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Abstract:

Global disruptions pose significant challenges for supply chains seeking to achieve development goals while maintaining resilience. Research highlights the crucial role of technology in Industry 4.0, promoting innovation and enhancing well-being in resilient supply chains. Next-generation connectivity, such as 5G, is critical for digitalizing supply chain operations and developing smart, resilient supply chain nodes like ports. This study examines the transformative role of 5G in developing smart ports to enhance supply chain resilience and sustainability and their interdependencies. We systematically reviewed more than 1,000 peer-reviewed papers, identified emerging research clusters, and proposed a multilevel framework that integrates technology affordances with transformation outcomes. We employed case research based on secondary data and thematic analysis to investigate 5G's role in developing sustainable and resilient smart ports. Our findings indicate that next-generation connectivity can shape the interplay between resilience and sustainability at multiple levels, including facilities, supply chain ecosystems, and society. 5G acts as an integrated data and technology platform to support policymakers and practitioners in business case development, justifying end-use applications for sustainability measures. This research underscores the importance of connectivity technology in supporting ecological resilience and community-centric initiatives, such as hinterland infrastructure development, asset maintenance, and stakeholder safety, driving sustainability-resilience convergence.

Keywords: Ecological Resilience, Next Generation Connectivity, Sustainability Resilience Interdependence, Smart Ports, Private 5G.

[Department statements, if appropriate, will be added by the editors. Teaching cases and panel reports will have a statement, which is also added by the editors.]

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1 Introduction

In the book *Power of Resilience: How Best Companies Manage the Unexpected* (MIT Press), Sheffi (2015) provides a narrative account of global supply chain disruptions, their response and recovery phases, and their overall socioeconomic and business impacts. African food and flower exporters suffered in 2010, when a volcanic eruption in Iceland disrupted air traffic across Europe. The 2011 floods in Thailand affected 877 local factories and halted the global production of 30% of hard disk supplies worldwide (Sheffi, 2015). The 2011 earthquake and tsunami in Japan significantly damaged the automotive and electronics industries and affected the Fukushima nuclear reactor, causing economic losses estimated between $195 billion and $305 billion (Pettit et al., 2013). Toyota alone incurred losses of $72 million in daily profits, and a decline of over 17% in its market value (Pettit et al., 2013). Between 2009 and 2013, nearly 50% of organizations experienced weather-related supply chain disruptions (Sheffi, 2015). Intentional disturbances, such as cyberattacks, terrorism, worker strikes, thefts, protests, and legal actions, also create significant blockages. The 2018 EventWatch Supply Chain Disruption Report documented 1,069 disruption events, with global supply chain risk events increasing by 36% (Xu et al., 2020). The Business Continuity Institute's (BCI) report (2021) shows that while 4.8% of organizations witnessed ten or more supply chain disruptions in 2019, this figure rose to 27.8% in 2020 during the pandemic. Interlinkages and complexities across global supply chains amplify these effects (Craighead et al., 2007; Katsaliaki et al., 2022). The literature highlights the capacity of adaptive and resilient supply chains to limit disruption losses and support rapid recovery. Research in this field examines how capabilities such as visibility, agility, collaboration, flexibility, redundancy, and technology mitigate vulnerabilities and enhance resilience. Lee (2004) contrasts Nokia’s and Ericsson’s responses to a component shortage caused by a fire at a Philips plant, underscoring the value of visibility and agility in resilience-building. Yet, resilience addresses only part of the challenge, as disruptions may also arise from lapses in sustainable procurement, logistics, and green supply chain practices that enable adaptability (Fahimnia & Jabbarzadeh, 2016; Sharma et al., 2025). A key issue overlooked in earlier work is how resilient supply chains can also advance sustainable development goals, since the two domains have often been examined separately (Fahimnia & Jabbarzadeh, 2016; Warmbier et al., 2022). Recent and emerging research, however, increasingly tries to link the two disparate concepts through prisms such as financial performance (Doetsch & Huchzermeier, 2024), optimization through dynamic sustainability (Fahimnia & Jabbarzadeh, 2016), and digitalization using industry 4.0 technologies (Sharma et al., 2025). The interdependency and tension between sustainability and resilience in supply chain entities, which drives the triple bottom line (TBL) of environmental, social, and economic sustainability (Weber, 2023), is a critical research area. Carter and Rogers (2008) proposed the TBL framework which embraces economic progress, environmental impact, and social responsibility, and their intersections. TBL can be assessed using measures such as safety, well-being, energy consumption, and productivity (Slaper & Hall, 2011). While conceptual studies (Negri et al., 2021) acknowledge this interdependence, empirical evidence is sparse. Our research aims to contribute to this emerging area of conversation on sustainability-resilience convergence by exploring its dependence on smart supply chain operations through the mediation of advanced Industry 4.0 (I4.0) technologies in connectivity and data processing. Using case study research with secondary data, we show how next-generation wireless technologies such as 5G and its affordances, create business value at multiple levels, fostering societal transformation through community centricity and driving sustainability measures, while simultaneously improving visibility and agility as resilience drivers.

Industry 4.0 enables supply chains to achieve real-time information flow across all stages and links in the value chain (Ralston & Blackhurst, 2020), thereby improving visibility. It unlocks value generation by enhancing productivity and efficiency through digital transformation, applying principles such as system integration, interoperability, and real-time technology adoption (Hermann et al., 2016; Lu, 2017). However, sharing real-time information requires a robust next-generation connectivity infrastructure to enable digital transformation and strengthen agility. Connectivity facilitates information sharing within the supply chain and enhances visibility across organizational boundaries (Fawcett et al., 2007). According to a World Economic Forum 2020 report, intelligent connectivity, led by 5G, is a transformative lever, forming the bedrock of I4.0 with "$13.2 trillion of global economic value created by 2035, of which manufacturing alone will contribute about $4.7 trillion" (Galal & O'Halloran, 2020). 5G is expected to contribute approximately $3.6 trillion to the global value chain (Galal & O'Halloran, 2020). As a connectivity platform, 5G offers rapid transmission and edge-based processing near data sources, thereby reducing latency and contributing to information agility and visibility (French et al., 2021). Beyond connectivity, 5G functions as a

comprehensive digital infrastructure (Dolgui & Ivanov, 2022). It provides ubiquitous high-bandwidth ultra-reliable communication networks for millions of devices and accelerates digitalization through rapid transmission and processing in the I4.0 context (Taboada & Shee, 2021). 5G can contribute to 11 sustainable development goals (SDG) by influencing industrial safety, well-being, and infrastructure development, promoting "sustainable industrialization and fostering innovation" (Galal & O'Halloran, 2020). Its influence extends to the triple bottom line of environment, society, and governance (ESG), aligning with Industry 4.0 's impact on the circular economy (Birkel & Müller, 2021). Dolgui and Ivanov (2022) identify 5G's role in enabling digital supply chain ecosystems and advancing sustainability as strategic research directions. In this study, we build a case for the role of 5G in uncovering the interdependencies between supply chain resilience and sustainability within smart ports, which represent a critical supply chain infrastructure.

The role of technology in improving supply chain resilience has received increasing attention (Spieske & Birkel, 2021) but still warrants further development (Fischer-Preßler et al., 2020). Rapid real-time information processing and visibility frameworks using emerging I4.0 technologies offer significant potential for the early detection of supply chain disruptions and support agile responses (Kagermann, 2015). Although fragmented regarding technology's role, the extant literature shows that rapid information sharing enhances visibility and responsiveness to counter disruptions and risks across supplier tiers. A critical prerequisite for the effectiveness of technology during supply chain disruptions is the availability of post-disruption communication infrastructure (Sheffi, 2015). Dolgui and Ivanov (2022) propose a conceptual model in which 5G enhances supply chain digitalization across dimensions of "intelligence, connectivity, networking, end-to-end visibility, and transparency." Port infrastructure, often regarded as a lifeline of global trade, plays a central role in advancing supply chain resilience (Verschuur et al., 2022). The World Port Conference of 2024 presented collaboration between international ports to frame sustainability and supply chain resilience as significant goals between 2024 and 2029 (Rahman, 2024). Ports serve as economic powerhouses, multimodal transit, and economic activity hubs that link roads and rails, thereby developing industrial clusters for societal transformation (Verschuur et al., 2022). They handle more than 80% of global trade by volume and 70% by value (UNCTAD, n.d.). Given their vulnerability to supply chain and climate-induced disruptions (Becker et al., 2018), ports are ideal sites for examining the interdependence between resilience and sustainability. Ports connect the hinterland to the shipping network, thereby exposing national economies to the adverse effects of disruptions, including extreme weather and climate change-related risks (Notteboom et al., 2022). Given the significance of smart ports as critical supply chain nodes, we explore 5G as the next-generation connectivity in supply chains and its impact on port resilience and sustainability. Our review follows a structured research question (RQ) design that guides the review process, inclusion of studies, search strategy, and data collection (Briner & Denyer, 2012). Given 5G's potential and practitioners' interests, understanding 5G's role in the supply chain is imperative. Therefore, we ask:

RQ1: What is the role of 5G as a connectivity platform in the I4.0 supply chain in improving supply chain resilience and advancing the SDG?

Understanding how the adoption of 5G shapes digital transformation in critical supply chain entities susceptible to disruptions, creating socioeconomic value, and improving TBL is vital. Hence, the following points are worth exploring:

RQ2: How does private or public 5G adoption shape the transformation of critical supply chain entities to strengthen resilience and advance sustainability goals?

The significant contributions of our study include (1) a thematic analysis of extant literature on 5G in the I4.0 supply chain, identifying the intellectual structure examining 5G's role in the supply chain, (2) development of an integrative conceptual model to understand next-generation connectivity-led interdependencies between sustainability and resilience, and (3) construction of a theoretical model derived from case research to guide policymakers and practitioners on 5G's community-centric role in business case formulation for technology investments. We conducted a systematic search to identify relevant literature complemented by a scoping review with thematic analysis to address the absence of an integrative study of 5G's impact on the supply chain. Our conceptual model adopts a multilevel perspective framework: micro (firm or factory level), meso (supply chain level), and macro (societal level) (Daniel, 2022), distinguishing concept applicability and transformation needs at each level and aligning them with the TBL dimensions of organizational economy (efficiency and productivity), supply chain environment (partner ecosystem), and society (safety, well-being, community). We further extend this

framework through a case study of a critical supply chain node, smart ports, by drawing on secondary data from multiple sources to ensure effective triangulation and enhance study validity (Voss et al., 2002).

Section 2.0 of the remaining part of the paper discusses the business context and develops familiarity with 5G technology. Section 3.0 provides the methodology. Section 4.0 discusses the scoping review findings, key concepts, and categories. Section 5.0 analyzes the findings of the case research. Section 6.0 discusses and proposes a theoretical framework that extends the conceptual model. Section 7.0 concludes the study by highlighting its contributions, limitations, and research opportunities.

2 Literature Review

2.1 Disruption Resilience - Emerging I4.0 Technology Context

Supply chain disruption refers to unexpected events that threaten normal business operations (Bode & Macdonald, 2017; Katsaliaki et al., 2022), trigger financial losses, and erode market value (Hendricks & Singhal, 2005). Rapid recovery is crucial for maintaining business continuity (Dey, 2022; Katsaliaki et al., 2022; Munoz & Dunbar, 2015; Sheffi & Rice, 2005). Organizations strive to rapidly restore their desired performance levels following disruptions (Munoz & Dunbar, 2015; Ponomarov & Holcomb, 2009). Resilience, first conceptualized by Christopher and Peck (2004), refers to the ability to recover the expected performance level post-disruption (Craighead et al., 2007; Ponomarov & Holcomb, 2009). The key to resilience is early disruption detection and rapid response (Blackhurst et al., 2005; Sheffi & Rice, 2005), with capabilities such as visibility, agility, and flexibility (Pettit et al., 2010; Pettit et al., 2013). Supply chain visibility provides insights into inventory, demand, and supply conditions (Blackhurst et al., 2005; Christopher & Peck, 2004). Agility entails the capacity to respond rapidly to demand-supply volatilities (Christopher & Peck, 2004), enabled by a faster and seamless information flow (Adobor & McMullen, 2018). Real-time data sharing across supply chain nodes enhances responsiveness to disruptions (Blackhurst et al., 2005). Greater visibility improves resilience by fostering information sharing and collaboration (Scholten & Schilder, 2015). Responding to environmental changes requires continuous information flow enabled by connectivity (Fawcett et al., 2007). Industry 4.0 (I4.0), which encompasses front-end and base real-time technologies (Frank et al., 2019), holds the potential to make supply chains more resilient (Ralston & Blackhurst, 2020) and sustainable (Birkel & Müller, 2021). Real-time supply chain capability relies on data integration, visibility, and information sharing among partners (Oliveira & Handfield, 2019). I4.0 uses emerging technologies to provide real-time data-enabled connectivity and communication (Tang & Veelenturf, 2019). I4.0 technologies enable data-driven automation, communication quality, monitoring, supply chain mapping, transparency, flexibility, visibility, and information sharing. Collectively, these capabilities foster adaptive and responsive supply chains (Ghobakhloo et al., 2023) that respond to emergent disasters (Dennehy et al., 2021).

2.2 Sustainability Goals and Supply Chain Resilience

Sustainability, as the adoption of environmentally and socially beneficial practices, is a key driver of resilience in supply chains (Jain et al., 2017). The United Nations Sustainable Development Goals (SDG, https://sdgs.un.org/goals) emphasize industry, innovation, and infrastructure as the primary goals for industrial and societal transformation, alongside specific targets on clean energy, safety and well-being, and productivity. Industry 4.0 can promote sustainable transportation and industry through real-time technology-enabled, collaborative, data-driven planning, autonomous operations, and digital twins that optimize performance and processes (Sun et al., 2022). Resilience and recovery from disruptions depend on an organization's ability to pursue digital transformation, develop flexibility, prepare for the next cycle, institutionalize global visibility, and prioritize worker health and skill development (Sundarakani et al., 2024). The literature has further examined the interdependence among supply chain resilience and sustainability (Carissimi et al., 2023), Industry 4.0, and triple bottom line (TBL) goals (Birkel & Müller, 2021). Supply chain resilience and sustainability can influence each other both positively and negatively (Negri et al., 2021).

Resilience can be characterized as engineering resilience or the ability to return to a stable state after disturbance (Holling, 1973), ecological resilience or natural adaptation relying on excess capacities (Erol et al., 2010), and evolutionary resilience resulting in the transition to a transformed state (Adobor & McMullen, 2018). Among the three resilience types, ecological resilience emphasizes system adaptability or agility as a persistent system in the face of disruption (Holling, 1996, p.33), and evolutionary resilience begets transformation to a “newer and improved” state. Managing the post-disruption phase through

mechanisms such as social memory, trust, networking, and learning (Adobor & McMullen, 2018) is closely aligned with the impact on and feedback from resilience and sustainability. Fiksel (2006) highlights the need for a systems approach and cross-disciplinary research to understand sustainability and resilience through the lens of ecological resilience in an uncertain environment. Ports contribute to sustainability-resilience interdependence by developing sustainable industrial hubs, supporting a circular economy through ship recycling, and promoting community development through resource conservation, efficient waste and water management, and biosphere preservation (Notteboom et al., 2022). These practices sustain disruption recovery and enable a transition toward a new equilibrium state.

2.3 5G as the Next-Generation Connectivity Platform

Fifth-generation mobile technology (5G) rests on the three core pillars of enhanced Mobile BroadBand (eMBB), ultra-reliable low-latency communication (uRLLC), and massive machine-type communication (mMTC) (Cheng et al., 2024; Varga et al., 2020, 2022; Wen et al., 2022). 5G offers significant performance improvements owing to technological innovations and enhances organizational capability for seamless connectivity across boundaries (Taboada & Shee, 2021). 5G integrates with the Internet of Things (IoT), artificial intelligence (AI), and edge computing to accelerate use cases, such as predictive maintenance, worker safety, autonomous material movement, remote operations, and rapid response to operational disruptions (Cheng et al., 2018; Rao & Prasad, 2018). 5G provides end-to-end visibility through AI-based processing of real-time data gathered from devices and sensors (Shim et al., 2022; Dolgui & Ivanov, 2022; French et al., 2021). By enabling real-time information sharing, 5G imparts efficiency to supply chain operations and reliable connectivity to respond effectively to emergent and dynamic conditions (Taboada & Shee, 2021). 5G's distinct advantage over other high-speed connectivity technologies is its mobility and wide area coverage relevant to supply chains (Oughton et al., 2021). 5G and other next-generation connectivity technologies offer complementary capabilities (Oughton et al., 2021). We used the term next-generation connectivity for 5G or equivalent platforms while focusing on 5G as the representative medium. 5G's socioeconomic benefits remain largely ambiguous (Eisinger Balassa et al., 2024), and more research is needed to promote awareness.

2.4 Smart Ports

Ports encompass a broad community network of port operators, logistics service providers, shippers, customs, and industrial units using port facilities (Inkinen et al., 2021; Potter et al., 2024), with 90% of global trade conducted through oceans (Belmoukari et al., 2023). The evolution of smart ports necessitates the integration of advanced technologies for intelligent automation aimed at improving productivity and reducing energy consumption (Niu et al., 2024). Smart ports use advanced technologies for efficient business functions underpinned by information systems, data-driven applications, and performance metrics (Potter et al., 2024). Information systems include data generators, processing devices, data transmission technologies, and industrial automation (Potter et al., 2024). Digital technologies encompass IoT, cyber-physical systems, and the integration of "control, computing, and communication" functions (Liu et al., 2024). The core characteristics of smart ports include real-time data usage, automated operations, sustainability, and ecosystem development (Liu et al., 2024), which collectively create a connected network that enhances collaboration and safety (Belmoukari et al., 2023). However, ports and hubs servicing industrial clusters remain vulnerable to severe economic impacts from natural hazards and supply chain disruptions, adversely affecting global trade and damaging critical assets and hinterland connectivity (Verschuur et al., 2022). Port resilience is critical among supply chain nodes because its vulnerabilities can lead to infrastructure and asset failures, including disruptions within shipping networks (Notteboom et al., 2022). Ports should display the resilience dimensions of “absorptive, adaptive, and restorative capacity” by demonstrating agility and flexibility (Notteboom et al., 2022). The key concepts from this review are summarized in the conceptual model illustrated in Figure 1.

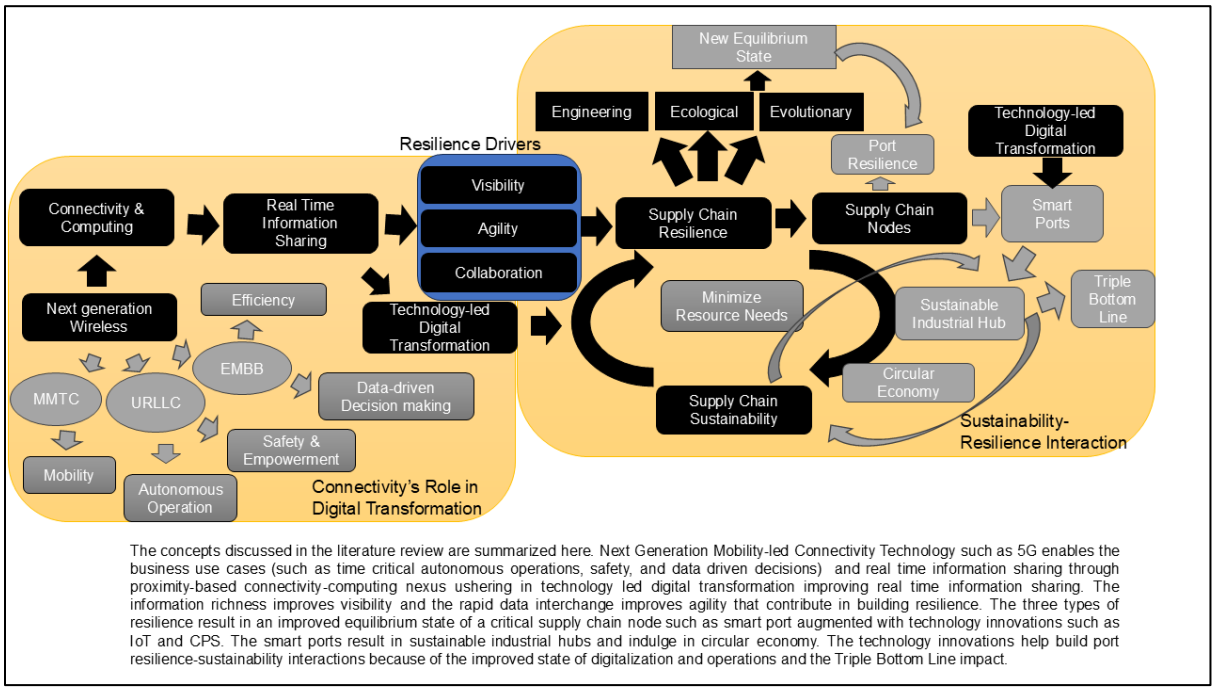

Figure 1. Summarized Concepts and their Interactions to Build Sustainable and Resilient Ports

2.5 Need for Proposed Study

Resilience–sustainability convergence is often considered paradoxical, as proactive resilience measures may adversely affect sustainability principles (Warmbier et al., 2022). The literature addresses this paradox through models employing mixed-integer programming and multi-objective decision optimization to design sustainable and resilient supply chain networks (Fahimnia & Jabbarzadeh, 2016; Nayeri et al., 2021). Technically, this paradox extends to the domain of sustainability. Although 5G integrates with the cloud for effective digitalization, its data transfer and bandwidth requirements may lead to disproportionate energy consumption. As a data-proximity-based distributed computing framework, a multi-access edge can contribute to energy efficiency (Taboada & Shee, 2021). Dolgui and Ivanov (2022) propose a conceptual framework for 5G's role in the supply chain, enhancing the pillars of intelligence, visibility, connectivity, and dynamic networking, improving logistics, and imparting smart capabilities to physical entities. They recommend further research at the strategic (including new business models), operational, and cross-disciplinary levels to deepen the understanding of 5G's impact on sustainability and resilience. However, exploring 5G's applicability in specific supply chain nodes beyond the factories of the future and in practical settings beyond simulations could facilitate broader analytical generalizability. Our research seeks to extend the understanding of 5G's role beyond manufacturing, while also examining its contribution within the manufacturing supply chain. We address these paradoxes by identifying areas of convergence where 5G mediates the dual influences of sustainability and resilience in transformation processes, thereby impacting the triple bottom line (TBL). Our goal is to build a theoretical foundation that explains how next-generation connectivity in smart supply chain nodes can augment the power of digitalization.

3 Methodology

To respond to RQ1, we conducted a scoping review to understand the key concepts, beginning with a clearly articulated objective and research question (Levac et al., 2010). Dentoni et al. (2021) proposed going beyond the narrow boundaries of organizational sustainability to ecological resilience at the societal level. Our research transcends the organizational level to understand the impact on societal transformation as a critical prerequisite for the TBL that encompasses "people, planet, and profit" (Elkington, 1997). To respond to RQ2, we conducted a qualitative empirical case analysis of a critical supply chain infrastructure node, the smart port, to build on our proposed framework.

A systematic search is valued for its reproducibility, transparency, and contribution to research (Tranfield et al., 2003). We systematically searched Scopus and Web of Science (Brylowski et al., 2021) using the keywords in Table 1 for scoping reviews of emerging research patterns. Following Snyder (2019), we assessed relevance through title and abstract selection and a full-text search for final scope identification. We presented the search strategy using the PRISMA methodology (Moher et al., 2010) and identified the final literature set based on the inclusion and exclusion criteria in Appendix A (Levac et al., 2010) to address RQ1. To address RQ2, we conducted a single case study research using secondary data. Case research is distinguished by the spatial and temporal boundaries imposed upon its settings and may contain "embedded cases" (Eisenhardt, 1989; Løkke et al., 2014). We considered only one case from the secondary data in this study because of the paucity and sparsity of relevant data. Single-case studies provide depth of analysis and are desirable for cases that narrate situations that have not been previously analyzed or if it is a critical case for theory testing (Benbasat et al., 1987). Case research can help in a complex environment involving new technology phenomena (Løkke et al., 2014), such as 5G in smart ports. The use of secondary data is an accepted practice in case research because of its potential to reduce researcher bias (Ellram & Tate, 2016). The benefits include the lower cost of collecting data of acceptable quality, objectivity compared to primary sources such as surveys and interviews, and the ability to be combined with other sources for holistic and comprehensive views (Ellram & Tate, 2016). We used thematic analysis in the dissemination stage to group the data into relevant themes to connect ongoing conversations with the RQ. We followed the thematic analysis (TA) framework of Byrne (2022) and Braun and Clarke (2019) to analyze and interpret data as concepts. We established relationships among concepts to develop categories, which were then aggregated into higher-level abstractions that formed themes aligned with the research question. The concepts were derived inductively from documents through manual line-by-line analysis. They helped develop first-level codes, which were subsequently organized into clusters to yield higher-level abstractions. Through progressive abstraction and generalization, candidate themes were formulated, aligned with the sustainability and resilience drivers identified in the extant literature. The coding process followed the guidelines of Saldaña (2016). We derived codes from the identified concepts, categorized them through progressive abstraction into higher-level codes, and clustered categories into themes. As an illustrative example (with sample codes and concepts under each theme presented in Table 2), we identified the initial concepts of Network Slicing, Network Reliability, Device Density, and Network Virtualization. The concepts adopted were a mix of In Vivo and interpreted codes to improve reliability and reduce ambiguity. The raw concept of network slicing was abstracted into the code Differentiated Quality of Service (QoS) as the main purpose behind slicing. We rolled up these level zero codes to higher-order generalization Network Characteristics, which, with other similar categories centered around Data Processing, Connectivity, Service, and Data Transmission, are abstracted into the theme of Data, Connectivity, and Processing Coordination as 5G's role. The theme explains the journey and processing stages of data interwoven through a high-speed 5G transmission network and its interplay with computing engines, such as edge. The analytical process involved iterative initial concept extraction, category identification as abstraction, and theme development with independent validation to ensure analytical rigor. From the scoping review, more than 150 concepts from 28 documents were abstracted into 21 codes, further clustered into six themes. For the case study research, we identified the initial concepts of collaborative initiative, seamless collaboration, strategic collaboration, partnership to accelerate digital innovation, and mindset driving collaboration, grouped under partnership and collaboration as a higher-level code. Together with the value creation category encompassing cross-functional expertise, leveraging ecosystems for business model innovation, and scaling pilot initiatives for driving transformation, these were abstracted into the theme of Cocreating Value: Collaboration and Partnership Ecosystem Driving Deployment. The process of coding and progressive generalization to derive themes is presented in Appendix D.

3.1 Scoping Review Process

Our search process identified 1069 5G-relevant documents, including peer-reviewed journals, conference papers, and review papers. The search terms in Table 1 use a Title-Abstract-Keyword-based search for document identification (Montecchi et al., 2021; Wong et al., 2012). To respond to RQ1, we followed Tortorella et al. (2022) and Brylowski et al. (2021) in conducting a scoping review of 5G in the I4.0 supply chain. A scoping review, performed before a systematic review to identify the relevance, scope, and volume of the work, is suitable for exploring broad themes in areas comprising a wide range of literature, highlighting research gaps reliably and rigorously (Arksey & O'Malley, 2005; Tranfield et al., 2003). Reviews should accompany a review protocol in the planning stage (Tranfield et al., 2003), as presented in the form of research problems, specific questions, and search strategy. We followed Munn et al. (2018)

and Arksey and O'Malley (2005) to develop an a priori protocol using the problem context and broad research questions, conduct a systematic, transparent, and replicable search of the literature, and present key concepts using the PRISMA methodology (Page et al., 2021) and thematic analysis. We report the search strategy for replication (Tranfield et al., 2003) and refrain from assessing the quality of the reviewed research (Levac et al., 2010), as is generally done in systematic reviews. We focus on analyzing the literature and identifying and discussing specific concepts related to 5G in supply chains (Brylowski et al., 2021; Levac et al., 2010; Linnenluecke et al., 2019). In addition to summarizing and disseminating the extant research, we identify gaps where researchers can make future systematic contributions (Arksey & O'Malley, 2005).

We provide an exhaustive list of inclusion and exclusion criteria to reduce the volume of technical literature in unrelated areas (Arksey & O'Malley, 2005; Levac et al., 2010). Double checking of the excluded records ensured that no records were missed. Post-exclusion checking resulted in further refining the filter and exclusion criteria, such as including Industry 5.0 and Multi-Access Edge (MEC) in the inclusion list. The process flow diagram in Figure 2 provides a complete and transparent view of the search process and its outcomes at various stages (Snyder, 2019). The preprocessing steps for removing duplicates across the two databases helped obtain the final set through a rigorous assessment of each accessible record. We judged subject relevance and merit by examining titles, abstracts, and keywords (Wong et al., 2012). Conceptual and review papers were included if they met the inclusion criteria. We undertake a scoping review following Arksey and O'Malley (2005) and Levac et al. (2010), synthesize the literature, use thematic analysis to clarify complex concepts from the data, and lay the foundation for the conceptual model. Following Arksey and O'Malley (2005), we provide themes, categories, and ideas by collating, summarizing, and presenting a model.

Table 1. Search Criteria for the Distributed and Decentralized Technologies in Supply Chain

Scopus	(TITLE-ABS-KEY (5G * AND supply AND chain) OR TITLE-ABS-KEY (5G * AND industry 4.0))
Web of Science	5G and Supply Chain (Topic) or 5G and Industry 4.0 (Topic)

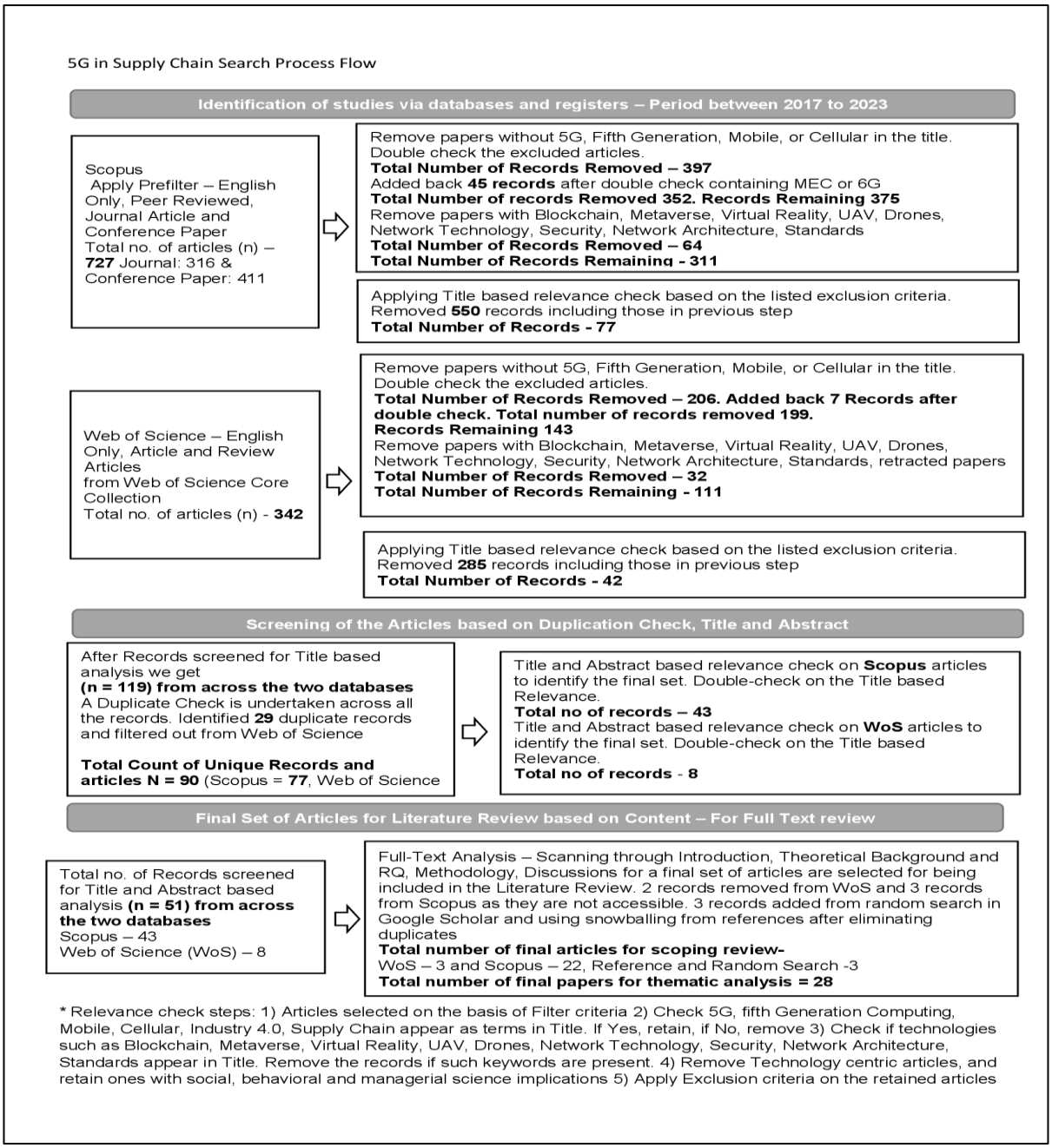

Figure 2. 5G in Supply Chain and Industry 4.0 – Literature Review and Screening following PRISMA

3.2 Case Research

Case research explores a "phenomenon and its context," such as 5G's impact on supply chain information velocity (Shanks, 2002). It uses documents and text as data sources to facilitate inductive theory building (Shanks, 2002; Voss et al., 2002). Generalization from a single case study is possible through an in-depth analysis of a critical case (Flyvbjerg, 2006). Our case analysis reinforces the importance of resilience in sustainability studies and underscores the criticality of technology in achieving convergence between the two, thus providing a theoretical foundation. The selected case is a Western European smart port, one of the first to deploy a private 5G network for community improvement, extensively using digital systems for "developing agile, efficient, and secure supply chains " with real-time data (D'Amico et al., 2021). The

case organization was purposefully chosen to fit our criteria of being a sustainability leader, 5G adopter, and resilient and smart through the extensive use of digital systems. Using data triangulation, through a rigorous search process, we went through the available documents, news articles, reports, and other data sources on the case organization, thus improving research validity (Voss et al., 2002). We performed thematic analysis of the case data (Braun & Clarke, 2012; Li et al., 2024). We employed a line-by-line coding approach for Level Zero codes, identifying second-level codes as abstractions derived from the relationships among the Level Zero codes, using Atlas.ti to document them. These abstractions were expanded into themes aligned with sustainability principles and resilience drivers (Braun & Clarke, 2006). Twenty documents on the above cases were scanned, and 326 level 0 and 25 level 1 codes (categories) were analyzed. Multiple document sources helped establish construct validity (Shanks, 2002). Details of the documents and coding procedures are provided in the Appendices C and D. One inductive strategy suggested by Yin (2014) is to work through data in a ground-up manner, identifying concepts for a pattern that matches those derived from the framework. We used thematic analysis to a) find level zero codes and concepts from cases, b) formulate higher-level abstractions as categories based on common properties, and c) identify the degree of matching between concepts from the literature and cases using pattern matching. A match between the predicted and empirically derived patterns helps build the study's internal validity (Shanks, 2002; Yin, 2014). Pattern matching is relevant for descriptive or exploratory case research (Yin, 2014) because we predict patterns prior to case data collection as part of the scoping review. We maintain a case research database to ensure replicability and improve reliability (Yin, 2014). Our search process for case documents involved 1) providing relevant search criteria (Name of the Organization + Smart Port + 5G) using various search engines, 2) identifying and classifying relevant documents as reports, articles, research papers, or news items, and 3) documenting them in a case database for thematic analysis. We selected only non-duplicate and non-overlapping documents covering the same case from different perspectives, improving reliability and generalizability and reducing biased coverage.

4 Findings - Scoping Review Results and Thematic Analysis

We present scoping review findings as a thematic analysis, treating each document as the unit of analysis and adopting both narrative and tabular synthesis, as recommended by Arksey and O'Malley (2005). Thematic analysis involves identifying, analyzing, and reporting patterns across the literature (Byrne, 2022; Snyder, 2019) following guidelines for developing codes grounded in both conceptual frameworks and data (Saldaña, 2016). Data familiarization was achieved using Atlas.ti as a primary tool for organizing the initial codes. Themes were constructed by identifying shared patterns and concepts, consistent with a reflexive or interpretivist paradigm (Byrne, 2022). Codes were combined according to their interpreted meanings, following Braun and Clarke (2006). The higher-order abstraction network characteristics aligned with the theme of Data-Connectivity-Processing coordination contribute to agility (rapid processing), flexibility (software-defined network configuration and network as a service), and visibility (information to insight). These were derived from the network properties of network slicing, quality of service, reliability, and device density. Each theme aggregated the underlying second-level codes. For instance, the theme of human–machine collaboration was an aggregation of the category of human-machine interaction dealing with coordination and communication among devices, systems, and human operators, and the category of machine-enabled reality, which facilitates such interaction through virtual realities or digital twins. Themes were identified through systematic mapping, categorization, and abstraction of concepts and codes with common properties across the documents: (1) Data-Connectivity-Processing Coordination integrating data generation, transmission, and processing technology features, (2) Human-Machine Collaboration, (3) Platform Unification and Integration, (4) Autonomous Business Operations enabling smart factories and logistics, and (5) Private 5G Adoption Ecosystem, including associated challenges and benefits for business case formulation. These themes are independent but interwoven into the conceptual framework that illustrates how 5G impacts SC resilience and sustainability. Together, they explain 5G's role as a connectivity platform in the I4.0 supply chain, addressing RQ1. 5G as the next-generation wireless platform 1) links data to computing by bringing data near the network edge, reducing the response time in mission critical use cases, 2) drives transformational use cases encompassing automation and collaboration because of its capability to reliably, safely, and seamlessly handle massive data volumes, and 3) supports integration across devices, networks, and platforms to form an integrated supply chain. It also fosters privacy and security through enterprise private 5G adoption, building an ecosystem of partners with unique capabilities that help organizations innovate with new business models and differentiated services. The themes also find empirical support through

bibliometric coupling and co-occurrence analysis conducted using VOSviewer and review data. The IoT–Edge–5G co-occurrence (see Appendix E1) highlights data-connectivity-processing coordination in the Industry 4.0 supply chain. The clusters of literature sharing these common themes are provided in Appendix E2.

Table 2. Emerging Themes on the Three Technology Applications in Supply Chain

Themes	Categories [Concepts]	References
1. Data-Connectivity-Processing Coordination (Section 4.1)	Network Characteristics [Network Slicing - Quality of Service, Network Reliability, Device Density, Ultra Low Latency, Network Virtualization, Network Cloudification, Decoupling, On Demand Scaling, Agility, Autonomous Operation, Wide Area Networks/Public Networks] Transmission Characteristics [Data Rate, Real-Time Flow, High Bandwidth] Service Characteristics [Open RAN, Control Plane-Data Plane Decoupling, Heterogeneous Networks (HetNet)] Edge Computing and IIoT [Multi Access Edge, Industrial Internet of Things, Cyber-Physical Systems]	Varga et al. (2020), Varga et al. (2022), Wollschlaeger et al. (2017), Aijaz (2020), O'Connell et al. (2020), Taleb et al. (2019), Rao & Prasad (2018), Li et al. (2018), Cheng et al. (2018), Sasiain et al. (2020), Taboada & Shee, (2021), Li et al. (2023), Lagorio et al. (2023), Cheng et al. (2024), Wen et al., (2022), Cimini et al. (2023), Bajracharya et al. (2020),
2. Human-Machine Collaboration (Section 4.2)	Human-Machine Interaction and Communication [Instructing Technology, Collaborative Robots] Machine-enabled Reality [Augmented and Virtual Reality, Tactile Internet, Digital Twins]	Varga et al. (2022), O'Connell et al. (2020); Li and Wang (2021), Cheng et al. (2018), Cheng et al. (2024), Cimini et al. (2023), Mourtzis et al. (2021), French et al. (2020)
3. Platform Unification and Integration (Section 4.3)	Enterprise Integration [ERP, Manufacturing Execution Systems] Cloud Integration [Big Data] Device Data Integration [Machine and Sensor Data, Control vs Monitoring Data, IT-OT collaboration] Capability Integration [Spectrum, Cyber-Physical Systems, Internet of Things, Industrial Communications, Public and Private networks] Technology Convergence Business Process Integration [supplier, customer, warehouses, inter-organizational communication]	Varga et al., (2022), Wollschlaeger et al. (2017), Aijaz (2020), Aijaz (2020), O'Connell et al. (2020), Taboada & Shee, (2021), Dolgui & Ivanov, (2022), Cheng et al. (2024), Bajracharya et al. (2020), Biswas et al. (2023), Küpper et al. (2022)
4. Autonomous Operations (Section 4.4)	Smart and Connected Entities [Smart Logistics, Smart Factories, Smart Warehouses, Disaster Signalling, Connected Goods] Use Case Drivers [Time Critical, Non-Time Critical and Remote Operations, Latency Sensitive, Seamless Communications, Industrial Internet]	Varga et al. (2022), Varga et al. (2020), Aijaz (2020), O'Connell et al. (2020), Taleb et al. (2019), Walia et al. (2019), Rao & Prasad (2018), Taboada & Shee, (2021), Dolgui & Ivanov, (2022), Lagorio et al. (2023), Cheng et al. (2024), Gupta et al. (2019), Mourtzis et al. (2021)
5. Private 5G Adoption Ecosystem (Section 4.5)	Resource Dedication [Network Slicing, Dedicated Spectrum, Coverage, Quality of Service] Control Enactment [Business Use Case, Technology Application, Spectrum Allocation] Deployment Model [Licensed, Unlicensed, Shared, Campus Network] Business Value [Security, Privacy, Societal Transformation]	Aijaz (2020), O'Connell et al. (2020), Ordonez-Lucena et al. (2019), Walia et al. (2019), Eswaran & Honnavalli, (2023), Wen et al. (2022), Taleb et al. (2017)
6. Challenges and Benefits of Adoption (Section 4.6)	Technology Benefits [Scalability, Reliability, Availability, Energy and Data Efficiency, Safety Flexibility, Mobility] Enterprise Transformation [Integrated Manufacturing and Logistics, Connected Products, New Business Models, Servitization] Requirements [Global vs. Local Coverage and interworking, Multi-tenancy, Use Case diversity, Separation of Concern] Challenges [Cost, Skills, Technical Hurdles]	Varga et al. (2022), Wollschlaeger et al. (2017), Aijaz (2020), O'Connell et al. (2020), Taleb et al. (2019), Walia et al. (2019), Li et al. (2018), Dolgui & Ivanov (2022), Cimini et al. (2023), Wen et al. (2022), Biswas et al. (2023), Attaran & Attaran (2020)

4.1 Data-Connectivity-Processing Coordination

4.1.1 Network Characteristics

5G networks offer reliable (failure-proof), high-bandwidth, dense networks bounded by quality-of-service requirements for critical communication among a massive number of device data sources (Cheng et al., 2024; Cimini et al., 2023; O'Connell et al., 2020; Varga et al., 2022; Wollschlaeger et al., 2017). Cloudification and software-hardware decoupling enable networks to respond to the agility-driven requirements of machine-to-machine communication, autonomous network operations, and on-demand scaling for real-time insight generation (Taleb et al., 2019; Varga et al., 2022). Reliability distinguishes 5G networks from unlicensed ones (Varga et al., 2020). Ultra-low latency drives mission-critical smart factory applications for improved flexibility. The network slicing feature helps provide differentiated services tailored to each application requirement (Varga et al., 2020; Wollschlaeger et al., 2017). As a wide-area network, 5G facilitates cross-geographic communication and enhances supply chain visibility through rapid information sharing among partners (Taboada & Shee, 2021; Wollschlaeger et al., 2017).

4.1.2 Transmission Characteristics

The ultra-reliable low-latency feature of 5G addresses critical, time-sensitive communication requirements in the supply chain, including closed-loop control in autonomous movements, reducing the possibility of disruptions, such as accidents (O'Connell et al., 2020). Large data volumes created by multiple technologies working in conjunction with a factory shop floor require scalability and flexibility enabled by 5G (O'Connell et al., 2020; Taleb et al., 2019). 5G can reduce the problem of signal interference in industries owing to the proliferation of network access points (Cheng et al., 2024).

4.1.3 Service Characteristics

The new trends of network virtualization and service-oriented architecture, open radio access networks (ORAN), and decoupling between control and data planes help reduce barriers to 5G deployment in industries (Aijaz, 2020; Wen et al., 2022), thus enabling a shared network infrastructure. A decentralized network promotes disaggregation, interoperability, and vendor neutrality (Eswaran & Honnavalli, 2023). Cloud manufacturing and smart factories as a service, as new business models are enabled through highly reconfigurable dynamic network resources through network slicing capabilities for remote and flexible production (Taleb et al., 2019).

4.1.4 Edge Computing and the Industrial Internet of Things (IIoT)

Edge computing reduces the information processing delay by processing data closer to the IIoT sources. It improves privacy, data security, and energy efficiency, and minimizes the overall delay for mission-critical operations (Taleb et al., 2017), which is significant for real-time data processing (Wen et al., 2022). A multi-access edge (MEC) is a prominent feature of 5G that allows cloud-like capabilities near data aggregation points and sources, reducing the decision-making time owing to its proximity to operations (O'Connell et al., 2020; Taleb et al., 2017). Edge computing can coexist with a cloud environment by offloading heavy-duty analytics to the cloud while processing real-time data (Wen et al., 2022), with 5G handling data transfer and improving decision-making agility.

Cyber-physical systems in an IIoT environment require high data transmission, coverage, and connection density, with secure, reliable, and private connections that can deliver information rapidly in real-time (low latency) (Cheng et al., 2018; Cheng et al., 2024). 5G, enabled by virtualized network functions and decoupled services, can provide a security perimeter for protecting constrained wireless sensor network (WSN) devices that use lightweight protocols (Sasiain et al., 2020).

4.2 Human -Machine Collaboration

4.2.1 Human-Machine Interaction and Communication

Collaborative robots or cobots enable human-machine collaboration in factories and warehouses, ensuring a safe work environment through intelligent human presence detection and adaptive workload sharing (O'Connell et al., 2020). 5G's near real-time communication capabilities enhance this collaboration by facilitating task synchronization and coordination between humans and machines (Mourtzis et al., 2021; O'Connell et al., 2020). 5G wireless technology can help decongest factory floors by replacing

Ethernet cables (O'Connell et al., 2020) and improving worker safety and flexibility. Intelligent devices use the convergence of the core technologies of an industrial supply chain, such as artificial intelligence (AI), big data, and the cloud (Li & Wang, 2021), for autonomous decisions.

4.2.2 Machine-enabled "Reality"

5G, because of its high data speed and low jitter (unevenness in transmission), can unleash innovative virtual and augmented reality supply chain applications such as 1) remote expertise and learning: on-demand availability of knowledge and 2) remote maintenance and repair addressing operational disruptions with immediate intervention using a virtual knowledge repository and remote visualization (Cheng et al., 2024; French et al., 2020; O'Connell et al., 2020). Tactile internet, as a "network of networks," is meant for remote access and operation of devices in real time by human agents (Gupta et al., 2019; Mourtzis et al., 2021). An immersive experience helps improve operational agility and visibility, such as sensing operating conditions and quicker perception and manipulation of industrial objects (Cheng et al., 2018; Gupta et al., 2019), thus enabling workers to operate remotely in hazardous environments (Cimini et al., 2023). The network allows real-time cloud data transmission, facilitating cloud robotics and digital twin integration for synchronized physical-virtual operations (Cheng et al., 2024).

4.3 Platform Unification and Integration

4.3.1 Enterprise Integration

An "ecosystem-wide interoperability" and inter-organizational connectivity environment is necessary for pushing information to enterprise systems, such as enterprise resource planning and manufacturing execution systems, for real-time visibility (Varga et al., 2022).

4.3.2 Device Data and Cloud Integration

5G enables cloud-based big data processing and industrial automation through high-throughput machine data, device controllers, and industrial automation layer integration (Varga et al., 2022) to provide predictive insights. 5G is an integrative platform for controlling industrial applications with a guaranteed quality of service (Aijaz, 2020). Machine-to-machine (M2M) communication with ubiquitous sensors helps identify machine anomalies and issues (O'Connell et al., 2020), reducing operational disruptions. Cloud manufacturing operations facilitated by 5G integrated networks from devices to the cloud ensure operational and information technology (OT-IT) convergence (O'Connell et al., 2020). 5G integrates with global positioning systems (GPS), blockchain, and radio frequency identification (RFID), developing long-distance product tracking capabilities (Cheng et al., 2024).

4.3.3 Capability Integration

5G integrates disparate technology platforms, such as wireless, wired, satellite-based, low and high data rates and power consumption, types of radio spectrum (licensed or unlicensed), industrial communication platforms, such as time-sensitive Ethernet networks, and industrial enablers, such as the Internet of Things and cyber-physical systems. Seamless communication that integrates public and private 5G networks improves the local and global visibility of supply chains (Wollschlaeger et al., 2017).

4.3.4 AI and 5G – Unified Data-Driven Decision-Making

5G provides high-volume data from diverse sources for real-time actionable insights using the intelligent processing capabilities of artificial intelligence (AI) (O'Connell et al., 2020). Technology convergence ensures rapid high-volume data transfer for interpretation and visibility near data sources or in the cloud (O'Connell et al., 2020). AI and 5G convergence provide real-time data analytics capabilities (Cheng et al., 2024) and local interactive applications for collaboration and synchronized decisions (Wen et al., 2022).

4.3.5 Supply Chain Integration

5G's three essential capabilities are developing visibility, adaptable networking resource allocation, and ubiquitous connectivity, which facilitate agile product development and process reconfiguration (Dolgui & Ivanov, 2022). 5G as reliable connectivity can enhance rapid information exchange across integrated suppliers, customers, facilities, and supply chain logistics, imparting efficiency in supply chain operations and responding rapidly to dynamic and emergent supply chain conditions (Taboada & Shee, 2021). Next-

generation connectivity platform-enabled device data integration and rapid data transmission support applications, such as smart logistics for autonomous insight generation and consumption (Taboada & Shee, 2021; Varga et al., 2022), improve flexibility and agility.

4.4 Autonomous Business Operations

Industry 4.0 smart factories using the IoT and cognitive capabilities of cloud computing rely on the reliability of wireless, massive device-to-device connectivity, and rapid and low-energy processing of data (Taboada & Shee, 2021; Varga et al., 2020). Three use cases in an autonomous supply chain include (1) time-critical scenarios such as indoor real-time control of robots and drones that can benefit from 5G and time-sensitive network (TSN) technology integration (Rao & Prasad, 2018; Taboada & Shee, 2021; Varga et al., 2020; Walia et al., 2019; Wen et al., 2022). (2) Non-time critical, such as asset movement tracking or end-of-line inspection (Rao & Prasad, 2018), and (3) remote control of operations for employee safety and enablement (Rao & Prasad, 2018; Taboada & Shee, 2021; Varga et al., 2020). 5G-enabled connected goods and accurate positioning amplify the benefits of tracing and tracking operations in the supply chain (Taboada & Shee, 2021) and extend product life cycles through servitization (Rao & Prasad, 2018). Next-generation network-induced high reliability and bounded latency drive the remote control of supply chain equipment, remote monitoring, diagnostics of assets (O'Connell et al., 2020), and synchronized material movement in smart warehouses (Aijaz, 2020). New business models, such as on-demand manufacturing, emerge from network slicing, facilitating the dynamic configuration of networks and computing resources (Taleb et al., 2019), meeting the needs for internetworking and collaboration across devices, things, autonomous agents, and human workers, and ensuring secure, energy-efficient data-driven operations (Cheng et al., 2024). 5G features equip installed assets for self-diagnosing conditions, issuing alerts for services, and improving agility through predictive maintenance and remote inspection (Cimini et al., 2023).

4.5 Private 5G Adoption Ecosystem

Private 5G, also called Non-Public Networks (NPN), implies a dedicated spectrum and infrastructure for an enterprise facility and offers exclusivity in terms of network coverage, spectrum usage, and service customization for high availability and security (Aijaz, 2020; Eswaran & Honnavalli, 2023; Wen et al., 2022). A private 5G network is set up for one organization across single or multiple sites (Wen et al., 2022). It helps enterprises control their networks for greater privacy and security and cater to variable resource demands (Aijaz, 2020; Eswaran & Honnavalli, 2023; Wen et al., 2022). The network uses a regulatory body-funded dedicated licensed spectrum, such as citizen broadband radio service (CBRS) in the US and local spectrum in Germany, or a mobile network operator-provided spectrum in the mid-band (sub 5 GHz) (Aijaz, 2020). Deployment models can include a subscription to a public network with dedicated network-slicing resources (dual/campus networks), or the development of a dedicated enterprise network isolated from the public network (Eswaran & Honnavalli, 2023; O'Connell et al., 2020; Ordonez-Lucena et al., 2019). Network virtualization ensures enterprise control, customization opportunities, data security, and privacy (Ordonez-Lucena et al., 2019; Walia et al., 2019). Public-private network coupling ensures seamless outdoor coverage and service continuity, which is ideal for supply chains (Ordonez-Lucena et al., 2019). Resource commitment, investment capacity, and current automation levels help determine the deployment model (Eswaran & Honnavalli, 2023; Walia et al., 2019). A multi-access edge (MEC) can provide storage and computing for time-critical and latency-sensitive proximity-driven operations (Ordonez-Lucena et al., 2019). Appendix B presents the recommended deployment models for the partnership projects (3GPP).

4.6 Enterprise Adoption Considerations – Benefits and Challenges

4.6.1 Benefits

Private 5G lowers the cost of operations for enterprises through cloud-based network resources and scalable data transmission, enhancing the reliability of time-critical industry 4.0 operations (Varga et al., 2020; Varga et al., 2022). Data processing offloaded to a multi-access edge results in energy and data efficiency through cloud data volume reduction (O'Connell et al., 2020; Varga et al., 2022). Wireless technology offers benefits such as a manufacturing layout and mobility-driven flexibility in connecting devices (Aijaz, 2020; Cheng et al., 2024; O'Connell et al., 2020; Wen et al., 2022). Beyond operations, 5G offers strategic value that facilitates new business models (Dolgui & Ivanov, 2022) and opportunities for revenue sources, such as servitization or product and asset monitoring and maintenance as a service

(Cimini et al., 2023). Success factors include leadership, partner ecosystems, local empowerment, and regulatory support (Biswas et al., 2023). Enterprise private 5G provides added layers of security, data protection, control, and efficiency with dynamic resource allocation and customized use case-specific service quality (Aijaz, 2020; O'Connell et al., 2020) and facilitates digital platform creation, integrating with technologies such as IoT and blockchain (Dolgui & Ivanov, 2022).

4.6.2 Challenges

Challenges for smaller enterprises may include 1) the high cost of a private network setup that requires a commensurate business case, 2) the requirement of skilled resources to deploy and maintain next-generation networks, such as 5G, and 3) technical hurdles, including low penetration capabilities and interference from other radio signals or obstacles (O'Connell et al., 2020), interoperability with devices, and managing scaling of network resources (Li et al., 2018). High entry barriers for private networks include significant investments from enterprises (Ordonez-Lucena et al., 2019), whereas public networks create dependencies on network operators (Ordonez-Lucena et al., 2019). Managerial problems include 5G-relevant critical and valuable use-case identification justifying investments (Attaran & Attaran, 2020), knowledge and expertise (Cimini et al., 2023), and trust between the owners and operators of public and private networks (Wen et al., 2022). The availability of 5G-supported equipment, enabling legacy devices, and assurance of service continuity while ensuring mobility and data security are implementation bottlenecks (Wen et al., 2022).

4.7 Critical Analysis

Research clusters based on dominant themes include technology features, such as network slicing and software-defined networks (Sasiain et al., 2020; Varga et al., 2020; Walia et al., 2019), Industry 4.0, and smart factory business use cases and applications (Cimini et al., 2023; Gupta et al., 2019; Rao & Prasad, 2018; Taleb et al., 2019; Taboada & Shee, 2021; Varga et al., 2022), private 5G deployment (Aijaz, 2020; Eswaran & Honnavalli, 2023; Ordonez-Lucena et al., 2019; Wen et al., 2022), and economic and social value generation (Attaran & Attaran, 2020; Dolgui & Ivanov, 2022). While these studies address the technology features, business and industrial use cases, and applications of 5G in the Industry 4.0 supply chain, they do not adequately demonstrate areas where 5G can influence technology investment decisions or provide robust frameworks for evaluating business cases. Studies on business model innovation, such as servitization (Cimini et al., 2023) do not sufficiently depict how new models inspired by 5G's advanced capabilities can be assessed across various phases for fit and viability (Gilsing et al., 2022). Most conceptual research papers lack large-scale deployment success stories in private 5G adoption, making benefits and use cases, such as potential economic impact and justification for capabilities, such as network slicing, largely speculative. The exhaustive focus on Industry 4.0-based manufacturing industries and factories of the future raises concerns around generalizability. Given these limitations, this research explores a case that: (1) is not limited to a single industry, as ports function as industry-agnostic economic hubs; (2) illustrates a real-world success story involving both private and public 5G; and (3) puts together a compelling argument for demonstrable economic and social impacts.

4.8 Conceptual Framework

We map the concepts derived from the scoping review across three levels in the conceptual model presented in Figure 3: micro (firm or factory), meso (supply chain), and macro (society) (Daniel, 2022; Van Wijk et al., 2019). The multilevel perspective provides a descriptive theory of how high-speed next-generation connectivity enables societal transformation by rolling up through levels of technology-induced value creation. Figure 3 extends the framework shown in Figure 1 by identifying the factors and drivers of sustainability and resilience at higher abstraction levels. The conceptual model links to RQ1 on 5G's role as a critical unified data-connectivity-processing platform, enabling Human-Machine Collaboration and supporting autonomous business operations leading to seamless collaboration, integration, and optimization. Safety, energy efficiency, and real-time decisions, as 5G-enabled business outcomes, shape the societal value of innovation and empowerment (SDG goals) at multiple levels, improving adaptive and ecological resilience, facilitating transformation to a new, improved state, and meeting TBL goals.

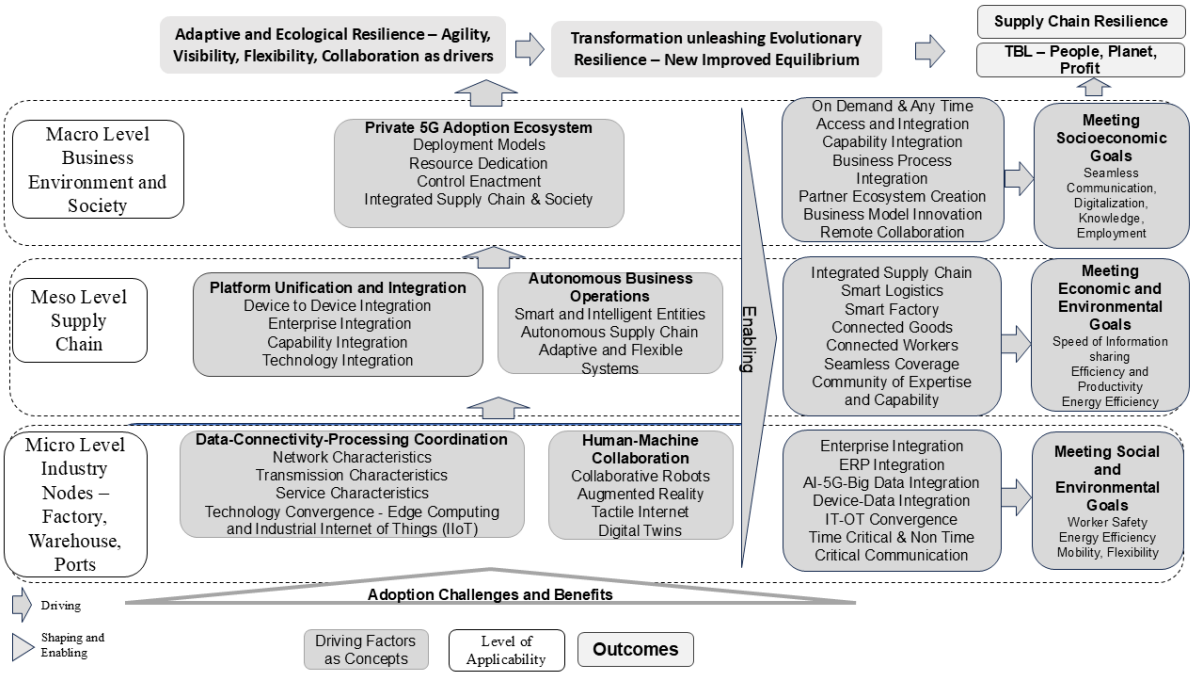

Figure 3. Conceptual Model Exhibiting 5G's Role as Sustainability and Resilience Driver

5 Case Analysis

Our case research deals with one of the largest container ports in Western Europe, located near an estuary. It handles different forms of cargo, annually, 9000 vessels, has 300 available berths, more than 50 barges, supports more than 7000 logistics companies, and has a large freight train network. It managed 8.7 million twenty-foot equivalent unit (TEU) containers in 2018. Closely affiliated with a nearby city, it manages more than 10,000 trucks daily, underscoring the need for efficient traffic governance. Therefore, the smart port infrastructure directly impacts the neighboring city's community development. The port authority adopted a policy for sustainable growth and initiated an adaptive smart port plan in early 2016. Despite severe disruptions from the pandemic and geopolitical crises resulting in delays and cancellations, the port is expected to grow to handle 18 million containers annually by 2025. To support this, a 5G testbed covering 8,000 hectares was established in 2018 for improved service quality, overcoming the inadequacy of legacy communication technologies to meet the stringent quality of services and data volume demand. Funded by the European Commission, the deployment enabled three network slices or different logical networks, enabling differentiated quality of services and dynamic resource availability, adapting to the needs of the individual use cases through 'network virtualization.' The port connects to a complex network of transport modes, such as waterways, road infrastructure, and railways. Governing and monitoring these critical assets and managing truck movements efficiently and autonomously are core business problems. The size of port operations requires skilled technicians to maintain and repair critical assets. According to the 5G Infrastructure Public Private Partnership (5G-PPP), a joint venture between the European Commission and European industry players, the major use cases include 1) autonomous centralized port and community traffic management with a dedicated 5G network slice ensuring reliability and real-time data analysis (ultra-reliability, low-latency 5G feature) for centralized monitoring and control, and improving safety and security for vehicles and commuters. 2) Augmented reality using HoloLens and the enhanced mobile broadband feature of 5G, ensuring on-demand availability of engineers for rapid actions, knowledge, and documentation for planning and monitoring construction, maintaining, constructing, and inspecting port assets, and ensuring the timely availability of remote experts on critical assets such as railway switches. 3) Real-time data from over ten thousand barge sensors (massive machine-type communication) for emission measurements to control air quality and hazardous substances and to improve community well-being. The massive deployment of sensors can detect any environmental condition in real time (less than 5 ms), such as the levels of gases emitted from the vessels. Integrated data from devices, such as traffic signals and barge sensors, are analyzed to ensure safety and green supply chain operations. Fixed and movable assets equipped with

sensors also measure and monitor the critical parameters of the condition and health of these assets, such as watergates, buoys, and bridges, thereby enabling predictive maintenance. Dual connectivity to two 5G base stations improves redundancy and coverage. The partner ecosystem-driven initiative acts as a consortium, with each partner bringing about its unique capability through telecom infrastructure operations, mobile networks, devices, and port operations. It is responsible for delivering next-generation communication solutions. The three use cases cater to the distinct needs of autonomous operations, human-machine collaboration, and data-connectivity-processing coordination for intelligent insights improving operational, social, and environmental conditions: safety and smart governance, emissions and pollution reduction, and knowledge and expertise availability. A key enabler of multiple use cases and their dynamic service requirements is the network flexibility offered by 5G network slicing. The deployment model provides a testimony to the criticality of 5G partner ecosystem capabilities and expertise. In addition, the 5G network is expected to improve and secure port operations, share data with business partners such as shippers, terminals, and industries, provide real-time vessel information for cargo maintenance, and facilitate the calling of vessels. The port is poised to become a 'living lab' by commissioning innovative use cases through business partnerships, such as autonomous trucks and automated coordination across the port logistics corridors, establishing a dedicated test track leveraging traffic infrastructure, automated driving and collision warning, automated truck platooning, and advanced driver assistance systems (ADAS). One of the largest container terminal operators partnered with a telecom service provider to deploy a 5G campus network in this port to secure logistics applications under the 'port as a service' project. Service models include container-handling automation and autonomous material movement by connecting a high volume of data to the cloud. A seamless handover across public and private 5G networks will ensure smooth coordination across port and hinterland communities. Port authorities have determined that organizational readiness is a key challenge in technology adoption, and collaboration and information sharing among partners are key success factors that drive deployment. The port reported an increase in container traffic after the pandemic, indicating its resilience. Living up to its commitment to sustainability, the port also explores cleaner alternative energy using hydrogen as fuel, and is concerned with protecting nearby ecologically sensitive regions. Our analysis reveals the following themes -

5.1 Driving Sustainable Innovations: Supply Chain Business Use Cases and Applications

The different business use cases discussed drive rapid decision-making and new business model innovation, such as data-driven analytics applications and the creation of social value by the 5G partner ecosystem using AI-driven applications. They help achieve operational excellence by minimizing human errors and incidents, improving real-time collaboration, and providing insights governing safety-critical applications. They provide the needed succor to the environment through sustainable practices and a safe and community well-being-centric work environment, fostering a value-centric community, transcending a complex and dynamic environment that is susceptible to disruptions. Innovations such as dual connectivity have improved reliability by catering to the mobility needs of sensors on floating barges. The campus network for the port as a service supports time-critical cases, such as autonomous material movement and seamless coverage with dual slices using public infrastructure for customer, employee, and business partner communication needs and private slices for critical port operations. The dedicated test track for autonomous vehicle movement demonstrates vehicle-to-infrastructure (V2I) applications using intelligent traffic assets and routing in the port hinterland, reducing congestion, encouraging safe driving, and driving business model innovations.

> "*The new standard will form the basis for solving tricky industry challenges and is the last push we need to make a breakthrough in digitalization*."

5.2 Shaping Community Welfare through Connected, Intelligent, and Autonomous Supply Chain

The deployment of 5G across various cases offers three significant capabilities: time-critical applications requiring millisecond-level latency, non-time-critical high-data-intensive use cases such as immersive experience, and seamless connectivity across multiple devices to improve visibility. Agility is affected by remote and autonomous operation enablement and a connected and digitally equipped workforce that utilizes high data throughput for improved service quality, faster automated task execution, and smooth communication. The connectivity backbone helps reduce environmental waste, minimizes human error,

and provides expertise and information on critical assets on demand, elevating operations and improving resource efficiency. High service availability is well-positioned to cater to the needs of smart ports, where uninterrupted, seamless communication coverage can elevate the experience of dependent industries such as shipping and logistics. Moreover, integration across technology landscapes, such as 5G with artificial intelligence, industrial IoT, and cloud computing, can drive real-time data processing, rapid decision-making capabilities, and the development of smarter, more resilient enterprise systems and processes, focusing on the continuous improvement of operations. Optimizing traffic flow is expected to reduce emissions and congestion in ports and hinterlands because trucks exhibit high fuel consumption. The digitalization initiative eliminates the travel time for hundreds of port engineers who can plan and monitor site assets and infrastructure from the main office, thus improving well-being and productivity through remote enablement.

5.3 Cocreating Value: Collaboration and Partnership Ecosystem Driving Deployment

Organizational information-sharing network design ensures internal and external collaboration within and across organizations, thereby improving visibility. Next-generation connectivity is crucial for improving information sharing by bringing every entity–devices, systems, employees, customers, partners, and suppliers–to a collaborative virtual platform that connects devices and systems to people and processes. As evident in this case, strategic collaboration results in a complex connectivity partnership network that steers real-time business model innovation and technological cohabitation. Collaboration initiatives extending beyond boundaries foster innovation by cocreating next-generation connectivity-led solutions and help scale test-bed initiatives to breach productivity frontiers. Other business partners, such as container service providers and shipping companies, provide critical inputs through their sensors and network convergence. Connecting their data to the parent network enables superior analytics capabilities, visibility of material flow, and tracking and response to emergent situations.

5.4 Improving Quality of Service Enabling Resilience and Sustainability Driver Interaction

5G delivers service quality, integrates many deployed devices, and enables a robust and secure network that is essential for mission-critical applications. Service isolation through network slicing ensures high privacy, data security, and uninterrupted connectivity, thus avoiding the network congestion that characterizes public networks. Network virtualization enables ease of maintenance and remote autonomous operation of devices, systems, and applications, protects sensitive data in critical industries, and caters to unique and dynamic resource needs. A multi-access edge (MEC) enabling proximity-based processing reduces latency to 10ms, thus supporting time-critical use cases. Legacy technologies, such as fiber cables, incur considerable costs for scaling or maintenance. A dedicated, reliable, high-speed cellular network offers flexibility and mobility and is cost-effective.

> "*5G network slicing" is an area that will have a particular impact on operations, laying the 'foundation for new IoT applications' and 'business models' that will boost the competitiveness of the entire port industry*."

5.5 Socio-Economic Transformation Landscape – New Equilibrium and Sustained Development

The landscape of port connectivity fosters transformative business models and unique capability integration among ecosystem partners. The outcome spawns an intertwined connectivity and collaboration framework that integrates all levels of the supply chain: machines, systems, processes, partners, and people. Digital transformation at the smart port level is driven by technology convergence and interdependence-led autonomous operations, as well as by overcoming legacy system challenges. It rolls up to the community level, transcending hinterland boundaries and unlocking significant growth potential. It improves visibility through seamless coverage, mitigates the technology risk of data protection, and fosters innovation and business model transformation from on-site to cloud-based virtual operations. The connectivity platform defines customer experience through unification and integration across multiple technologies and platforms, focusing on safety and people-centricity, and creating new avenues for value generation. The network can handle emergency response services during significant disruptions caused by environmental hazards that benefit the living community.

> "*Ports, in general, need to run smoothly and incredibly efficiently…we have demonstrated that 5G can play a big role in this regard*."

The case stands as a testimony to how public and private 5G deployment transforms a critical supply chain node, such as a port, from digitization and automation to spearheading community improvement, addressing RQ2. A smart port is resilient if it can continue port operations in the face of any unplanned disruption, termed viability (Padovano & Ivanov, 2025). The port analyzed may have other socio-economic and technological factors contributing to the resilience that has continued to shape and sustain its journey, focusing on hinterland transformation and superior service to the marine ecosystem. 5G, as a next-generation network, may add value by defining the resilience-sustainability overlap zone, where service innovation, partner integration, business process cloudification, and technology convergence help bring diverse community stakeholders and their interests on a common platform.

5.6 Conceptual Model Alignment

Benbasat et al. (1987), in their seminal paper on case study research in information systems pointed out that in case study research, in contrast to deductive studies, researchers may have "less apriori knowledge of the variables of interest." We have highlighted the inadequacies of the extant literature in our critical analysis (Section 4.7), which we bridged through case research. Our conceptual framework (Section 4.8) provides a nascent descriptive theory that follows Weber's (2012) guidelines for having constructs, concepts, their proposed associations, and states of ecological and evolutionary resilience as parts. The class comprises a next-generation connectivity system as a technology capability, and attributes such as platform unification and integration and human-machine collaboration define the class while interacting among themselves across the three levels, culminating as a transformative force developing ecological and evolutionary resilience. The a priori knowledge reflected in the framework derived from the scoping review can be further extended in the research context of the smart port to inculcate explanatory power moving beyond frameworks, to "guide managerial actions" (Benbasat et al., 1987), as represented in Table 3.

Table 3. Applicability of the Derived Themes in Smart Port

Themes	Context Specificity	Explanation -
Data-Connectivity-Processing Coordination	"*Being up to ten times faster than LTE with a maximum bandwidth of 10 Gigabit per second, and introducing isolated virtual networks – so-called 'Network Slices' – 5G is able to fulfill the extensive demands of the Smart Sea Port*." (D3) "*In another example, traffic lights have been linked to the mobile network and can be operated remotely by the HPA control centre in order to control traffic as it flows through the port. Trucks, for example, are guided quickly and safely around the site*." (D7) "*Environmental sensors installed on HPA ships provide real-time data on the current environmental status*." (D8)	Improving quality of service, enabling resilience-sustainability interaction, Data connectivity coordination ensures high data throughput and customized services catering to specific business cases with differentiated quality and resources needed by each operation. Responsiveness is ensured through on-demand resource provisioning Concepts Network Characteristics Transmission Characteristics
Human-Machine Collaboration	"*The engineers are supported in their day-to-day work with easy mobile access to construction plans and information on buildings and other technical installations within the port area, by on-demand provisioning of the available data and documentation through AR/VR applications on tablets or goggles on site." (D4)*	Shaping community welfare through a connected, intelligent, and autonomous supply chain is ensured through the collaboration of human experts and AR tools that provide information access in real time for critical maintenance tasks for community benefits Concepts Machine-enabled Reality
Platform Unification and Integration	"*The testbed includes mobile sensors on barges for emissions measurement. These are environmental sensors installed on HPA ships providing real-time data on the current air quality. The sensors are connected through the 5G mobile network with a dedicated slice. Enhanced maintenance experience: The*	Different technology platforms come together to deliver a unified experience serving different business cases co-creating value and shaping a collaboration and partnership ecosystem, and their unique skills and capabilities

	testbed also includes Augmented Reality (AR) applications for the port's engineering team connected via mobile broadband." (D13)	Concepts Device-Data-Cloud Integration Unified Data-driven Decision
Autonomous Business Operation	"*The connected traffic light requires very high reliability, which is only available so far with fiber connections. The goal is to operate and monitor the traffic lights remotely from the HPA control center to enable steering of the road traffic as it flows through the port*." (D12)	Autonomous traffic management systems in the port and hinterland shape community welfare and socio-economic transformation landscape, contributing to sustainable growth Concepts Smart and Connected Entities Use Case Drivers
Private 5G Adoption Ecosystem	"*Each company has to concentrate on the core values and competencies to secure the pole position or extend its business to increase diversity. It is very important that the partners in the ecosystems share some common goals*." (D17) "*Secondly, sustainable ecosystems are one of the key factors for digitalisation to succeed. The logistics industry is, by nature, complex and global. No company can really survive without collaboration with other organisations*." (D17)	Private 5G adoption drives value cocreation through ecosystem participation with the common goals around TBL realization and developing a sustainable ecosystem. Concepts Business Value Control Enactment

6 Discussions

Industry 4.0, supported by the superior network capabilities of 5G (Wollschlaeger et al., 2017), pioneers the digital transformation of industries, including connected products, integrated manufacturing and fulfilment, and collaborative machines (Pfohl et al., 2015). It builds technology capabilities at the factory and supply chain or organization levels to drive societal transformation at the industrial and socio-environmental levels. A supply chain is a complex socio-ecological system that develops resilience through adaptation (Wieland & Durach, 2021). The "adaptation and transformation" journey develops safety, productivity, knowledge, and information-sharing systems, collaboration, expertise, flexibility, agility, and employability as drivers and socioeconomic externalities promoting sustainability (El Baz et al., 2022). Resilience depends on rapidly detecting unexpected events and triggering an agile response for immediate corrections (Erol et al., 2010), such as supply chain reconfiguration (Ambulkar et al., 2015). Aligning technology capabilities and organization-level outcomes, such as collaboration, knowledge sharing, agility, flexibility, and visibility, influences resilience drivers (Pettit et al., 2013; Scholten et al., 2014) shaped by "renewal and reorganization" (Wieland & Durach, 2021) using connectivity technology as a lever for improving information sharing (Fawcett et al., 2007). It galvanizes growth and uplifts society to a newer and improved state (evolutionary resilience) through anticipated seamless communication and accessibility to digitalization, thus opening up new service vistas and opportunities (Eisinger Balassa et al., 2024). While paradoxical tensions between sustainability and resilience can be a research theme, "congruent capabilities" such as agility, collaboration, innovation, visibility, safety, and flexibility, among others, improve environmental, social, and economic performance (Warmbier et al., 2022). We propose that next-generation distributed data platforms aided by wireless connectivity, such as 5G, can influence this congruence and enable convergence, thereby addressing this paradox. Our research extends recent studies examining technology's role in smart ports, including Potter et al.'s (2024) business use case-driven analysis of 5G adoption barriers and enablers, Liu et al.'s (2024) investigation of technological advancement impacts on resilience and sustainability at Tianjin port, and Belmoukari et al.'s (2023) systematic review of smart port concepts emphasizing technology, sustainability, supply chain integration, and community infrastructure development. We incorporate insights from Verschuur et al. (2022) on the importance of resilience and climate risk management in protecting critical infrastructure, such as ports for the global supply chain, and Schneir et al.'s (2022) business case for 5G use cases in seaports. We contribute to the extant knowledge base by integrating across these studies to identify the role of the emerging I4.0 technology of 5G as a next-generation connectivity-driven unified data platform in building resilience-sustainability interdependency across organizational, supply chain, and societal levels.

Figure 3 depicts this idea in a concrete form and proposes a model based on the concepts derived from the review. Ecological resilience requires the building of flexible systems that can operate even when

severely disturbed (Erol et al., 2010). Technology capabilities, applications, and use cases such as cobots, digital twins, and virtualized platforms operate at a supply chain facility (micro) level, adopting an enterprise 5G roll-up to deliver societal transformation at the macro level, enabling safety, massive connectivity, ubiquitous communication, and business value generation (Eisinger Balassa et al., 2024). Platform and system unification and integration, human-machine collaboration enablers, smart and intelligent entities, and seamless communication at a meso (supply chain/organizational) level help shape intelligent operations, paving the way for an autonomous integrated supply chain and time-critical reliability-sensitive application use cases (Shim et al., 2022). In our smart port context, this is evident in the three use cases, which rely on massive integration, high data throughput, and low latency, thereby enabling a human resource pool of engineers and ensuring port-level operational efficiency. At the meso and macro levels, integration and technology convergence drive capability and business process integration, further accentuated by partner ecosystem creation as a business environment evolution and new dynamic business model innovation to achieve a new equilibrium state. The impact on the business and societal environment is manifested through the evolution of new business models that can spawn employment, growth, and revenue opportunities for holistic transformation to a new and improved state. Port resilience building involves identifying disruption events and assessing their impact on risk management and preparedness, as well as enabling responsiveness and adaptivity (UNCTAD, n.d.). In our case study, resilience is “embedded within infrastructure” as port assets must withstand disruptions and damages involving maritime logistics and connectivity to the hinterland (Notteboom et al., 2022). Resilience is also ensured through reliability or ‘failsafe’ operations. Ports should overcome natural climatic and man-made disruptions such as accidents and blockages (Notteboom et al., 2022). Therefore, safety measures are paramount, and autonomous operations enabled by reliable time-sensitive networks can help reduce errors and facilitate manual intervention. Figure 4 enhances the theoretical model based on the case study, morphing into a technology-organization-environment and multilevel digital transformation shaping resilience-sustainability, addressing the two research questions. RQ1 asks about 5G’s role in improving resilience and sustainability. This is explained through the technological capabilities that shape organizational capabilities, such as autonomous operations, unification, and integration affordances, resulting in an improved state of productivity and workforce enablement, while catering to the community's needs to drive sustainable value creation. RQ2 specifically calls out 5G’s influence in transforming critical supply chain nodes such as smart ports. This case illustrates how 5G testbeds and associated use cases have triggered a new equilibrium state in port operations and the hinterland by anchoring value and knowledge cocreation and transforming critical assets, such as roads and road infrastructure operations, enabling employee safety, seamless access and movement, and streamlined and responsive port maintenance and maritime operations. Digital transformation in supply chains creates value by reducing emissions while optimizing operational efficiency through socially responsible decisions on operations and risk management (Schilling & Seuring, 2024), as is evident from this case.

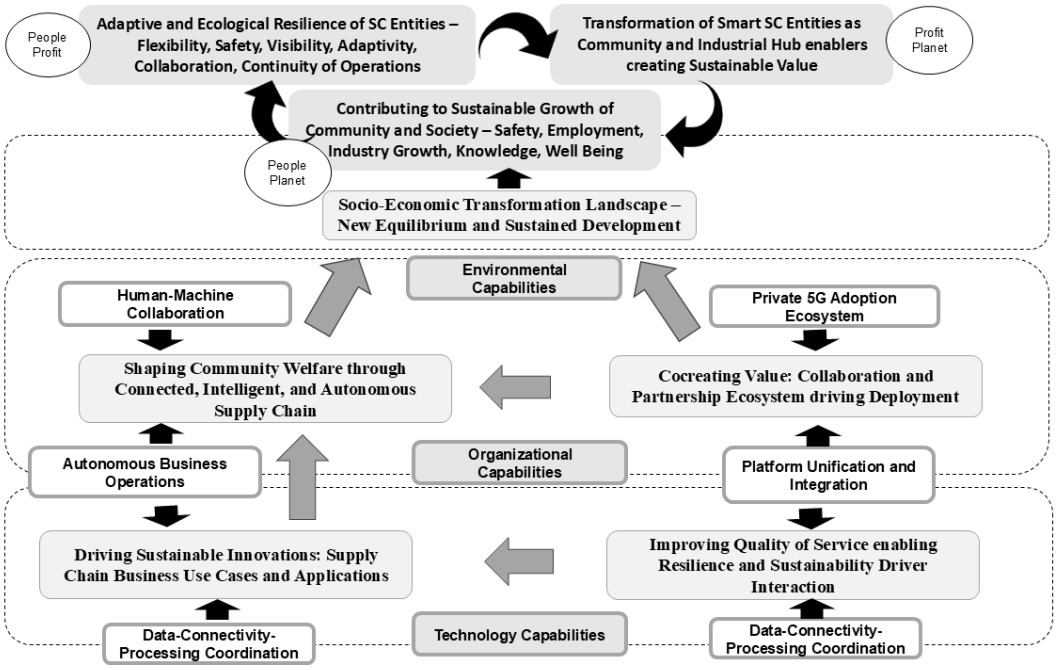

Figure 4. 5G-Induced Transformation Shaping Resilience and Sustainability in Smart Ports

Smart ports help self-organize industrial clusters and communities using digital technologies to analyze real-time data and optimize material and information flows, improving environmental and social resource governance (D'Amico et al., 2021), and affecting the TBL of people, planet, and profit. The model aligns with the Technology-Organization-Environment framework in technology adoption studies (Baker, 2012; Chatterjee et al., 2021). Technology (5G) in a smart port context (organization) influences society and the community ecosystem (port environment) to transform the interplay between sustainability and resilience drivers, such as flexibility, safety, visibility, collaboration, and knowledge. Our model builds on the recent frameworks such as that of Doetsch and Huchzermeier (2024) and Sharma et al. (2025) on sustainability-resilience interaction by incorporating both boundary transcendence and context specificity a) how multilevel transformation drivers and outcomes influence each other in a specific context of smart ports b) their impact on the TBL going beyond the performance measures such as profit c) influence of technology, organization, and environment capabilities in driving the interplay and thus providing a theoretical and empirical justification using a case study research, d) impact of different resilience types in shaping the interaction, and e) systematic review of literature to explore 5G's role in supply chain influencing the drivers. Sustainability may also relate to resilience through viability, which enables organizations to function during long crisis horizons, as demonstrated in the framework proposed by Padovano and Ivanov (2025). For port authorities, our conceptual model demonstrates how people (community empowerment), products (services), networks (partner ecosystems), and technology dimensions, as critical resilience components (Padovano & Ivanov, 2025), collectively contribute to sustainable, viable port operations by moving to an improved state of ecological resilience. For supply chain practitioners, our model demonstrates enabling "supply chain digital twins through seamless integration and real-time connectivity, which builds decision-making capabilities under uncertainty (Padovano & Ivanov, 2025). Data-connectivity-processing coordination and localization improve service quality and platform integration, connecting systems to influence collaboration and partnership ecosystems, and enhancing the ability to comply with regulations, such as supply chain-level emission (Scope 3) reports, which are critical for every industry. This brings cross-functional skills to the port's 5G testbed enablement. The interaction between sustainability and resilience enabled by 5G is played out at the intersection of drivers and enablers: collaboration, rapid information sharing, capability and expertise, safety, visibility, and agility at the organizational and societal environment levels. At the conceptual level, our systematic scoping review identifies the decisive role of capability integration unifying across technologies and challenges shaping the adoption roadmap. Our study corroborates the assertion that sustainability focus goes beyond profit-maximizing motives to transform into a holistic perspective balancing people, profit, and planet needs (Schilling & Seuring, 2024), which can be of interest to policymakers and regulators. The smart port case responding to RQ2 emphasizes ecosystem collaboration with diverse partner skill sets as a key factor

driving digital transformation and underscores the importance of resilience-sustainability interaction, which finds only passing reference in the reviewed literature, highlighting the differences in perspectives among academics, practitioners, and policymakers and offering an integrated reference.

7 Conclusion

7.1 Summary

In this study, we conducted a systematic scoping review of 1069 documents to identify research gaps in a critical technology area for digital supply chains and society. Our study identified pertinent concepts and developed a framework for 5G's applicability in driving transformation goals from twenty-eight documents based on thematic analysis. We aimed to understand 5G's applicability in improving visibility and agility to contribute to supply chain resilience and sustainable development goals. We represented the concepts as a multilevel model showing how 5G can potentially contribute to sustainability and resilience in a supply chain and drive TBL through mutual reinforcement and interactions among the driving factors. The proposed framework was extended and validated using empirical qualitative critical case research on a smart port based on a thematic analysis of 20 secondary documents, building an integrated theoretical framework.

7.2 Contribution

7.2.1 Theoretical

In this study, we provide a foundational theoretical model of 5G that can enrich supply chain research and the role of Industry 4.0, technologies along the sustainability, and resilience dimensions. Studies on port resilience are sparse (Liu et al., 2024). As port disruptions can affect hinterland trade and multiple stakeholders, including port operators, global businesses, shipping lines, and industrial hubs, research contributing to port resilience studies can benefit policymaking. The role of 5G in smart ports in developing supply chains and contributing to sustainability is one of the least explored areas. Our study provides an exploratory assessment of the state of research on 5G in the supply chain and society in smart ports, going beyond technological and conceptual contributions to derive an empirical framework following an inductive process.

7.2.2 Managerial Implications – Policy makers and Port Authorities

This study can help policymakers and industry leaders build business cases for adopting private 5G in organizations using resilience-sustainability convergence, as demonstrated in the critical nodes of smart ports, going beyond business cases for specific port operations in extant studies (Rendon Schneir et al., 2022). Our study demonstrates that next-generation connectivity technologies (5G) reshape the interdependence of supply chain resilience and sustainability at critical infrastructure nodes, such as smart ports. Through a three-tiered analysis of operational facility workflows, organizational decision-making systems, and societal impact frameworks, we identified how advanced connectivity enables the alignment of disruption preparedness and environmental stewardship. This research provides policymakers and port operators with a unified, data-driven methodology to 1) qualify trade-offs between resilience investments and sustainability outcomes and 2) justify technology adoption through multi-stakeholder value mapping. This work bridges the theoretical discussions of Industry 4.0 with practical implementation strategies for next-generation port ecosystems.

7.2.3 Managerial Implications – Supply Chain Executives

The managerial implications for this study include: 1) developing integrated business investment needs to deploy next-generation connectivity infrastructure with differentiated quality of service capabilities in supply chain nodes through the prism of multilevel transformation, rather than focusing only on micro or meso levels of productivity and efficiency that may not justify technology costs; and 2) understanding the value realized from data and computing localization and privacy, collective resilience at a community level, and value cocreation with a stable partnership ecosystem defying traditional mindsets and focusing on TBL. As Doetsch and Huchzermeier (2024) point out, an integrative approach to sustainability and resilience calls for reconciliation among strategic objectives beyond meeting compliance needs, including adopting common success metrics to overcome barriers to technology investments.

7.3 Limitations

Technology adoption decisions should be accompanied by a holistic assessment of their impact on "economic vitality, ecological integrity, or community well-being" (Fiksel, 2006). Our research focuses primarily on secondary data sources that may not reconcile conflicting perspectives. Interviewing diverse participant stakeholders in a smart port context can provide richer insights to strengthen the framework and make it more relevant for practice. Our empirical study, based on secondary data sources, can be augmented by the opinions of experts and industry analysts. Multiple case studies (Eisenhardt, 1989) on 5G in smart ports can be conducted to improve analytical generalizability. For an integrative evaluation of 5G's impact on sustainability and ecological resilience, we should study policy documents, whitepapers from regulatory authorities, standards bodies such as 3GPP, and consultant reports, in addition to the academic literature. The study may have omitted critical texts in identifying the inclusion and exclusion criteria and selecting the content for thematic analysis. Themes and concepts are subject to various interpretations.

7.4 Research Opportunities

While technology, standardization, and policy formulation research should focus on 5G, the scope can diversify into emerging areas, such as 5G's role in inter-organizational information sharing and collaboration, empirical studies on 5G adoption, action research in building adoption roadmaps, value creation, ecosystem enablement, and supply chain visibility. A longitudinal study on a 5G adoption case can help establish the credibility and viability of our framework along a temporal dimension. A 5G adoption study and its impact on the supply chain using case research has the potential to uncover issues, challenges, and contributions to productivity and efficiency improvement, and empirically establish a mid-range theory. For business cases, researchers and policymakers need to explore TBL metrics beyond financial metrics, such as their impact on people and the planet.

Declaration of Conflict of Interest

The authors declare no potential conflicts of interest concerning this research, authorship, and/or publication.

Data Availability Statement

The authors confirm that data sharing does not apply to this paper, as no new data were created or analyzed in this study. Data supporting the finding are available within the paper, except codes.

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Appendix A: Inclusion and Exclusion Criteria

Table A1. Inclusion and Exclusion Criteria

Scope	Criteria
Inclusion	5G, private 5G, 6G in industry 4.0, edge computing application, edge AI, multi-access edge, 5G applications in supply chain, logistics, smart factories, and industry 4.0, AI applications using 5G, emerging technology in industry 4.0/5.0, 5G applications such as tactile internet, digital twins, 5G components - Time-sensitive networking, network slicing and multi-access edge applications, connectivity in supply chain, 5G-enabled applications such as automated guided vehicles
Exclusion	Technical or engineering related such as mmWave or 5G antenna, network technology, O-RAN or Open Radio Access Network, AI and machine learning in 5G telecom network, telecom infrastructure and equipment, technology architecture of components (software-defined network, time-sensitive network, beamforming, massive input and massive output (MIMO), network slicing), standards and policies, spectrum, 5G network engineering (wireless channel management), algorithms, network optimization, telecom infrastructure consumer IoT such as LoRaWAN, resource orchestration in telecom network, containerization in deploying network software Technology Integration with emphasis on the other technologies: blockchain, UAV, drones, metaverse, virtual reality, security, cybersecurity, IoT without 5G, tactile internet, automated guided vehicles and robotics without 5G, Applications: smart cities and smart ports, sustainability, Smart grids, digital twins, cyber-physical systems, Cloud computing, Smart Water, connected and autonomous cars, applications such as

Appendix B: Deployment Model

Table B1. 5G Deployment Models (3GPP)

Deployment Features	Types	Impacts
Spectrum Allotment (Eswarana & Honnavalli, 2023, Wen et al. 2022)	Licensed spectrum of very high (mmWave or millimeter Wave) frequency ranges	Very high data speed High cell density Low signal penetration
	Unlicensed spectrum	High flexibility and interference Low Reliability
	Shared spectrum (local)	Dedicated enterprise access Low investment level High responsibility and ownership level, better control
Network Ownership (Eswaran & Honnavalli, 2023)	Dedicated Private Independent Network	High privacy and security, high coverage and control
	Public Network	Low investment, seamless coverage, mobility
	Campus Network (hybrid, private network sliced from public)	End-to-end coverage, lesser flexibility, security Lower investment as compared to dedicated private
Management and Operations (Wen et al., 2022)	Mobile Network Operator provided	Dependent on the network operator for spectrum, services, quality, and availability
	Enterprise owned	Fully controlled, high Capex, low Opex
	Shared Responsibility	Flexibility, focus on core competence

Appendix C: Case Analysis Data

Table C1. Case Analysis Samples Selected

Document Name, Author, Year	Code	Type	URL
Starting signal for the project 'Giganetwork 5G MoNArch	D1	Newsletter	https://www.hamburg-port-authority.de/en/themenseiten/monarch-5g/
Connected container terminals, 2023	D2	Blog	https://www.hafen-hamburg.de/en/press/news/connected-container-terminals/
Port of Hamburg – 5G-MoNArch, 2019	D3	Report	https://sustainableworldports.org/project/port-of-hamburg-5g-monarch/
Smart Sea Port Use Case	D4	Use Case	https://5g-monarch.eu/smart-sea-port-use-case/
Connected container terminals: Telekom builds 5G campus networks for EUROGATE, 2023	D5	Newsletter	https://www.telekom.com/en/media/media-information/archive/telekom-builds-5g-campus-networks-for-eurogate-1047880
Nokia, Deutsche Telekom and Hamburg Port Authority collaborate in 5G research in industrial environment, 2018	D6	Newsletter	https://www.nokia.com/about-us/news/releases/2018/02/02/nokia-deutsche-telekom-and-hamburg-port-authority-collaborate-in-5g-research-in-industrial-environment/
"THE PORT OF HAMBURG, A 5G TESTING GROUND"	D7	Report	https://www.porttechnology.org/wp-content/uploads/2019/05/HAMBURG-83.pdf
"5G Mobile Network Architecture Hamburg Smart Sea Port Testbed"	D8	Report	https://5g-mobix.com/assets/files/5G-MoNArch_CAM_Smart_Sea_Port_Testbed_210603_125410.pdf
Hamburg Living Lab	D9	News	https://5g-loginnov.eu/hamburg-living-lab/
Port of Hamburg Tests 5G	D10	Report	
Insight: The Dawning of 5G	D11	Article	
5G Smart Sea Port: Hamburg Port Authority	D12	Report	https://govwhitepapers.com/whitepapers/5g-smart-sea-port-hamburg-port-authority
5G-MoNArch: 5G Smart Sea Port	D13	Report	https://global5g.org/5g-monarch-5g-smart-sea-port
Port of Hamburg: An old port thriving in today's world	D14	Article	https://spire.com/blog/maritime/port-of-hamburg-an-old-port-thriving-in-todays-world/
Deutsche Telekom implements campus network for the Port of Hamburg, 2021	D15	News	https://www.rcrwireless.com/20210628/internet-of-things/deutsche-telekom-implements-campus-network-port-hamburg
Port of Hamburg Hails 5G Success, 2024	D16	News	https://www.worldports.org/port-of-hamburg-hails-5g-success/
smartPORT Hamburg: embracing port digitalisation	D17	Article	https://www.innovationnewsnetwork.com/smartport-hamburg/600/
Take me to the river	D18	Article	https://www.landmobile.co.uk/content/features/take-me-to-the-river
5G INFRASTRUCTURE PPP	D19	Report	5G PPP Report on 5G Use Cases MoNarach
Smart and Resilient Cities and Ports. Perspectives for Hamburg, 2015	D20	Article	https://portusonline.org/smart-and-resilient-cities-and-ports-perspectives-for-hamburg/

Appendix D: Theme Derivation Illustrative Example

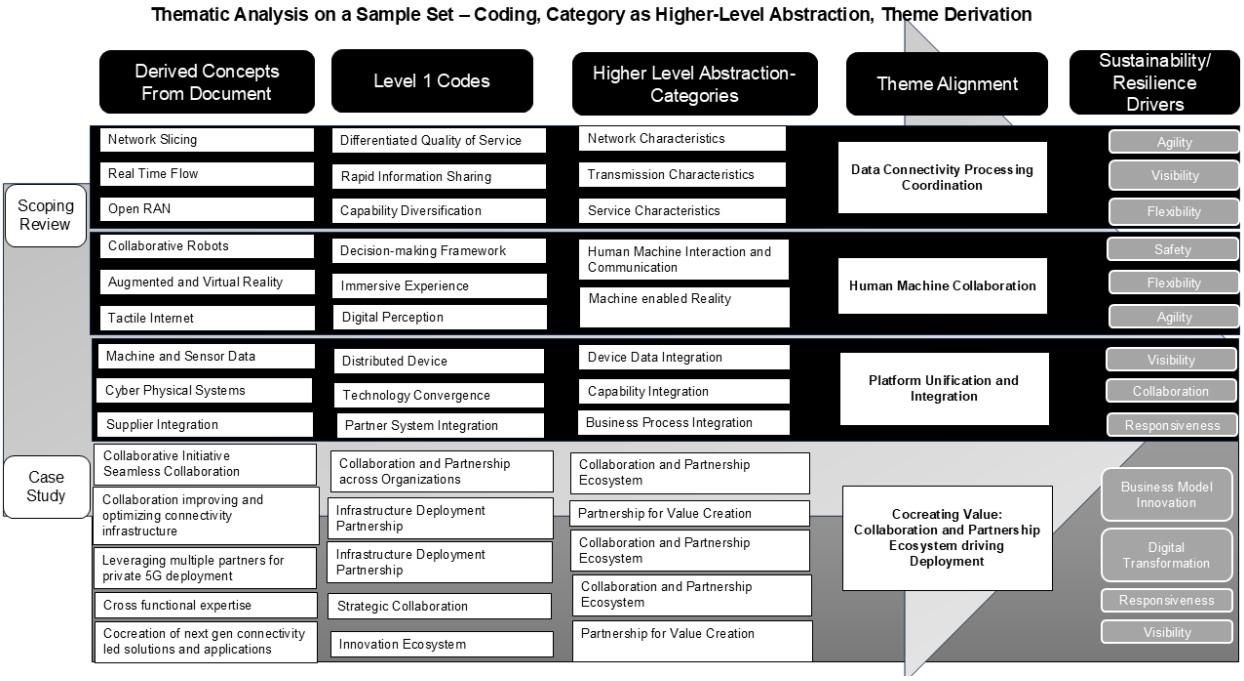

Figure D1. Overall Conceptual Framework

Appendix E: Bibliometric Analysis

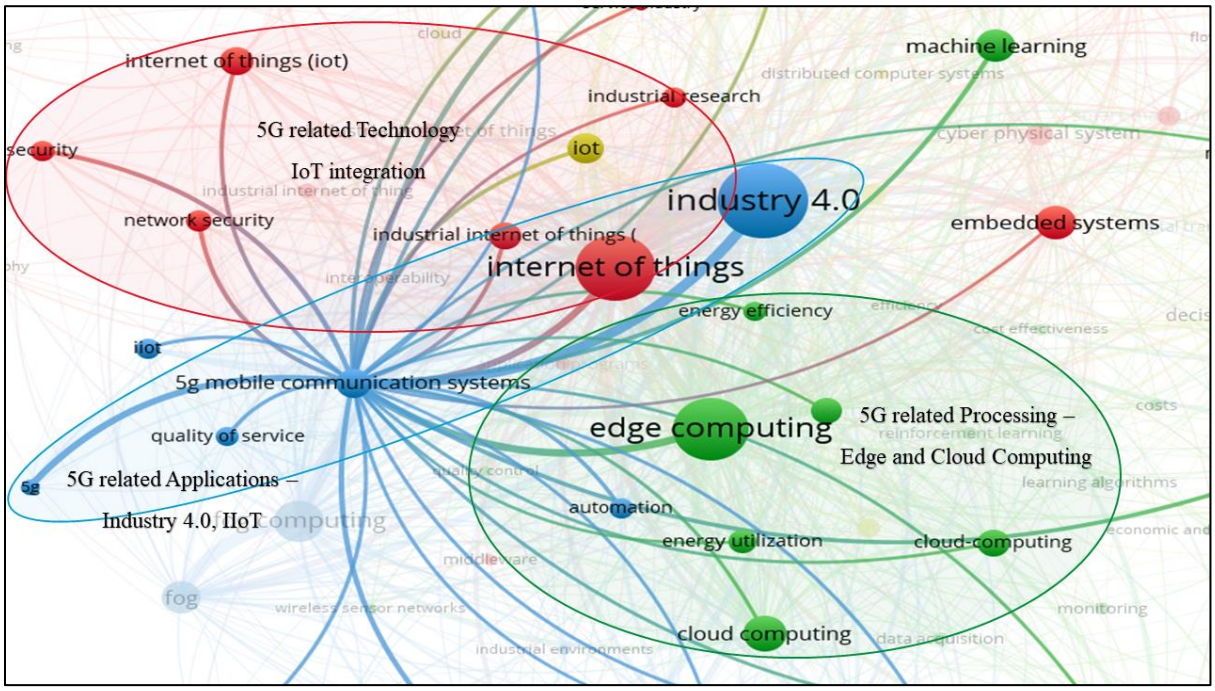

Figure E1. 5G's Strong Association with Edge and IIoT – Cooccurrence Analysis in VoSViewer

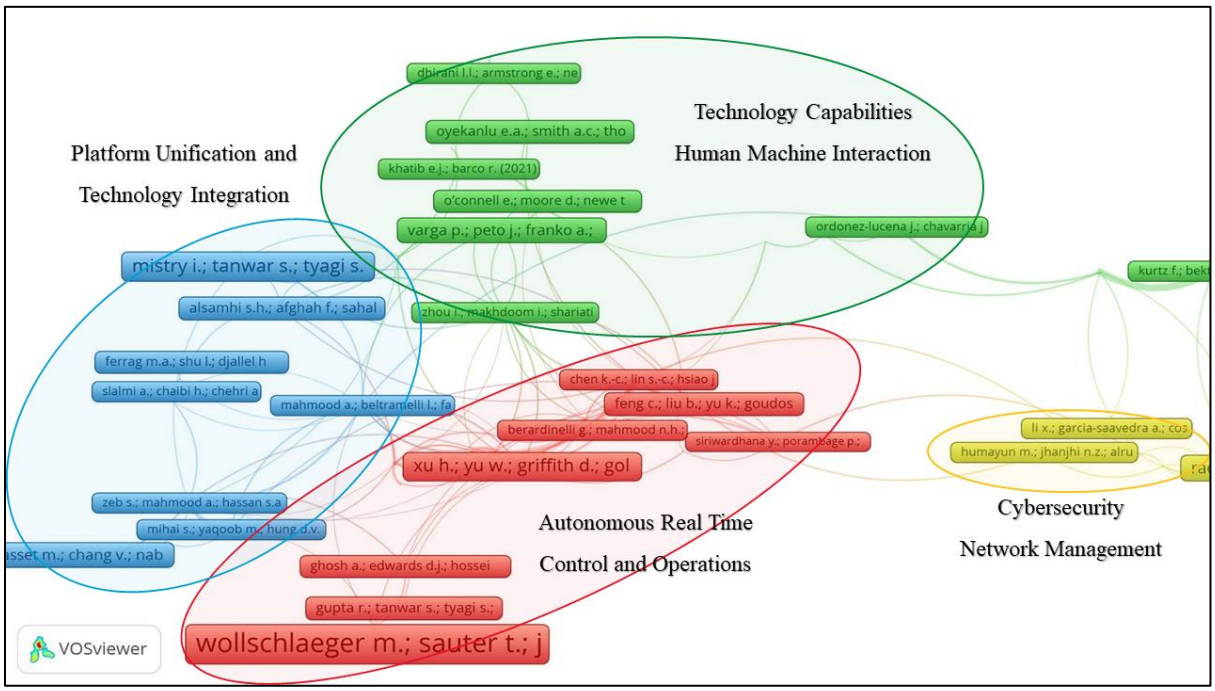

Figure E2. Bibliometric Coupling – Support for the Themes Using VoSViewer

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