory affect demand fulfilment, service delay, congestion and cost-efficiency.

The results show that increasing battery inventory improves demand fulfilment, as both the actual number of e-vans serviced and service efficiency increase when more fully charged batteries are available. However, this improvement gradually levels off once the station has enough batteries to meet the relevant daily demand. This plateau appears earlier for 10–20 e-vans/day, while 40–50 e-vans/day require both more batteries and more BSBs before serviced volume approaches the demand ceiling.

System operation also improves as battery inventory increases. Average waiting time decreases because fully charged batteries become more available. However, under 40–50 e-vans/day, additional BSBs are also needed to reduce waiting time effectively, indicating that immediate service capacity becomes a bottleneck as demand increases. Average WIP first increases and then decreases, showing that insufficient battery availability creates internal congestion, while improved battery inventory and BSB capacity support smoother service flow.

The economic results show that average cost per swap initially decreases as fixed costs are spread across more completed swaps. However, once demand fulfilment and service performance plateau, additional batteries generate limited service improvement but increase inventory-related costs, causing cost per swap to stabilise or rise.

Overall, three battery inventory zones can be identified. The shortage region occurs when insufficient battery availability limits throughput and increases waiting time and WIP. The adequate region occurs when additional batteries improve service performance and reduce cost per swap. The redundant region occurs when extra batteries no longer improve throughput, waiting time or service efficiency, while cost per swap stops decreasing or rises. These results show that BSS configuration is demand-specific: 10–20 e-vans/day can be supported by smaller configurations, whereas 40–50 e-vans/day require both larger battery inventory and greater BSB capacity

4.2 Screening and ranking results

The two-stage evaluation method described in Section 3.2 is applied to identify the recommended BSS configuration for each daily demand level. After infeasible alternatives are removed, the remaining configurations are normalised and ranked

using the weighted scoring method. The score in Table 4 is the weighted sum of the normalised indicator values calculated using Equation (3), with a higher score indicating stronger overall performance under the economic-priority weighting scheme. Table 4 presents the recommended configuration for each daily demand level.

Daily demand level	Recommended configuration	Weighted score
10 e-vans/day	2 BSBs with 10 batteries	0.8576
20 e-vans/day	2 BSBs with 18 batteries	0.9057
30 e-vans/day	2 BSBs with 27 batteries	0.8236
40 e-vans/day	3 BSBs with 33 batteries	0.8092
50 e-vans/day	3 BSBs with 39 batteries	0.8280

Table 4: Recommended configurations for each demand after two-stage evaluation

The ranking results show that the recommended configuration does not increase linearly with demand. From 10 to 30 e-vans/day, the recommended number of BSBs remains two, while battery inventory increases from 10 to 27 batteries. This indicates that, within this range, increasing battery inventory can support higher throughput without immediately increasing BSB capacity. However, once demand reaches 40 e-vans/day, battery inventory alone is insufficient to maintain efficient service flow, and the recommended configuration increases to three BSBs. This reflects a shift in the system bottleneck from battery availability to immediate service capacity. The 30 e-vans/day scenario represents a transitional case: although 2 BSBs with 27 batteries has the highest score, alternatives with 3 BSBs and slightly fewer batteries are also competitive. Therefore, the final decision at this demand level may depend on whether the operator prioritises lower capital investment, shorter waiting time or additional service redundancy.

4.3 Discussion of trade-offs and recommended configurations

The findings highlight three key trade-offs in the BSS configuration for last-mile e-vans:

(1) BSB capacity and battery inventory. BSBs determine immediate service capacity, while battery inventory determines the availability of fully charged batteries. Increasing battery inventory improves throughput and reduces waiting when battery availability is the main constraint. However, once BSB capacity becomes the bottleneck, adding more batteries alone cannot maintain smooth service flow.

(2) Service performance and economic efficiency. Higher-capacity configurations can reduce waiting time and improve service efficiency, but they may also increase average cost per swap if the additional resources are not fully utilised. Conversely, lower-cost configurations may reduce investment but can cause congestion or fail to meet demand. The two-stage evaluation approach reflects this trade-off by first removing configurations that do not meet minimum service requirements and then ranking feasible alternatives using an economic-priority weighting scheme.

(3) Configuration based on requirements and service standards. The recommended configurations should be viewed as planning suggestions rather than fixed solutions. They depend on daily swapping demand and the service standards used in screening. For example, relaxing the waiting-time threshold from five to ten minutes may allow lower-capacity alternatives at 10 e-vans/day, while the 20 e-vans/day recommendation remains unchanged. At 30 e-vans/day, multiple near-optimal alternatives emerge, indicating a transitional point between two-BSB and three-BSB configurations.

5 Conclusion

This paper investigates the configuration of an e-van BSS for urban last-mile e-vans using a MATLAB-based simulation model. Different combinations of BSB numbers and battery inventory are evaluated under five daily demand scenarios and assessed using indicators covering demand fulfilment, system operation and economic performance.

The results show that BSS configuration is a demand-dependent trade-off. Increasing BSB numbers and battery inventory can improve service performance, but over-configuration leads to diminishing marginal returns because additional resources increase capital and operating costs without generating proportional increases in completed swaps. For 10–30 e-vans/

day, increasing battery inventory can support higher demand without immediately expanding BSB capacity. However, once demand reaches 40–50 e-vans/day, battery inventory alone becomes insufficient, and additional BSB capacity is required to maintain service flow.

The study provides a practical simulation-based framework for comparing BSS configuration schemes from the perspective of potential BSS operators and logistics businesses considering BSS investment. For potential BSS operators, the findings suggest that station scale should be matched to expected daily swapping demand rather than selected by simply maximising capacity or minimising cost. This can help operators avoid under-provisioning, which may create waiting and unmet demand, as well as over-provisioning, which may create idle resources and increase cost per swap. For logistics businesses, the results can support early assessment of whether a BSS-based charging model is suitable for their expected e-van demand and service requirements.

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SURPLUS FOOD REDISTRIBUTION: A REVIEW OF CONTEMPORARY MODELS AND STAKEHOLDER PERSPECTIVES

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Introduction

Surplus food redistribution (SFR) has become an increasingly prominent strategy for addressing two interconnected societal challenges: food waste and food insecurity. Across many countries, large quantities of edible food continue to be discarded throughout food supply chains, while substantial numbers of individuals and households experience difficulties in accessing sufficient food (FAO et al., 2023). In response, governments, food businesses, and charitable organisations have increasingly promoted SFR as a mechanism through which surplus food can be redirected for human consumption rather than disposed of as waste (Facchini et al., 2018). As a result, SFR is often portrayed as a "win-win" solution capable of simultaneously reducing food waste and alleviating food insecurity (Papargyropoulou et al., 2022).

Within SFR systems, food retailers and non-profit organisations (NPOs) play important roles, particularly in the UK (WRAP, 2022). Retailers represent one of the largest sources of edible surplus food, while NPOs commonly undertake the collection, storage, coordination, and redistribution activities necessary to transfer food to beneficiaries (Alexander & Smaje, 2008). Consequently, the effectiveness of SFR depends not only on the availability of surplus food but also on the organisational arrangements through which retailers and NPOs coordinate redistribution activities. Reflecting the growing practical importance of these systems, scholarly interest in SFR has expanded considerably over the past decade (Chauhan et al., 2021).

Existing studies on SFR have investigated a wide range of topics, including food donation practices, food waste reduction strategies, redistribution logistics, food charity operations, environmental benefits, and social impacts (de Moraes et al., 2022; Giuseppe et al., 2014; Midgley, 2014). However, these studies often approach SFR from different disciplinary traditions and stakeholder perspectives, resulting in a dispersed body of knowledge that lacks a coherent overview. For example, retailer-focused studies typically examine SFR as a food waste management strategy and explore operational or managerial approaches to increasing food donations (e.g., de Moraes et al., 2022). In contrast, research focusing on NPOs frequently investigates redistribution efficiency, volunteer management, storage capacity, food safety, and service provision to beneficiaries (e.g., Akkerman et al., 2023). At the same time, other studies adopt broader network or system perspectives by examining environmental impacts, food donation potential, or wider stakeholder ecosystems (e.g., Papargyropoulou et al., 2022).

While these studies have collectively advanced knowledge of SFR, they have also produced a fragmented research landscape in which different actors and analytical levels are often examined in isolation. Previous reviews may have provided valuable syntheses of food waste management and SFR research (e.g., Chauhan et al., 2021), yet none have systematically mapped the literature according to both stakeholder focus and analytical level. Consequently, there remains limited understanding of how current knowledge has been constructed and where important gaps persist.

A second limitation concerns the way that SFR itself has been conceptualised organisationally. Existing studies commonly describe redistribution through a number of organisational arrangements, typically centred on food banks and other intermediary charities operating within centralised redistribution systems (Bramanti et al., 2017; EU, 2019). Such categorisations have provided useful foundations for understanding how surplus food moves from donors to beneficiaries. However, contemporary redistribution practices appear increasingly diverse. Alongside traditional food provision networks, recent studies document the emergence of digital food-sharing platforms, community-based redistribution initiatives, volunteer-led collection schemes, and mixed organisational arrangements that do not fit comfortably within existing classifications (Ayala et al., 2022; Berns et al., 2023; Weymes & Davies, 2019). Despite these developments, current categorisations remain largely concentred on traditional and centralised models of redistribution, potentially limiting their ability to capture the organisational diversity now evident across SFR systems.

SFR is not just simply moving surplus food from donors to receivers, it is also an interactive process that involves interlikns with different stakeholders. Understanding how SFR has been studied requires understanding both the perspectives that researchers have taken to examine redistribution and the organisational forms through which redistribution occurs in practice. Without a clearer mapping of existing research and a more comprehensive categorisation of redistribution models, it becomes difficult to identify overlooked actors, underexplored relationships, and emerging organisational developments within the field.

To address these gaps, this paper conducts a systematic literature review (SLR) of SFR research. The review pursues two objectives. First, it examines how SFR has been conceptualised across different stakeholder perspectives and levels of analysis. Second, it develops a general categorisation of SFR models represented within contemporary research.

Methodology

SLR was adopted to provide a structured and transparent synthesis of existing knowledge on SFR. Following established SLR procedures, such as those from Tranfield et al. (2003), a review protocol was firstly developed specifying search cosnideriations, which includes search database, search terms, search field, search timeline, as well as inclusion and exclusion criteria.

The literature search was conducted using four databases: Web of Science (WoS), Scopus, ABI/Inform, and Business Source Complete (BSC), due to their expansive coverage of journals in the supply chain field. Searches were undertaken within titles, abstracts, and keywords using combinations of terms relating to retailers, non-profit organisations, and surplus food redistribution. The review included peer-reviewed journal articles published in English between 2005 and 2024.

During the search, studies that investigate SFR for human consumtpion involving retailers and NPOs were included, while studies that did not look at SFR from a charitable perspectiive or were not within the area of business management were excluded, in order to maintain the focus of this review.

Screening was conducted in three stages. First, titles, abstracts, and keywords were initially reviewed for relevance. Second, abstracts, introductions, and conclusions were examined in greater detail in order to refine their relevance to the review focus. Third, full-text articles were reviewed to allow final inclusion and synthesis. Quality appraisal was undertaken using criteria adapted from Pluye et al. (2009), assessing study's problem framing, methodological transparency, theoretical grounding, and the robustness of its conclusions. Overall, 56 articles were retained for thematic analysis (Clarke & Braun, 2015), via Nvivo, in order to identify recurring patterns relating to stakeholder perspectives and organisational models. The screening results are illustrated in Figure 1 below.

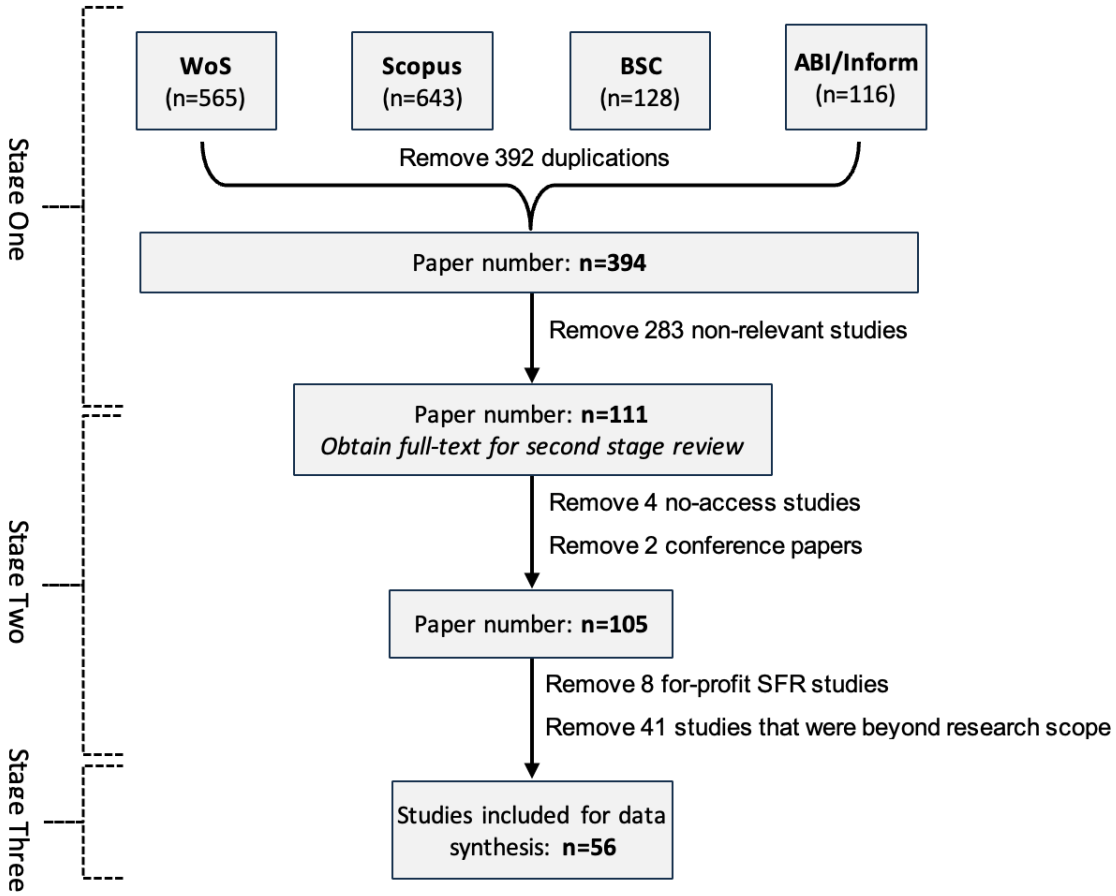

Figure 1: Screening results

The SFR Research Spectrum

Analysis of the reviewed studies revealed substantial variation in how researchers conceptualise SFR. To capture these differences, this study develops the SFR Research Spectrum (see Table 1[2]), which maps studies according to stakeholder focus and level of analysis.

SFR Spectrum			
Upstream actor	*Retailer*	*NPO*	*Beneficiary*
	A (8)		
	B+ (2)	B- (29)	
C+ (3)			C- (5)
D (9)			

Table 1: The SFR Research Spectrum (Authors' own)

Position A represents studies explicitly examining retailer–NPO interactions and collaborative arrangements (e.g., Midgley, 2019). These studies adopt a meso-level analytical lens, investigating how inter-organisational relationships enable or constrain redistribution activities. Because they directly capture the collaborative nature of SFR, Position A provides relational insights most aligned with the system's operational realities.

[2]In Table 2, the symbols "+" and "–" are used to indicate the primary research focus of each paper, with "+" referring to retailers side and "–" referring to NPOs side; these symbols do not imply any level of significance. The number shown in brackets indicates the number of papers that have adopted the corresponding perspective when examining SFR.

Position B consists of single-actor studies focusing either on retailers (B+) or NPOs (B—). Retailer-focused studies examine food waste management practices, donation policies, and organisational decision-making (e.g., Cakar, 2022). NPO-focused studies investigate operational issues such as logistics, volunteer management, food safety, and redistribution efficiency (e.g., Akkerman et al., 2023; Weymes & Davies, 2019). These works are situated at the micro level, analysing how individual organisations can improve their internal processes, performance, or capabilities to better support SFR. Although these studies provide valuable insight into the internal functioning of individual actors, they do not explicitly analyse the reciprocal interactions occurring between donors and redistributors.

Position C includes studies examining retailers or NPOs within broader stakeholder networks involving consumers, beneficiaries, manufacturers, volunteers, local authorities, or community actors (e.g., Vander Vennen & Parizeau, 2023). These studies still touch on retailers (C+) or NPOs (C-), but they do so within a broader constellation of actors. Research positioned in C therefore adopts a more network-oriented perspective that acknowledges SFR's complexity while remaining grounded in micro-level processes. These studies broaden understanding of SFR by showing how adjacent stakeholders shape redistribution practices, even though their focus is not primarily on donor–redistributor relationships.

Position D captures macro-level studies investigating SFR as part of broader environmental, economic, and social systems. These works do not focus on the interaction between donors and redistributors; instead, they examine SFR as part of wider social, economic or environmental systems (e.g., Facchini et al., 2018). Position D is crucial for understanding the broader implications of SFR, yet it provides limited insight into the operational roles and relationships within the redistribution chain.

Overall, the SFR Research Spectrum demonstrates that existing research is distributed unevenly across analytical levels and actor positions, with a substantial concentration at the micro level and relatively few meso-level studies addressing the retailer side or even collaborative interaction between retailers and NPOs.

The numerical distribution further reinforces this imbalance (see Figure 2 below): 31 studies are in Position B, making single-actor analyses the dominant approach, and 29 of these adopted an NPO perspective. When combined with studies in Position C, approximately 77% of all papers examined SFR primarily through the lens of NPOs, whereas only 11% focus on retailers, and 17% consider both actors simultaneously. Macro-level analyses remain limited (Position D, 9 studies), and meso-level relational work is particularly scarce (Position A, 8 studies). This result confirms the conclusions from Sundgren (2020; 2022) who has argued that more studies focusing on the interactive process of SFR is needed in current research.

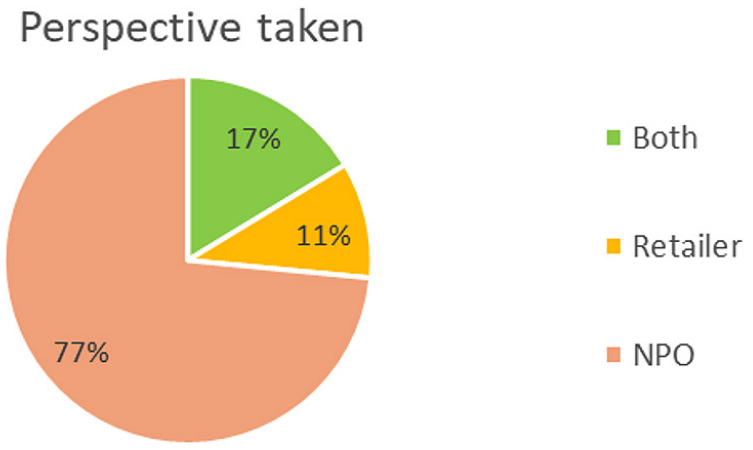

Figure 2: Current perspectives taken in SFR research

Common Types of Redistribution Models

The following sections explain the different groups of NPOs involved in SFR that were identified during the review.

Centralised Redistribution Models

Existing research commonly conceptualises SFR through centralised redistribution systems, in which food donations are normally collected, stored, and redistributed through 3 types of organisations: frontliner, mediator and hybrid.

Frontliners operate at the final stage of redistribution systems and engage directly with beneficiaries. These organisations provide food parcels, cooked meals, social supermarkets, and other forms of assistance (e.g, Lindberg et al., 2014). Mediators function as logistical coordinators responsible for collection, warehousing, sorting, and transportation of surplus food. Organisations such as FareShare exemplify this model within the UK redistribution system. Hybrid organisations combine the functions of frontliners and mediators. They manage food logistics while simultaneously providing direct support to beneficiaries. Examples include RiCibo in Italy, and a community café in UK (Williams et al., 2023) that expanded their operational roles over time.

Decentralised and Digitally Mediated Models

Alongside traditional centralised systems, the review identified increasingly prominent distributed redistribution arrangements, namely information and logitics facilitators.

Information facilitators operate primarily through digital platforms that connect food donors with recipients and community users (e.g., Ayala et al., 2022). These organisations facilitate information exchange regarding food availability and location but do not physically handle food donations (e.g., Olio and Neighbourly). Logistics facilitators support the physical movement of surplus food without maintaining centralised warehousing infrastructure, for example, the Robin Hood Army in Sri Lanka (Aloysius & Ananda, 2023). Typically volunteer-led, these initiatives coordinate collection and redistribution using local transportation networks (Rut et al., 2020).

General Categorisation of SFR Groups

The review demonstrates that contemporary SFR encompasses a broader range of organisational forms than recognised by previous categorisations (Bramanti et al., 2017; EU, 2019). While frontliners, mediators, and hybrids remain important within centralised systems, emerging information facilitators and logistics facilitators represent distinct forms of decentralised and digitally mediated redistribution. Together, these five categories provide a more comprehensive representation of contemporary SFR practice as illustrated in Figure 3.

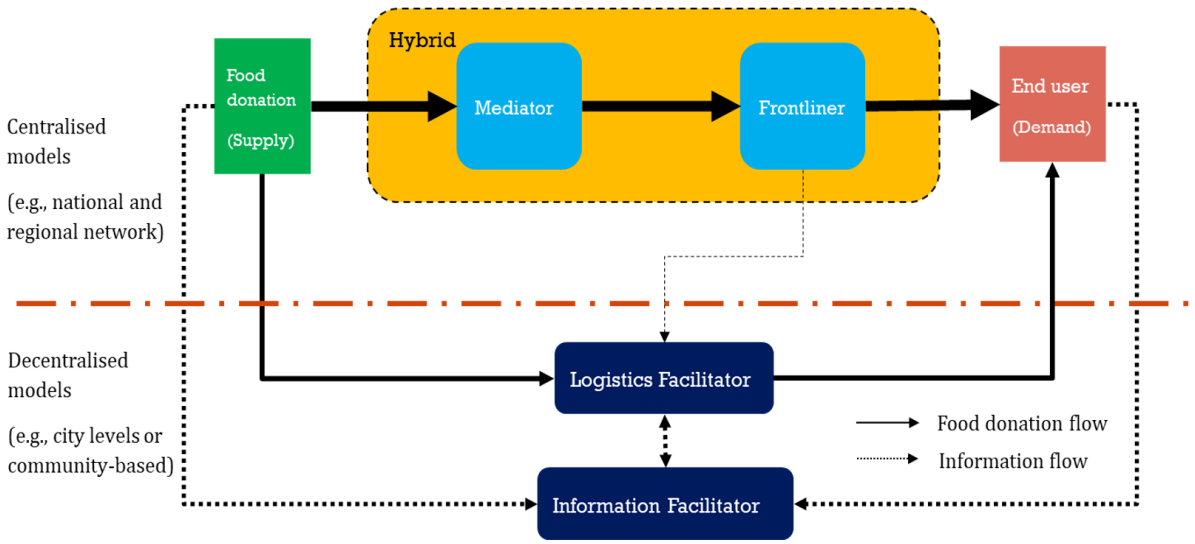

Figure 3: Illustration of general SFR groups (Authors' own)

Table 2 explains the key distinguishing features of the five organisational groups, highlighting how each group occupies a different position within the redistribution chain, performs distinct functions, and varies in its degree of direct engagement with beneficiaries.

Group	Position		Function		Direct contact with beneficiary	Structure
	Front	Back	Logistics	Information Exchange		
Frontliner	Y[3]				Y	Centralised
Mediator		Y	Y			
Hybrid	Y	Y	Y		Y	
Logistics facilitator	Y		Y	(Y)		Decentralised
Information facilitator		Y		Y		

Table 2: Key feature of each group (Authors' own)

Frontliners provide local, beneficiary-facing support; mediators manage upstream logistics to frontliners; and hybrids integrate both roles within centralised systems. In contrast, decentralised models diverge structurally: information facilitators focus exclusively on digital information exchange without handling food, whereas logistics facilitators undertake last-mile collection and redistribution without operating storage infrastructure. By systematically contrasting these operational and structural differences, the table clarifies the unique role each organisational group plays within SFR systems, offering conceptual differentiation not previously articulated in the literature.

Conclusion

This study reviewed 56 peer-reviewed articles published between 2005 and 2024 to examine how SFR has been conceptualised across stakeholder perspectives and organisational models. As a result, the SFR Research Spectrum (Table 2) was produced. The findings reveal that existing SFR research is unevenly distributed across both stakeholder perspectives and levels of analysis. While a substantial proportion of studies focus on NPOs and single-organisational issues, considerably less attention has been devoted to retailer–NPO interactions, despite their central role in facilitating and smoothing the redistribution of surplus food. This imbalance suggests that SFR has often been conceptualised as a challenge of organisational capability and operational management rather than as a collaborative process involving multiple interdependent actors.

The study also contributes to the literature by proposing a general categorisation of SFR models. Existing conceptualisations have largely focused on traditional centralised redistribution systems, such as food banks and intermediary charities. However, the review demonstrates that contemporary redistribution practices are increasingly diverse, encompassing not only frontliners, mediators, and hybrid organisations, but also decentralised and digitally mediated forms of redistribution, including information facilitators and logistics facilitators. The emergence of these models reflects broader developments towards more distributed, flexible, and technology-enabled approaches to redistribution. Consequently, existing understandings of SFR need to move beyond traditional centralised structures to better capture the organisational diversity characterising contemporary redistribution systems.

Together, these contributions advance current knowledge by clarifying the distribution of existing research and offering a more realistic representation of contemporary redistribution practices. Practically, they can support retailers, NPOs, and policymakers in understanding the range of organisational arrangements through which redistribution occurs and in identifying opportunities for more effective collaboration and coordination. Future research should build upon these findings by examining retailer–NPO interactions in greater depth, exploring how different redistribution models shape collaboration and system performance, and investigating the implications of emerging digitally mediated and decentralised approaches for the governance and sustainability of SFR systems.

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