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The role of human capital and Industry 4.0 in socio-technical dynamic capabilities for freight transport resilience

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ABSTRACT

This study examines the role of socio-technical dynamic resources and capabilities in enhancing the resilience of freight transport firms. Focusing on unique characteristics of freight transport sector, this study considers human capital and Industry 4.0 as socio-technical resources whereas network integration and operations planning as socio-technical capabilities. A survey is conducted on freight transport managers in the UK and partial least squares structural equation modelling (PLS-SEM) is employed to analyse the data. Our findings indicate that human capital and Industry 4.0 positively affect network integration and operations planning, which in turn enhance perceived resilience. Among two dynamic capabilities, network integration has a stronger impact on resilience than operations planning. Mediation analysis shows technical resources and capabilities partially enhance the impact of social resources and capabilities in SEM model. Our results suggest that socio resources and capabilities are at least as important as technical ones for building resilience in the freight sector. Practical and policy implications in our study suggest that freight transport firms and policy makers should invest and support skill-building initiatives, digital tools, supply chain analytics and collaboration platforms to increase freight transport resilience.

1. Introduction

Disruptions such as the COVID-19 pandemic, geopolitical conflicts, Red Sea shipping attacks and BREXIT have highlighted the fragility of global supply chains (Altuntas Vural et al., 2025). Among supply chain (SC) actors, freight transport operators play a critical yet vulnerable role in enabling operational continuity and resilience of other firms' SC (Wang et al. 2021). The critical role of freight transport has been witnessed during COVID-19 when skyrocketed freight costs and container shortage problem disrupted all SCs and during BREXIT period when driver shortages and border controls disrupted most economic activities such as supply deliveries to petrol stations and restaurants. However, despite its critical role, freight transport remains underexplored in resilience research (Zhou et al., 2024). Specifically, there is a lack of understanding of what enables transport firms themselves to be resilient in the face of disruptions. This presents a critical research gap, as freight operators are not only enablers of resilience for others but also require resilience capabilities of their own.

Most papers in literature tackle resilience in the generic SC domain, with majority of them adopting a universal approach that

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overlooks industrial characteristics (Dittfeld et al., 2022). This lack of focus limits our understanding of which capabilities of freight service operators actually support resilience. Moreover, most papers have also focused on product manufacturing industries with engineering perspective, neglecting services (Lin et al., 2023) and overlooking human element of resilience (Gu et al., 2023a). Without such focus on service-specific and human-centred capabilities, a risk of overlooking key enablers of resilience exists for both academia and practice. Hence, there is a need for research that addresses freight-specific resilience focusing on characteristics of freight transport.

Freight transport is a complex industry with characteristics that would require a particular set of resilience resources and capabilities. Freight is a services industry in which the production of service is accomplished with a large involvement of people (Vural et al., 2019). The human-centric element induces human capital – defined by Oxford as "skills labour force possess" – a key resource for transport operators. However, literature in freight transport is silent on the role of human capital in resilience capabilities. Examination of wider grey literature also suggests that SC research too ignores the role of human capital in resilience, with very few papers studying its role (Rajae and Miloudi, 2024).

Another characteristic of the freight transport is the significance of network integration (Yin et al., 2024). Freight network integration enables coordination and alignment between transport agents (Reis, 2019). Network integration enhances several performance outcomes such as decarbonisation of transport chains. The role of network in freight is also reflected in resilience literature that some papers investigate "freight network" resilience (Li et al., 2022; Wang et al., 2021; Zhou et al., 2024). The transportation service is run between numerous supply chain nodes involving several vertical and horizontal connections where vertical connections refer to linkages between different tiers of the supply chain, such as shippers, freight forwarders, and retailers, while horizontal connections involve collaboration among actors at the same level, such as coordination between competing carriers, terminal operators, or regional distribution centres. Collaboration in freight can help firms increase the capacity, expand service coverage, and be more flexible to market requirements (Vanovermeire et al., 2014). These enhancements can help transport firms to achieve resilience. While the role of network is evident in the literature, the impact of network integration on resilience is not thoroughly addressed.

Freight transport is an operation-intensive sector characterized by tangible assets and technical complexity. Particularly, a wide variety of goods are transported using different types of vehicles and transport modes, each with distinct technical specifications. These operations involve extensive physical movements, continuous information exchange, and frequent decision-making. As a result, the sector generates large volumes of data, often requiring real-time tracking and coordination through digital technologies. Recent advancements in digitalisation, such as Industry 4.0 tools, have become highly relevant to freight services. Their practical impact is evident, with significant efficiency gains and service improvements reported through the digitalisation of operations in recent years (McKinsey, 2023). Operations in freight transport also influence key performance outcomes, including customer satisfaction and loyalty (Balci et al., 2018). Given the real-time and complex nature of freight logistics, effective planning has emerged as a critical capability. In particular, planning enables timely pick-up and delivery of goods amid the sector's dynamic and fast-changing conditions (Xu et al., 2023).

Both social and technical resources and capabilities are needed to achieve resilience in freight transport. Socio-technical perspective is considered suitable for studying resilience in transport research (Chan et al. 2024), yet a limited number of research studies exists. While large number of studies in SC resilience literature focus on technical resources and capabilities such as Industry 4.0 and additive manufacturing (Belhadi et al., 2022), the role of social capabilities such as social capital (Ali and Gölgeci, 2020) and network relations (Asamoah et al., 2020) lag technical ones. Many studies also investigate social and technical capabilities in an isolated manner, yet "it takes two to tango", so both social and technical capabilities are required for achieving resilience. Firm or organisational resilience literature, on the other hand, has not disclosed the relationship between socio-technical capabilities and their impact on resilience. This study addresses this gap by positioning itself at the intersection of supply chain resilience, freight transport services and socio-technical capability development. The research problem this study aims to address is what socio-technical resources and capabilities enable freight transport resilience and how they affect each other. While existing research often focuses on resilience in manufacturing supply chains with a generic approach and mostly examining technical aspects of resilience, our work contributes by focusing on freight transport firms as operation-intensive service firms by evaluating both human and technical dimensions of resilience.

Underpinning socio-technical systems theory (Trist, 1981) and dynamic capabilities view (Teece et al., 1997), this paper aims to investigate the relationship between socio-technical resources and capabilities and resilience of freight transport firms in the UK. Our findings based on partial least squared structural equation modelling (PLS-SEM) indicate that both human capital and Industry 4.0 positively affect network integration and operations planning which positively influence resilience of freight transport firms. These results suggest both socio and technical capabilities improve resilience.

The study fills important gaps in the literature. First, it considers social and technical constructs as two essential set of resilience resources and capabilities and examines the interplay between them for achieving resilience. Second, it highlights that social resources and capabilities are at least as important as technical advancements to improve resilience. Third, it contributes to the ongoing discussion of Human – Industry 4.0 interaction (Sony & Naik, 2020). Fourth, it investigates the impact of Industry 4.0 on resilience in a services supply chain context (Ivanov et al., 2022). Finally, it utilises operations planning as a key dynamic capability for resilience. Results of the study offer valuable insights for both researchers seeking to advance knowledge in services SC resilience and practitioners and policy makers aiming to develop targeted strategies to improve freight transport resilience.

2. Theoretical background and literature review

Resilience refers to a firm's ability to adapt, prepare for unforeseen events, respond effectively to disruptions, and recover promptly and efficiently. It also involves sustaining operations or reorganizing them to maintain the preferred level of connectivity and control over their structure and functionality (Wan et al., 2018). Resilience, therefore, has elements of operational essence to respond and recover (relatively shorter term), as well as being prepared, transformative and adaptive to absorb uncertainties (relatively longer term) by foreseeing and influencing developments for change (Wieland & Durach, 2021). In freight transport domain, relying solely on technical indicators to describe resilience may be inadequate, particularly in broader scenarios related to supply chains (Dubey et al., 2023; Xu et al., 2023; Liu et al., 2024).

Resilience in freight transport requires preparedness and fostering collaboration among stakeholders to absorb uncertainties and prevent disruptions from escalating (Pavlov et al., 2019; Scholten et al., 2019; Liu et al., 2024). This involves not only maintaining flexibility but also empowering the workforce, technologies and processes. Resilience also includes contingency plans (Gu et al., 2023b) that detail ownership, costings, communications, timelines, documentation during disruptions and strategies to mitigate spill-over risks (Dittfeld et al., 2021). Resilience also leverages challenges as opportunities to strengthen trust, improve processes (reorganisation), and foster innovation and continuous improvement, to become transformative and adaptive (Wieland & Durach, 2021; Xu et al., 2023).

Considering that there are several interrelated resources, processes, stakeholders, routines and collective practices that influence the resiliency in freight transport, theoretical background for explaining transport resilience is underpinned by Socio-technical Systems (STS) theory and dynamic capabilities view. Socio-technical systems (STS) theory emphasizes the interdependence of social and technical components, highlighting the need for a balanced integration of human, organizational, and technological factors which is fundamental for freight transport functionality (Jin et al., 2010; Huo et al., 2016; Fatorachian & Kazemi, 2021; Pandey et al., 2023). These resources then influence and form practices and routines, which are to be underpinned by dynamic capabilities view, to explain resilience.

Socio-technical systems (STS) theory suggests that the performance of an organizational system can only be understood and optimized by considering the interplay between its social and technical components as interconnected elements within a complex system (Huo et al., 2016). The social subsystem encompasses people's attributes, such as their skills, values, and interpersonal dynamics, while the technical subsystem focuses on the processes and technological abilities that drive outputs (Sony & Naik, 2020). Freight transport operates as a socio-technical system, where human capital (social) and Industry 4.0 technologies (technical) serve as two fundamental resources shaping the sector. Human capital represents the social dimension, encompassing a set of skills, knowledge and abilities, and combination of thereof. Industry 4.0 technologies, on the other hand, constitute the technical dimension.

From an STS perspective, human capital is embedded in the skills and knowledge of managers and employees. Both attitudes and skills, particularly problem-solving skills, interpersonal skills and technological skills, are vital aspects of human capital (Fung and Chen, 2010; Jin et al., 2010). Given that human capital is often firm-specific and long-term factor empowering with the experience of people at job (Jin et al., 2010), it is embedded in unique processes, relationships, and activities, and interacts with various supply chain related routines and practices (Papaioannou et al., 2020). Employees with expertise in communication, negotiation, and relationship management enable seamless information sharing, process alignment, price setting and trust-building with external stakeholders (Durach & Machuca, 2018). Cross-functional collaboration within the organization, where employees' ability to share experiences and information is high, would also leverage technology (Bilican et al., 2024). Studies show that heterogeneity in education level, age and job experience in human capital impacts supply chain integration (Papaioannou et al., 2020). The working scheme of human capital has been shifting towards innovative systems such as plug-and-play worker and remote operator under black swan disruptions (Ambrogio et al., 2022). A culture of learning and problem-solving drives SC continuous improvement. Finally, internationally diverse backgrounds in human capital might improve SC customer relations management, fostering long-term relationships and customer satisfaction (Fung and Chen, 2010).

From an STS perspective, Industry 4.0 has brought transformative changes to supply chain research by incorporating advanced digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud-based information sharing and processing platforms, and data analytics tools. These technologies enable enhanced data exchange, real-time decision-making, and automation of processes (Lind et al., 2020). Still, most papers in the literature analyse the impact of Industry 4.0 on human capital and skills development (Danquah and Amankwah-Amoah, 2017; Baum-Talmor and Kitada, 2022), yet the number of studies on the role of human capital on Industry 4.0 implementation is limited.

The relationship between Industry 4.0 and supply chain practices are examined through three core dimensions: integration of processes and activities, adoption of cutting-edge technologies, and strengthening organizational linkages (Fatorachian and Kazemi, 2021). Several studies claim that Industry 4.0 technologies enable several practices such as supply chain agility (Raji et al., 2021), green supply chains (Feng et al., 2022) and supply chain visibility (Qader et al., 2022) as IoT-enabled tracking devices are improving shipment visibility, while digital platforms facilitate seamless communication between transport operators and stakeholders. Still, supply chain risks adversely impact Industry 4.0 performance (Pandey et al., 2023). Maturity and readiness of Industry 4.0 technologies has a direct impact on the supply chain performance (Ivanov et al., 2022). Industry 4.0 has been studied in freight transport in limited number of cases. The current body of research primarily concentrates on either the technical or social aspects without affording a holistic examination of both.

Dynamic capabilities, as a part of resource-based view, refer to a set of adaptive, learned routines and collective practices that organizations employ to manage and transform their operations in response to changing environments (Eisenhardt and Martin, 2000; Surucu-Balci et al., 2024). When tailored to sector-specific demands, dynamic capabilities become difficult to replicate, creating a source of sustained competitive advantage for particular cases. This uniqueness makes them critical for long-term performance improvements. There is an intricate relationship between resources of STS theory and dynamic capabilities view. Firms draw on socio-technical systems (STS) resources to develop dynamic capabilities (Weerawardena et al., 2015), which in turn enable them to build resilience. Resilience is ultimately supported by network integration capability and operations planning capability because these two dimensions enable firms to manage resources, anticipate disruptions, and adapt operations effectively across interconnected systems.

Supply chain network integration as a capability involves building cohesive and collaborative relationships across the freight network, ensuring seamless coordination among partners and within organisations (Yu et al., 2022). This capability extends beyond mere physical connectivity to encompass shared digital information, trust-based interactions, business process redesign, human capital working norms and the alignment of mutual goals among supply chain stakeholders (Ambrogio et al., 2022). Effective integration enables firms to connect to their network, exchange timely information, maintain continuous communication, and collaborate within transport alliances (Kuo et al., 2017; Surucu-Balci et al., 2024).

Network integration capability is deeply rooted in both technological infrastructure and human expertise, resources that STS theory offers. Advanced technical systems, such as cloud-based logistics management and AI-driven demand forecasting, enable connectivity and automation, reducing delays and inefficiencies (Sharma et al., 2022). Simultaneously, human capital plays a critical role in fostering collaboration, trust-building, and conflict resolution among network partners, ensuring a coordinated response to supply chain disruptions (Sharma et al., 2022) and technical resources mediate how human capital would shape network integration. Studies also suggest that interpersonal relationships and information sharing in the buyer–seller relationships support resilience and investments in interpersonal skills are antecedents of firm resilience (Durach & Machuca, 2018). Organizations with strong integration capabilities can dynamically adjust to disruptions and improve operational agility, reinforcing their competitive advantage in an increasingly digital and interconnected freight sector. Previous studies lack detailed understanding of combined impact of human capital and technological resources on supply chain network integration capability.

Operations planning capability enables companies to run their operations for different business functions smoothly and anticipate, design, and adapt their service offerings (Surucu-Balci et al., 2024). As a key supply chain capability, it builds on advanced planning technologies (e.g. Materials Requirement Planning and inventory control software) and experts' decision-making and negotiation attitudes, both rooted from STS resources. Particularly the level of integration between supply chain tiers has a clear impact on the planning of operations (Aprile et al., 2005). Formalized operations planning processes include planning operations management, operational risk analysis (Bai et al., 2022) and scenario evaluations, balancing both long-term strategic objectives and short-term operational needs. In freight transport, operations planning capability extends to route optimization, capacity allocation, hub network flows and contingency management to mitigate disruptions such as equipment failures, labour shortages, or regulatory changes. Technologies like AI-driven scheduling platforms, demand forecasting, enterprise resource software procedures enhance operational decision-making and can also improve human capacity to deliver better operations planning. Feedback loops help address variances between planned and actual performance, supporting continuous improvement (Hsu et al., 2008).

Measuring supply chain resilience in the freight transport domain is not straightforward, as the sector's unique complexities and service-driven approach necessitate tailored approaches. Particularly, previous freight transport resilience studies primarily focus on mathematical modelling of network optimisation under uncertainties and to ensure robustness of the network in the case of disruptions (Dubey et al., 2023; Xu et al., 2023; Liu et al., 2024). Network integration and operations planning capabilities are not simply operational practices, but strategically significant assets that enable firms to coordinate, reconfigure, and respond for resilience. Network integration facilitates joint action and resource sharing with external partners, while operations planning drives internal alignment and the foresight needed for disruption preparedness. Together, these capabilities underpin the resource orchestration necessary to realize resilience as a dynamic, firm-specific advantage. This perspective emphasizes the value of rare, inimitable, and organizationally embedded resources in sustaining competitive advantage. The ability to absorb uncertainties and prevent disruptions from escalating, through business reorganization, contingency planning, and cohesive integration with partners, depends heavily on how well firms leverage these two capabilities. Strong network integration enables rapid information flow and collaborative problem-solving, while robust operations planning allows firms to anticipate disruptions, allocate resources effectively, and adapt plans in real time. When deeply embedded and consistently refined, these capabilities form the basis of resilience, allowing firms not only to withstand disruptions but to emerge from them stronger and more competitive in the evolving business landscape.

3. Hypotheses development and conceptual model

3.1. The impact of human capital on Industry 4.0 (I4.0), operations planning, and network integration

Human capital (HC) in organisational context refers to knowledge, skills, and experience possessed by individuals in an organisation (Jin et al., 2010). The positive role of HC on digital technology adoption and digital transformation is evident in the literature, especially the adoption and implementation of I4.0 technologies as I4.0 requires advanced level of digitalisation such as AI, data analytics and cloud computing (Chatterjee, 2017; Danquah and Amankwah-Amoah, 2017; Lang et al., 2023). Skilled employees are essential to operate and maintain these advanced technologies. For instance, SmarTrucking of DHL uses internet of things (IoT) to increase visibility of cargoes and allows access to big data, yet the implementation of the technology and fully capture potential benefits demand certain skills and experience. Previous research has also documented that HC skills positively affect I4.0 implementation (Singh et al., 2022) and the digitalisation of logistics operations (Gupta et al., 2022). Accordingly, following hypothesis is built.

H1: Human capital positively affects Industry 4.0.

HC enables fostering Network Integration (NI) within freight transport services. NI necessitates coordination and collaboration with SC partners and other transport providers, and within the organisation through information sharing and relationship building (Yuen and Thai, 2017). Skilled and experienced personnel play a key role to build strong relationships with the members of the network and enable effective communication and collaboration. Karam et al. (2021) investigated barriers to collaborative transport networks and found experience and background of people as one of the core barriers to maintain the transport network platform. The human element in logistics relationship building is also underlined by several logistics businesses across the world such as Al Barrak group in Saudi Arabia and 3PL Links in the US. Therefore, human capital has a direct impact on NI.

H2: Human capital positively affects network integration.

Human capital plays a central role in Operations Planning (OP) of freight transport because the sector relies heavily on day-to-day and even real-time decision making in operations (Aprile et al., 2005). The real-time operations intensiveness and dynamic structure of the freight sector necessitates skilled managers with relevant experience to deal with complex challenges (Akkartal and Mızrak, 2024). Role of HC in operations become particularly evident during disruptions as human resources help to mitigate logistics operations risks (Özcan and Yumurtacı Hüseyinoğlu, 2023). For instance, driver shortage issue in the UK following BREXIT and COVID-19 complicated daily operations and caused firms to find alternative solutions and resource optimisation to ensure timely deliveries. The role of well-trained managers with technical knowledge and interpersonal against such unforeseen operational challenges was appreciated during the crisis time. Recognising the importance of skills, The Pallet Network in the UK, a network of freight service providers, initiated an e-learning platform to equip people with necessary skills to better implement operations in all levels. Hence, we hypothesise that companies can enhance their operations planning capabilities by investing in human capital.

H3: Human Capital positively affects operations planning.

3.2. The impact of Industry 4.0 on network integration and operations planning

I4.0 supports real-time tracking, communication, data analytics and seamless digital information sharing. The transparent and convenient information sharing enhanced by I4.0 technologies can foster trust and coordination of network partners, leading to better integration of the network. This view us supported by findings of Karam et al. (2021) who find that lack of information sharing tools hinders building collaborative networks in the freight transport industry. Lind et al. (2020) discuss that logistics collaboration can be improved by digital data sharing and data analytics. Alacam and Sencer (2021) also state that blockchain technology-based information sharing can improve collaboration between shippers and carriers in the road freight sector. Accordingly, we hypothesise that I4.0 can foster the network integration.

H4: Industry 4.0 positively affects network integration.

I4.0 implementations in freight transport such as AI, IoT, decision support systems and data analytics allow real-time monitoring and analysis of operations (Modica et al., 2023). AI tools such as AI-supported predictive maintenance help to avoid breakdowns and ensure freight operations are run without interruption (McKinsey, 2024). IoT sensors – which track vehicles and monitor cargo conditions – enable logistics managers to get simultaneous information for more accurate and real-time operations planning (Tang et al., 2025). Leveraging big data analytics can also help transport operators to better forecast demand fluctuations, which support freight operations planning decisions (Hassan et al., 2020). Hence, the integration of I4.0 in freight transport can lead to more effective operations planning.

H5: Industry 4.0 positively affects operations planning.

3.3. The relationship between network integration, operations planning, and resilience

Integration of transport network partners such as carriers, shippers, and other logistics providers can improve freight operations by enabling seamless communications and collaboration between carriers (Balci et al., 2019; Mason et al., 2007). The improved communication can empower freight operations planners through more informed decision based on accurate data (Abideen et al., 2023). NI allows resource sharing and collaboration between partners which are needed for operations planning. For instance, alliances between liner shipping carriers help them to optimise their resources and improve operations through sharing same vessels (Wang et al., 2025). Similar operational benefits are achieved in road freight through collaborative transport networks such as pallet collaborations between UK hauliers (Bjørgen et al., 2021; Puettmann and Stadtler, 2010; Munir et al., 2020). Hence, following hypothesis is built.

H6: Network integration positively affects operations planning.

Network integration can improve firms' resilience (RES) through various ways. The seamless communication and data-sharing between network members can allow to have a quicker response to disruptions (Yu et al., 2022). Integrated networks in freight allows sharing of resources such as vehicles and warehouse and access to wider set of resources. This flexibility access to wider resources can enable transport firms to adopt to changes and become more resilient against disruptions. Li et al. (2022) demonstrate how port collaboration and capacity sharing can enhance resilience of maritime freight network. Firms can also prepare for disruptions and better implement risk management by sharing best practices and improve organisational learning between network partners (Scholten et al., 2019). The literature in different freight modes also confirm positive role of integration on resilience. Liu et al. (2018) considers integration as a component of resilience in the maritime freight sector. Accordingly, following hypothesis is suggested.

H7: Network integration positively affects resilience (RES).

Operations planning can enable organisations to enhance resilience by managing resources efficiently and anticipating potential disruptions. Detailed schedules and identification of contingencies through risk analysis can help organisations to reduce likelihood of delays and take proactive actions against disruptions (Pavlov et al., 2019). The integration of data analytics and utilisation of recent digital tools into planning processes can enable real-time adjustments against emerging situations and achieve resilience (Gu et al., 2023b). Woodburn (2019) discuss the intertwined positive relation between rail freight resilience and operational responsiveness.

Dittfeld et al. (2021) document how sales and operations planning play a key role in managing risks proactively and reactively. Transport Resilience Review report issued by the UK government underlines the significant role of planning to stay resilient (DfT, 2015).

H8: Operations planning positively affects resilience.

In resilience-building processes, capabilities do not always operate in isolation; instead, they unfold through indirect pathways where one capability enables another to influence outcomes. Human capital, while critical, does not exert its full effect on coordination and planning unless embedded within a technological infrastructure that facilitates digital transformation (Fung and Chen, 2010). Accordingly, I4.0 technologies act as a mediating mechanism that channels the value of human capital into more integrated and analytically driven systems. Specifically, H9a and H9b propose that I4.0 mediates the relationships between human capital and both network integration and operations planning, suggesting that the strategic potential of a skilled workforce is realized only when amplified by data connectivity, digital platforms, and automation. These technologies enable human insight to be codified, shared, and scaled, thus fostering both external alignment and internal foresight. In turn, H9c suggests that operations planning mediates the relationship between network integration and resilience, reflecting the idea that strong inter-organizational ties improve resilience only when translated into deliberate planning routines (Flynn et al., 2010). These hypotheses collectively frame resilience not as a direct output of any one capability, but as an emergent outcome shaped by layered mediating processes involving digital tools, human assets, and planning competencies.

The conceptual model (See Fig. 1) is created to reflect this background of resilience resources and capabilities in freight transport. Underpinned by socio-technical resources and dynamic capabilities theories, human capital and network integration are considered as socio-resources and socio-dynamic capabilities while I4.0 and operations planning are considered as technical resources and capabilities. According to our conceptual model, resources lead to creation of dynamic capabilities which eventually positively affect resilience. Firm size (number of employees) and fleet ownership structure (own trucks vs subcontracted trucks) are used as control variables in the model. Firm size is selected because it oftens reflects in operational capacity and resource availability which can affect resilience of a firm. Fleet ownership is used because whether a firm operates with its own trucks or relies on subcontracted fleets may affect control over logistics operations or flexibility, which in turn can impact resilience of the firm.

4. Methods

4.1. Data analysis

This study has conducted a survey on road freight operators in the UK to test hypotheses through partial least squares structural equation modelling (PLS-SEM). Our study has adopted an SEM approach because it allows simultaneous assessment of constructs as both exogenous and endogenous variables. In our study, I4.0, Network Integration, and Operations Planning are both exogenous and endogenous variables, influencing other constructs while also being influenced themselves. We chose PLS-SEM, a variance based structural equation modelling, over covariance-based SEM (CB-SEM) due to several reasons. Hair et al. (2018) recommends PLS-SEM over CB-SEM when the purpose of study is to explore relationships between constructs instead of testing a theory. PLS-SEM is appropriate in our research because our study utilises socio-technical view as a theoretical background of our research, but its purpose is not to test the theory.

Moreover, El Baz and Ruel (2021) also supports PLS-SEM approach in supply chain risk management and resilience context because the theoretical foundation is not well developed. PLS-SEM is also considered more appropriate when the research model is complex

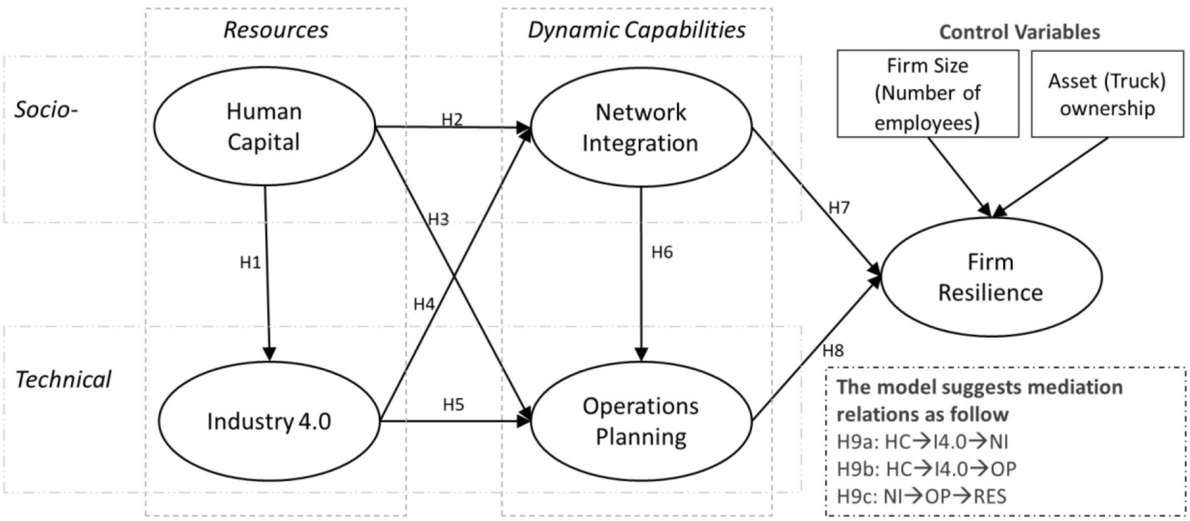

Fig. 1. Conceptual model.

(Hair and Alamer, 2022). Our model is relatively complex having 8 different hypotheses of direct relations and 3 hypotheses of mediation relations, including 5 constructs, and containing technical and human-related variables. PLS-SEM does not assume multivariate normality and is generally suitable for studies with relatively smaller samples compared to covariance-based SEM. However, adequate sample size is still required to ensure the reliability of complex models (Hair et al., 2019). We used G*Power software to determine the required minimum sample size in advance and to conduct post-hoc power analyses (Faul et al., 2009). The a priori power test, assuming a statistical power of 0.90 and a significance level of 0.05, indicated that a minimum sample size of 99 was required and our sample size satisfies this ($n = 203$). The post-hoc power analysis resulted in 0.998 which is above the minimum recommended threshold of 0.80 (Cohen, 1988).

4.2. Survey design, data collection, non-response bias and common method bias

The UK is the ideal region for the research because freight operators faced with both COVID-19 and BREXIT which resulted in major obstacles such as the driver shortage issue and border hiccups for European shipments. The data collection is accomplished through a self-administrative online survey which consisted of two parts including demographics and measurement questions. The list of UK Haulier, an online freight transport directory in the UK which was established in 2005, is utilised to determine the population. General cargo road haulage ($n = 1{,}493$) and pallet distribution firms ($n = 70$) are used in the directory of UK Haulier. Only companies which offer physical transport services to third party companies are selected. Non-freight companies like brokers, consultancy companies, or waste disposal are not included. We did not include specific segments like abnormal loads and car transporters. Accordingly, a total of 1563 firms were identified.

The survey implemented screening to ensure the right experts respond the survey. Only managers working in relevant departments such as operations responded the survey, while those working in human resources, IT, accounting and finance were eliminated. Also, the survey was answered only by experts with at least 5 years or more experience. Accordingly, a total of 203 valid responses were received (13 % response rate).

The non-response bias is checked through comparing early and late responses. No significant difference should be observed between early and late responses to suggest that it is unlikely that the survey suffers from non-response bias (Nikookar and Yanadori, 2022). Independent *t*-test and Levene's test of homogeneity of variances are conducted by utilising the first 50 and last 50 respondents as two categories of the grouping variable and using five different variables (first variables of each factor in the model). No significant differences are observed $(p > 0.05)$.

Both ex ante and post ante measures are implemented to prevent common method bias following the approach by MacKenzie and

Table 1
Profile of respondents.

Profile	Frequency	Percentage %
Age		
25–34 years	31	15.3
35–44 years	118	58.1
45 years and more	54	26.6
Experience in the freight sector		
5–9 years	30	14.8
10–14 years	132	65.0
15 and more years	41	20.2
Department in the organisation		
Operations	97	47.8
Marketing	37	18.2
Top Management*	69	34.0
Number of employees		
10–49	28	13.8
50–249	126	62.1
250 and more	49	24.1
Own or Subcontracted trucks		
Only own	115	56.7
Both own and subcontracted trucks	88	43.3
Domestic or International Transport		
Only UK distribution	120	59.1
Only International Distribution	19	9.4
Both UK and International Distribution	64	31.5

* Not part of a specific department, such as CEOs, regional managers, and founders.

Podsakoff (2012). Survey research is more likely to suffer common method bias when respondents are unwilling or incapable of answering questions. To prevent this, we implemented several ex ante measures such as avoiding complex and lengthy sentences and ensuring clarity of wordings in questions; increasing motivation of respondents by ensuring that the survey was anonymous, and the answers were to be used only for academic purposes, hence eliminating confidentiality concerns; and increasing the interest of respondents by explaining how accurate responses could be beneficial to understand for achieving freight transport resilience. Moreover, Industry 4.0 variables are worded different than other variables in terms of scale anchoring (See Table 1). We also implemented post ante measures to test if it is likely that the survey suffers from common method bias. First, Harman's single factor test is applied, and the unrotated principal component analysis results show that the first factor explained less than 50 % of the total variance. In addition, following the suggestion of Kock (2015) for checking common method bias in PLS-SEM, we checked inner VIF values, and they were all below 3.3 threshold level.

4.3. Measurement items

Measurement items (see Table 2) are adopted from the literature with some minor modifications to fit them to the freight transport context. All questions are asked in 5-point Likert scale (Totally disagree: 1, Totally agree: 5) except the Industry 4.0 construct which asked the adoption level as 1 being not used and 5 being fully adopted. Human capital construct is borrowed from Jin et al. (2010) by replacing "workers" with employees. The Industry 4.0 items were taken from Kumar and Bhatia (2021) by replacing "additive manufacturing" with "artificial intelligence applications" such as those for route and load optimisation and predictive maintenance. Internet of things devices were further explained by examples such as sensors and RFIDs (Table 2).

Network integration in the freight transport context refers to connectedness and information sharing with other transport providers and SC partners in their network while collaborating and maintaining effective communication with them. Accordingly, the network integration construct includes elements of SC collaboration and integration. Items of the construct are adopted from with them variables are adopted from Uddin and Akhter (2022) and Zhao et al. (2013). Operations planning items are adopted from Srinivasan and Swink (2015) by having minor modifications to reflect road haulage sector such as including scheduling, route optimisation and demand forecasting. The role of technology in planning is also stressed by interviewees, hence item number 5 is also included in the construct. Resilience construct is adopted from Dennehy et al. (2021) and Gölgeci and Kuivalainen (2020). Questions of resilience

Table 2
Measurement Items.

Measurement Items	Code	Mean	SFL*
Human Capital – *Source: (*Jin et al. 2010*)*			
1. Our employees have multiple recent technological skills	HC1	4.17	0.792
2. Our employees have problem-solving skills	HC2	4.21	0.825
3. Our employees have the necessary interpersonal skills to work well with people	HC3	4.21	0.799
4. Our employees have experience that is relevant to their jobs	HC4	4.10	0.835
Industry 4.0 – *Source: (*Kumar and Bhatia, 2021*)*			
1. Artificial intelligence applications (e.g., route and load optimisation, predictive maintenance)	I4_1	3.74	0.843
2. Internet of things devices (e.g., RFID, sensors, GPS-based tools)	I4_2	3.99	0.780
3. Cloud technology platform (e.g., real-time data sharing)	I4_3	4.04	0.772
4. Data analytics tools	I4_4	4.07	0.896
Network Integration – *Source: (*Uddin and Akhter, 2022; Zhao et al. 2013*)*			
1. Our organisation is connected to its network using digital tools.	NI1	3.88	0.775
2. Our organisation exchanges timely information with its network.	NI2	4.19	0.738
3. Our organisation maintains mutual communication with its network.	NI3	4.15	0.776
4. Our organisation shares resources and knowledge with its network.	NI4	4.12	0.756
5. Our organisation collaborates with a transport alliance.	NI5	4.30	0.631
Operations Planning – *Source: (*Srinivasan and Swink, 2015*)*			
1. We use formalised, disciplined operations planning processes such as scheduling, route optimisation and demand forecasting.	OP1	4.30	0.741
2. Our operations planning identifies contingencies with risk analysis and scenario evaluations.	OP2	3.98	0.829
3. Our operations planning processes address both long-term and short-term objectives.	OP3	4.10	0.808
4. Our operations planning processes include feedback loops to address reasons for variances between plans and execution	OP4	4.12	0.750
5. Our operations planning utilises recent technologies in scheduling, route optimisation, and demand forecasting.	OP5	4.22	0.827
Resilience – *Source: (*Dennehy et al. 2021; Gölgeci and Kuivalainen, 2020*).*			
1. Our firm's supply chain is well prepared to face constraints disruptions like BREXIT and COVID-19	Res1	4.07	0.818
2. Our firm's supply chain rapidly plans and executes contingency plans against disruptions like BREXIT and COVID-19	Res2	3.99	0.825
3. Our firm's supply chain adequately responds to BREXIT and COVID-19 disruptions by quickly restoring its transport service.	Res3	4.08	0.823
4. Our firm's supply chain is able to cope with changes brought by BREXIT and COVID-19 disruptions.	Res4	3.98	0.870
5. Our firm's supply chain has returned to its original state after being disrupted by BREXIT and COVID-19	Res5	3.91	0.863
6. Our firm's supply chain has gained a superior state compared to its original state after being disrupted by BREXIT and COVID-19	Res6	3.90	0.864

construct are asked specifying BREXIT and COVID-19 disruptions to reflect the UK context as well as to define the disruptions rather than asking in a generic way (Dittfeld et al., 2021).

4.4. Profile of respondents

Respondents in our survey are at least 25 years old or above with minimum 5 years of experience (see Table 3). Approximately 85 % of respondents have at least 10 years or more experience in the freight sector. Almost 50 % of respondents work in operations related departments including special cargoes such as dangerous goods and out of gauge. A total of 34 % respondents work in top management roles such as CEOs, region managers, and founders. Regarding number of employees, about 14 % of respondents' companies are small businesses while about 62 % of them are medium and 24 % of them are large businesses. Approximately 57 % of respondent firms use only their own trucks while 43 % of them use both own trucks and subcontracted trucks. This means all respondent firms use their own trucks either fully or partially. This particularly ensures Industry 4.0 questions e.g., predictive maintenance, are relevant to respondents. Approximately 59 % of respondents offer only UK distribution services while 9 % of them offer only international and 31 % offer both international and UK freight transport services.

5. Results

5.1. Measurement model analysis

We assessed the measurement model by checking reliability and validity of constructs (See Table 3). Bagozzi and Yi (2012) suggest that Cronbach's Alpha and composite reliability scores of constructs should exceed 0.7 to ensure internal consistency. Items of all constructs in our study exceed the minimum suggested cut-off value. Standardised factor loadings and average variance extracted (AVE) values are assessed to check convergent validity of constructs (Cheung and Wang, 2017). Standardises factor loading (SFL) values are above 0.6 ($p < 0.001$). AVE scores of all constructs are also above the minimum suggested threshold of 0.5 (Hair et al., 2018). Discriminant validity is assessed by evaluating heterotrait–monotrait ratio of the correlations (HTMT) and Fornell-Larcker tests (Fornell and Larcker, 1981; Henseler et al., 2016). HTMT values are lower than suggested value of 0.85 while square root AVE values are greater than correlations. These results suggest that discriminant validity is ensured in our model.

Presenting model fit results in PLS-SEM is debated in the literature because, unlike CB-SEM, PLS-SEM does not rely on the concept of model fit (Hair et al., 2019). Hair et al. (2011) also suggested model fit is not required when the purpose is not theory testing. Nonetheless, the recent study conducted by Schuberth et al. (2023) recommends presenting goodness of fit indices in explanatory research such as drawing statistical inferences from the model or testing theories. We used Standardized Root Mean Square Residual (SRMR) to test the model fit. SRMR represents the gap between the observed correlation matrix and the one predicted by the model. It serves as an absolute indicator of model fit by quantifying the average size of these differences. Henseler et al. (2014) proposed using SRMR in the context of Partial Least Squares Structural Equation Modelling (PLS-SEM) to help identify and prevent model misspecification. A SRMR value less than 0.10 or 0.08 is considered to show a good fit (Hu and Bentler, 1999). Our SRMR value is 0.077, which is below the threshold value of 0.08, hence indicating an acceptable fit.

5.2. Structural model analysis

SmartPLS4 software is used to examine path relations. Prior to structural model analysis, each indicator's VIF is checked to assess whether a multi-collinearity exists, which means that path relationships could be biased. All VIF values are below 5 as suggested by Hair et al. (2011), thus it is unlikely a multicollinearity exists in the model. Bootstrapping with 5,000 sub-samples is conducted to assess the structural model and path relationships. As shown in Fig. 2, all hypothesised relationships are statistically significant ($P < 0.001$).

Standardised path coefficients (β) in path analysis results (See Table 4 and Fig. 2) shows that HC positively affects I4.0 ($\beta = 0.453$, $P < 0.001$), NI ($\beta = 0.349$, $P < 0.001$), and OP ($\beta = 0.234$, $P < 0.001$), confirming H1, H2, and H3. I4.0 positively affects NI ($\beta = 0.444$, $P < 0.001$) and OP ($\beta = 0.417$, $P < 0.001$), confirming H4 and H5, while NI positively affects OP ($\beta = 0.289$, $P < 0.001$) and RES ($\beta = 0.469$, $P < 0.001$), H6 and H7. Finally, OP also positively affects RES ($\beta = 0.376$, $P < 0.001$), confirming H8. Results suggest that those socio-technical resources positively affect dynamic capabilities which also positively influence resilience against disruptions. The positive effect of these resources and capabilities on resilience is also verified by R^2 value of resilience in the model (0.597) which

Table 3
Reliability, convergent validity, and SFL.

Construct	Cronbach's alpha	Composite reliability	AVE	SFL*	Number of items
HC	0.830	0.835	0.661	0.79 – 0.83	4
I40	0.842	0.852	0.679	0.77 – 0.89	4
OP	0.851	0.857	0.627	0.74 – 0.83	5
NI	0.789	0.787	0.544	0.63 – 0.77	5
RES	0.919	0.921	0.712	0.82 – 0.87	6

* SFLs of each construct are significant $P < 0.001$.

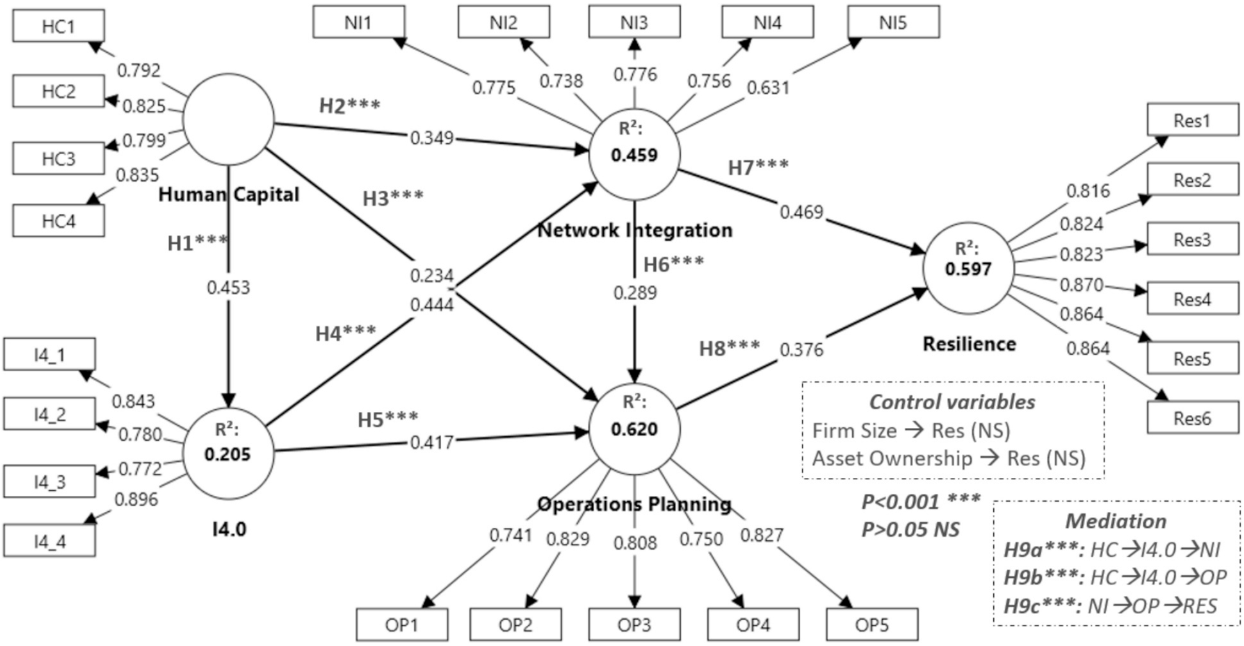

Fig. 2. Results of structural model.

Table 4
Structural path relations.

Path relations	β (standardised path coefficients)	p value	T value	Hypothesis
HC → I4.0 (H1)	0.453	0.000	6.874	Confirmed
HC → NI (H2)	0.349	0.000	5.474	Confirmed
HC → OP (H3)	0.234	0.000	4.220	Confirmed
I4.0 → NI (H4)	0.444	0.000	8.221	Confirmed
I4.0 → OP (H5)	0.417	0.000	6.413	Confirmed
NI → OP (H6)	0.289	0.000	3.981	Confirmed
NI → RES (H7)	0.469	0.000	7.497	Confirmed
OP → RES (H8)	0.376	0.000	5.476	Confirmed

suggests a moderate to substantial explanatory power for resilience in the structured model.

The control variables (firm size and fleet ownership) did not have a statistically significant effect on resilience (see Table A.2. in Appendix). The “domestic or international transport” category was not included as a control variable because one of its groups (“only international distribution”) had a very small number of observations (n = 19), which could lead to unreliable estimates. Nonetheless, we also checked mean latent scores of constructs considering different categories (as a guidance regarding what difference would be observed (see Table A.3. in Appendix). The results show only small variations among groups except the category of domestic or international. Firms engaged exclusively in international distribution reported the highest average resilience score (4.37). However, this category included only 19 observations. Therefore, these differences should be interpreted with caution as they may reflect the unequal distribution of cases across categories rather than systematic effects.

Results show that both direct and specific indirect effects (see Table 5) between independent and dependent variables in our model are positive. This finding suggests that all mediation relations hypothesized in our model are partial mediation. That is, mediators in our model partially explains the impact of independent variable on dependent variable, but do not fully explain the relationship between them as the direct impacts of independent variables on dependent variables are positive as well. For instance, I4.0 strengthens the relationship between HC and NI and the relationship between HC and OP. This result shows that I4.0, a technological resource,

Table 5
Mediation results.

Hypotheses	Specific indirect effect	T statistics	P value	Mediation type
H9a: HC → I4.0 → NI	0.201***	4.854	0.000	Partial Mediation
H9b: HC → I4.0 → OP	0.189***	4.359	0.000	Partial Mediation
H9c: NI → OP → Resilience	0.109***	3.583	0.000	Partial Mediation

enhances the total effect of human capital on socio and technical dynamic capabilities, namely network integration and operations planning (partially confirming H9a and H9b). Our results also show that operations planning, a technical capability, strengthens the impact of network integration on resilience. These findings suggest that technical mediators in our model enhance the impact of socio resources and capabilities in our study.

5.3. Multigroup analysis

The Multigroup Analysis (MGA) was conducted to assess whether any heterogeneous effects are revealed considering asset ownership as "only own trucks" vs "both own and subcontracted trucks". Cheah et al. (2023) suggest that similar sample sizes should be selected in MGA of more than two groups in PLS-SEM. Accordingly, asset ownership was selected among company demographics for MGA because its categories have a relatively balanced distribution, providing a sufficient number of observations in each group, whereas firm size and domestic vs. international categories were not included due to significantly imbalanced distribution (see Table 1).

Prior to conducting the MGA, the measurement invariance of composite models (MICOM) was assessed following the three-step procedure recommended by Henseler et al. (2016). Configural invariance was established by design, as the same indicators and model specifications were applied across both groups. Compositional invariance was examined in the second step using 5,000 permutations with a two-tailed 5 % significance test in SmartPLS 4. The results indicated that the original correlations were greater than the 5 % quantile and all p-values were non-significant ($p > 0.10$), confirming that compositional invariance was achieved (Henseler et al., 2016). In the third step, we assessed whether full measurement invariance was established by testing the equality of means and variances. The results showed that the original mean and variance differences were within the 2.5 % and 97.5 % quantile boundaries, indicating that full measurement invariance was established (Nguyen-Phuoc et al., 2022; Singh & Kathuria, 2023). Therefore, MGA could be conducted, as configural, compositional, and full measurement invariance were all established.

MGA results for both groups are shown in the Table A.1. (see the Appendix). In MGA analysis, significant differences occur between categories considering specific path relations if p values of Henseler's MGA and permutation tests are smaller than 5 % ($p < 0.05$) in permutation test. Results show only the path between I4.0 and OP are statistically significant ($p < 0.05$) while the path between HC and OP can be considered marginally significant (p values slightly over 0.05). This indicates that the effect of I4.0 on OP is stronger in firms that operate solely with their own trucks, whereas the effect of HC on OP is higher in firms that employ both owned and subcontracted trucks.

This result supports the practice because firms that only use their own trucks typically have more control over their operations and assets. They can therefore benefit more from I4.0 technologies (IoT devices, predictive maintenance) because these systems integrate directly with internal resources. On the other hand, firms that use both owned and subcontracted trucks operate in more complex and hybrid networks that require coordination with external partners. In this context, the ability to plan effectively depends more on human capital items such as interpersonal skills and problem solving. Overall, these findings indicate that the relative importance of technological and human capabilities in enhancing operations planning depends on the firm's asset ownership structure.

6. Discussion and Conclusions

Geopolitical tensions, climate change, and other disruptions severely disrupt the movement of goods. Increasing disruption risks entail resilience of freight transport firms who play an imperative role for supply chains and economic activities (Zhou et al., 2024). Our research has investigated how socio-technical dynamic capabilities are associated with stakeholders' perceived resilience in freight transport operations. A survey study is conducted with freight transport managers in the UK. A structural model is built and tested by using PLS-SEM to assess the relationships between socio resources and capabilities (HC and NI), technical resource and capabilities (I4.0 and OP) and freight transport resilience. All hypotheses are found significantly positive.

Our results suggest that both socio and technical capabilities play a positive role for building resilience among freight transport firms. Our results validate that both human capital and Industry 4.0 technologies contribute to network integration and operations planning, which in turn positively affect perceived resilience of managers. These findings support the argument that resilience in freight transport is not solely dependent on technical advancements but also on the human and network-related dimensions that are intrinsic to the sector.

The positive relationship between human capital and Industry 4.0 also suggests that technological adoption in freight transport is not an isolated process, it is facilitated by skilled labour and managerial expertise. This finding aligns with prior literature which suggests that digital transformation in supply chains is contingent on workforce capabilities (Sony & Naik, 2020). The results also confirm that human capital positively affects network integration and operations planning which emphasise that employees' expertise, experience and adaptability are fundamental in managing freight transport networks and planning efficient transport operations. These findings address a critical gap in the resilience literature in which the role of human capital is overlooked (Rajae and Miloudi, 2024).

Industry 4.0 was also found to significantly enhance both network integration and operations planning, reinforcing the argument that digital technologies enable real-time coordination, data-driven decision-making, and enhanced operational efficiency (McKinsey, 2023). This highlights the growing influence of digitalisation in freight transport and suggests that advanced technologies such as sensors and predictive maintenance are not only important in the supply chain context, but also instrumental in resilience-building for freight transport service providers.

The strong positive impact of network integration on operations planning and resilience further confirms that network relations are essential for effective coordination and adaptive capabilities in freight transport. Our results suggest that the impact of NI on perceived resilience is also slightly larger than the impact of OP. This finding highlights the critical role of collaboration and coordination in freight transport. This suggests that resilience in freight transport is driven not only by internal operational efficiency and excellence but also by external adaptability. In fact, according to our results, the external adaptability could play a larger role to achieve resilience. This confirms network-dependence of freight transport operators.

The mediation relations in our model also suggest that technical resources and capabilities further enhance the impact of social resources and capabilities. For instance, the impact of network integration on resilience further increases with the mediation of operations planning. The impact of human capital on dynamic capabilities also enhances with the mediation of I4.0. This result reflects the necessity of integration of both social and technical factors by freight transport operators.

Our findings not only validate prior research emphasizing the role of technical capabilities in supply chain resilience (Belhadi et al., 2022), but also extend this body of knowledge by empirically demonstrating that socio capabilities demonstrate a stronger influence. Few studies, such as Ali and Gölgeci (2020), have considered socio resource or capabilities in resilience, but our results advance this understanding by indicating how technological resources and capabilities can play a mediating role and enhance the impact of socio capabilities.

The control variables included in the model, firm size (number of employees) and fleet asset ownership structure (own versus subcontracted trucks), did not exhibit a significant effect on resilience. This finding suggests structural firm characteristics such as scale and ownership model do not independently enhance the ability to withstand and recover from disruptions in our sample. Rather, resilience appears to be primarily driven by the socio-technical resources and dynamic capabilities captured in the model. The MGA analysis also indicate that the effect of NI and OP on resilience did not differ based on the asset ownership structure. However, the impact of HC and I4.0 on OP changed significantly, indicating that relative importance of technological and human capital resources in improving operations planning varies depending on firms' operational context and asset ownership structure.

6.1. Theoretical contributions

Our findings contribute to a freight transport resilience literature by considering key characteristics of freight transport – operations-intensiveness, network-dependence and services business – validating the interplay between social and technical resources. While previous studies have largely focused on technical elements or treated social and technical elements in isolation, our study confirm that their integration is essential for resilience-building in freight transport resilience.

First, we extend STS theory by demonstrating that social resources—specifically human capital—positively influence technical resources and capabilities. While previous studies, such as Sony & Naik (2020), have explored Industry 4.0 integration within STS theory, our work specifically highlights human capital and Industry 4.0 as critical enablers of socio-technical interactions. We show that human capital not only facilitates the Industry 4.0 technologies but also enhances the important socio-technical capabilities. In exchange, Industry 4.0 plays a partial mediator role and enhances the impact of human capital on socio-technical capabilities. This supports a more nuanced understanding of STS theory by positioning human capital as a key driver of socio-technical capability development and confirming the importance of the interaction between social and technical elements.

Second, our model contributes to the theoretical integration of RBV and STS theory. We argue that resources within STS (human capital and Industry 4.0) collectively shape socio-technical dynamic capabilities, particularly in supply chain network integration and operations planning. This perspective extends RBV by emphasizing that resources are not only firm-specific but also embedded in broader socio-technical structures. By illustrating how these resources dynamically interact to build operational resilience and efficiency, our study reinforces the importance of resource complementarity in modern operations management.

Third, our study contributes to the theoretical understanding of resilience in operations management by illustrating how socio-technical capabilities affect freight operators' perceptions of their organisation's ability to be resilient against disruptions. While prior research has distinguished between engineering resilience and social-ecological resilience (Wieland, 2021; Wieland & Durach, 2021), our study provides a novel mapping of socio-technical resources to resilience outcomes through dynamic capabilities. We propose that resilience is reinforced from the interaction between human capital, Industry 4.0 technologies, and socio-technical capabilities, suggesting that firms must strategically manage these elements to enhance adaptive and transformative resilience. This offers a more integrated approach to resilience theory, bridging the gap between technical and organizational perspectives.

6.2. Practical and policy implications

Our results suggest both socio and technical capabilities positively affect perceived resilience of freight transport firms. This result implies that managers in freight transport should not only focus on technical aspect such as optimisation, scheduling, and route planning, but also human capital aspect of their operations to enhance their resilience against potential disruptions. In fact, our results suggest that network integration, a socio capability, has a slightly larger impact on perceived resilience than operations planning, a technical capability. Our research echoes the call by Russo (2024) and reminds freight transport managers the importance of human element in freight transport and logistics.

Our results confirm that human capital does not only facilitate the adoption of I4.0 but also improve network integration and operations planning that leads to enhanced resilience according to managers' perceptions. Thus, freight transport firms should prioritise training and skill development programs. Such programs could be difficult for small and medium firms to implement. Policymakers should launch or promote skill development schemes in the freight sector by providing necessary funding and resources. It is particularly essential to promote freight and logistics to younger generation to ensure sustainability of human capital. One example is

Generation Logistics scheme in the UK, funded by Department for Transport, which aims to promote the logistics industry to younger generation (DfT, 2024). Programs like Generation Logistics are imperative considering aging population of transport managers – i.e., the Freight Transport Association (UK) survey in 2019 found over 80 % of managers in the survey were over 45 years old. Collaborations between industry partners and schools also play a critical role to sustain human capital and equip future leaders with contemporary skills required in the industry.

Our analysis also demonstrates network integration as a socio capability positively affects operations planning and perceived freight transport resilience. This result suggests transport managers should foster collaborative relations with their network partners. To do this, managers can pursue relational bonding strategies as suggested by Balci et al. (2019). Also, stakeholders in the sector can explore collaborative network platforms and seize the opportunities platform economy brings (Xu et al., 2022). Such collaborative platforms face challenges as well. For instance, members should be equipped with sufficient digital capabilities, both technical and skills wise. As confirmed in our findings, integration through these platforms requires digitalisation of members such as adopting I4.0 tools.

Besides contributing to integration, I4.0 tools such as IoT, AI, and data analytics can improve operations planning as well. The significant role of I4.0 requires freight managers to invest in digitalisation process. However, the digitalisation process could be particularly challenging for SMEs in freight transport (Surucu-Balci et al., 2024). Policymakers can play an important role to boost digitalisation process through fundings. For instance, the Freight Innovation Fund in the UK supports SMEs for the development of greener and efficient transport solutions. Knowledge platforms supported by policy makers can also facilitate the digitalisation process. Alice project (Alliance for Logistics Innovation through Collaboration in Europe) is a good example of such platforms.

Our results show that technical resources and capabilities (I4.0 and operations planning) enhance the impact of socio resources. This suggests that firm-level and policy efforts to digitalisation should be paired with efforts for improving workforce skills. Specific trainings in techno-skills such as data analytics, AI implementations, and digital tools can yield greater results when combined with investments in I4.0 and other digital tools.

Firms and public decision makers can create practical metrics to monitor and assess socio-technical resources to ensure resilience of freight transport operators. Network integration and operations planning are measured with Likert-style statements in our study. However, from a practical perspective, they can be tracked through operational KPIs to support managerial decision-making. Network integration can be monitored using indicators such as the proportion of partners connected via digital platforms and frequency of information sharing whereas operations planning can be assessed through forecast accuracy, vehicle utilization and schedule adherence. Using these KPIs may allow firms and policymakers to assess these dynamic capabilities that are essential for resilience.

Resilience of freight transport is imperative for all economic activities impacting the society at a large scale. Hence, relevant regulatory framework and actions should be initiated for resilience by governments, just like they are designed for net-zero and decarbonisation. Promoting Resilient Supply Chain Act 2023 by the US government sets a good practice as a starting point for policy makers. Similarly, Critical Imports and Supply Chain Strategy is developed by the UK government to safeguard critical supplies such as medicines and semiconductors. Policymakers should initiate similar strategies for freight or dedicate a special section for freight transportation. After all, resilience of freight transport affects all supply chains and flow of critical supplies. Such strategies and regulations will help freight transport operators to plan and report their resilience actions.

Implications made in this study would be useful for road freight operators, particularly general cargo haulage operators in the UK. The perceived level of resilience of firms in our study does not change based on firm size or fleet ownership structure. Hence, our results suggest that companies that simultaneously invest in human capital and leverage I4.0 technologies are better positioned to achieve higher resilience. However, these investments also require certain resources which may not readily be available in SMEs. Thus, as suggested in earlier recommendations, government bodies and industrial organisations play a key role in skills development and digitalisation adoption.

6.3. Limitations and future research

This study is subject to some limitations. First, the study focuses on road freight transport firms in the UK, which may limit the generalisability of the findings to other regions and segments of freight transport. Future research could explore cross-country comparisons and different segments of freight transport to assess whether similar relationships hold in different geographical contexts and transport segments. Population of our research consisted of general cargo road haulage and pallet distributors and did not include different segments such as abnormal goods, tanker haulage, agricultural goods, heavy haulage, and bulk haulage. Hence, results of our study should be carefully interpreted for different freight transport segments. While resources and capabilities in our model are selected to reflect a comprehensive yet concise structure, we also acknowledge there are several other socio-technical capabilities and resources such as organisational learning, autonomous trucks, and digital platforms.

Our study captures resilience as a structural outcome based on survey data at a given point in time. However, resilience is dynamic capability that evolves in response to ongoing disruptions and industry transformations. Recent ongoing geopolitical crises reflect how dynamic the transformations are. Longitudinal studies could shed more light on how resilience capabilities develop over time in response to emerging challenges. We also acknowledge that resilience is a complex concept comprising several sub-dimensions and has been measured as a second-order construct in several studies. While we paid close attention to reflecting all elements of the resilience definition of Ponomarov and Holcomb (2009) and addressed the major constructs identified by Dennehy et al. (2021), other elements of resilience such as resource configuration and resistance may also be considered. This study also measures resilience based on subjective views of experts. Future studies may consider utilising more objective resilience items such as time to recovery, service continuity rate and percentage of on-time deliveries. Objective measures may help policymakers benchmark and monitor resilience at an industry level.

Another limitation of this study is that it does not account for potential reciprocal or interactional effects among certain constructs such as Industry 4.0, Human Capital and Network Integration. While these constructs may affect one another, e.g., adopted digital technologies could influence workspace skills, directions of path in our model were based on earlier research and practical justification. For instance, in our model, human capital is considered as a source that enables the adoption of I4.0 rather than resulting from it. Having said that, building on our results, future studies could explore the reciprocal or interactional effects, in which case a larger sample size is recommended because the model would be more complex.

CRediT authorship contribution statement

Gökcay Balci: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ebru Surucu Balci:** Writing – original draft, Investigation, Data curation, Conceptualization. **Çağatay Iris:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Multigroup analysis results.

	Only Own Trucks coefficient	Both Own and Subcontracted Trucks coefficient	Coefficient difference	Henseler MGA p value	Permutation p value
HC −> NI	0.332	0.385	−0.053	0.685	0.670
HC −> OP	0.134	0.343	−0.209	0.051	0.066
I4_−> HC	0.490	0.423	0.067	0.639	0.628
I4_−> NI	0.428	0.468	−0.040	0.717	0.722
I4_−> OP	0.556	0.231	0.325	0.013	0.015
NI −> OP	0.225	0.402	−0.177	0.201	0.234
NI −> Res	0.488	0.436	0.053	0.676	0.708
OP −> Res	0.363	0.415	−0.052	0.696	0.730

Table A2
Effect of control variables on resilience.

Path	β (standardised path coefficients)	p value	T value	Result
Asset Ownership (Both own and subcontracted is reference group)*				
OnlyOwnà Res	0.160	0.075	1.781	Non-significant
Firm Size (Large is reference group)*				
Small → Res	−0.006	0.969	0.039	Non-Significant
Medium → Res	0.016	0.904	0.120	Non-Significant
Firm Size (Medium is reference group)*				
Small → Res	−0.021	0.824	0.216	Non-Significant

*Examines whether indicated firm categories differ from reference firm groups in their effect on resilience.

Table A3
Mean scores of constructs across different firm demographics.

Category	I4.0 Mean	HC Mean	NI Mean	OP Mean	Res Mean
Firm Size					
Small	3.99	4.08	4.12	4.10	4.00
Medium	3.97	4.24	4.16	4.13	4.01
Large	4.02	4.11	4.03	4.18	3.92

(*continued on next page*)

Table A3 (*continued*)

Category	I4.0 Mean	HC Mean	NI Mean	OP Mean	Res Mean
Asset Ownership					
Only Own	3.97	4.17	4.09	4.13	4.02
Both Own and subcontracted	3.99	4.21	4.17	4.16	3.94
Domestic or International					
Only UK	3.96	4.14	4.03	4.07	3.85
Only International	4.19	4.45	4.27	4.28	4.37
Both UK and International	3.95	4.20	4.25	4.23	4.12

Data availability

Data will be made available on request.

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