Maritime Policy & Management
The flagship journal of international shipping and port research
ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tmpm20

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To cite this article: Andrew Potter, Yingli Wang & Mohamed Naim (16 Sep 2024): Scaling-up 5G adoption in smart ports: barriers and enablers, Maritime Policy & Management, DOI: 10.1080/03088839.2024.2399524

To link to this article: https://doi.org/10.1080/03088839.2024.2399524

Published online: 16 Sep 2024.

MARITIME POLICY & MANAGEMENT
https://doi.org/10.1080/03088839.2024.2399524

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Scaling-up 5G adoption in smart ports: barriers and enablers

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ABSTRACT

As the fifth generation of mobile communication technology, 5G is predicted to be a significant focus for investment by the logistics industry in the coming years. One area where it is expected to have a significant impact is ports, enabling further digitization and the development of Smart Ports. The aim of this paper is to investigate the barriers and enablers to 5G adoption, focusing on the UK port industry. Data has been collected from nine senior representatives from the UK port sector as well as two technology providers. Potential use cases are identified, along with barriers and enablers to their adoption. These including building a business case with appropriate use cases, the trade-off between legacy systems and 5G capability, technology maturity, skill development within the workforce, and the role of government in supporting innovation. This work contributes by giving insights into the challenges when introducing 5G within the port environment. Research of 5G applications in logistics currently focuses more on the technological applications rather than the business implications from adoption.

ARTICLE HISTORY
Received 31 December 2023
Accepted 6 August 2024

KEYWORDS
Digitization; use cases; logistics; wireless communication

1. Introduction

Ports are a vital component of supply chains, facilitating the movement of imports and exports. The efficiency of port operations is crucial in ensuring the seamless flow of goods. Over the past three decades, the integration of technology into port operations has been significant (Inkinen, Helminen, and Saarikoski 2021). While many port processes have traditionally been very manual and labour intensive, technological developments have offered significant opportunities for efficiency gains and therefore a move towards digitalization and Smart Ports has occurred, albeit not in a uniform manner within the sector.

The latest generation of ports, known as Smart Ports, are ports that use advanced technologies to optimize their business operations (Li et al. 2023). Yau et al. (2020) identify three attributes that combine in a Smart Port—components of the information system, use cases, and performance measures. The components of the information system include sensors, wireless devices, data centres, communication networks, and automation technology (Y. Yang et al. 2018; Yau et al. 2020). These are then used in use cases that monitor and manage operations across the port activities including vessels, cargo, energy, and resources. While Smart Ports are often coordinated by port operators, Inkinen, Helminen, and Saarikoski (2021) recognise that the wider port community (such as shipping lines, logistics providers,

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and customs) are also integrated into the use cases. Finally, performance is focused not just on operational efficiency and effectiveness, but also safety and sustainability (Li et al. 2023; de la Pena Zarzuelo 2021).

The emergence of the fifth generation of mobile communication technology (5G) is seen as a key enabler of Smart Ports, because it provides the high-speed, low-latency, and reliable wireless connectivity required for these advanced technologies to function effectively. There is much interest in the potential use cases that can be enabled by 5G in logistics (Verma and Lalwani 2019; Wang et al. 2022), and these are typically characterized in one of the three scenarios:

- Massive Machine-Type Communications (mMTC), where large numbers of devices use wireless networks to communicate with each other. Catering specifically to the communication needs of the Internet of Things (IoT), mMTC prioritises efficient connection management for a vast number of low-power devices with limited data transmission requirements. This enables the creation of large-scale sensor networks for applications in smart cities, smart ports, industrial automation, and remote monitoring, ultimately fostering a more interconnected and data-driven world.
- Ultra-reliable low latency communication (URLLC), acts like a high-speed, guaranteed delivery service for critical data. Unlike waiting for a regular package, URLLC ensures information gets delivered almost instantly and very reliably. This caters to applications where even a slight delay or error can be catastrophic, such as remote surgery, autonomous vehicles, and industrial control systems. By prioritizing reliability and speed, URLLC paves the way for a new era of real-time data exchange in mission-critical applications.
- Enhanced Mobile Broadband (eMBB) focuses on significantly boosting data speeds and capacity compared to 4G. This allows for activities like high-resolution video streaming, ultra-responsive gaming, and immersive virtual reality experiences, fundamentally transforming how we use mobile data and opening doors for new applications that demand high bandwidth.

This categorisation highlights how 5G is an enabler of digitization through use cases, rather than being a solution on its own. Use cases provide narratives which demonstrate the sequence of activities that enable a system to deliver value to users, capturing the complex dynamics related to system requirements that are found from design through to implementation (Bittner and Spence 2003). The use case approach has proved popular in communicating the benefits of 5G to industry sectors (for example, see Hofman 2023).

The logistics industry is expected to invest heavily in 5G technology in the coming years (Reuters Events 2021), particularly in the context of ports. The integration of 5G is expected to further facilitate digitization and the development of Smart Ports. However, the port industry is known for struggling with innovation (Acciaro et al. 2018), despite the competitive advantages that can be gained for performance (Hazen and Byrd 2012), as well as in addressing important aspects such as sustainability (Björklund and Forslund 2018) and risk management (Kwak, Seo, and Mason 2018). Consequently, the application of 5G in ports is still in the nascent stages of deployment. Clearly understanding the enablers and barriers that could accelerate this deployment is of benefit for port operators and technology providers alike.

Given the above, the aim of this paper is to examine the factors that hinder or promote the adoption of 5G by ports. While the use cases and their potential are often the focus of research, there has been less focus has been on the adoption of information system components. Mobile communication networks are a key integrator of hardware and software, and therefore examining the transition to 5G can provide wider insights into Smart Port development. More generally, there is also a lack of management research in relation to the use of 5G in logistics applications (Taboada and Shee 2021). We particularly focus on the UK, which has one of the largest port industries in Europe in terms of volume handled with a wide range of port sizes and a diversity of business ownership models.

The paper proceeds by reviewing literature relevant to the research questions before detailing the method adopted in collecting relevant data. We then present the findings, focusing first on the potential use cases being considered by UK ports before exploring the enablers and barriers. The findings are discussed and conclusions drawn. In doing so, we highlight the academic contribution of the work as well as several potential managerial implications.

2. Literature review

To address the research aim, we draw on two bodies of literature. The first relates to Smart Ports and the use cases that feature within them, while the second identifies a range of barriers and enablers to digitization.

2.1. Use cases in smart ports

As ports grow more digital, we witness a variety of digital technologies being deployed to enhance port operations. However, all such digitization efforts necessitate a robust wireless communication network to enable secure, real-time transmission of large amounts of data. In this context, 5G technology emerges as a key enabler for smart ports and port digital transformation (Wang et al. 2022). The high-speed, low-latency capabilities of 5G not only support the seamless integration of diverse digital systems within the port environment but also enable the implementation of emerging technologies. The adoption of 5G in smart ports not only enhances operational efficiency but also lays the foundation for a more connected and responsive maritime ecosystem (DHL 2020). Table 1 demonstrates the wide variety of different use cases considered for smart ports in the literature and categorises them according to the 5G scenario that most closely aligns to these. Further, examples where 5G is being used to enable the use case are also highlighted.

In terms of mMTC, port use cases see sensors used in a variety of different applications to monitor the whereabouts and/or condition of vessels, road vehicles, equipment, cargo, and the natural environment within the port (Heilig, Lalla-Ruiz, and Voβ 2017; Inkinen, Helminen, and Saarikoski 2021; Molavi, Lim, and Race 2020; Y. Yang et al. 2018). As Parola et al. (2021) note, these types of use case are the most developed for Smart Ports, and several ports have started using 5G as an enabler for these use cases. At Zeebrugge, 5G has been used to track vessels and monitor the natural environment (Port of Antwerp Bruges 2020), while Felixstowe has trialled condition monitoring on dockside cranes (Port of Felixstowe 2021). A trial involving Bristol has seen sensors installed in a container to monitor the location and condition of cargo throughout the port (WECA 2022).

URLLC type use cases tend to focus on process automation within the port, through robotics and remote control (Inkinen, Helminen, and Saarikoski 2021; Parola et al. 2021). 5G is beginning to be used in these use cases, including remote controlled cranes in Busan (Port Technology International 2021) and Qingdao (Ericsson 2021), and the use of automated guided vehicles (AGVs) in Livorno (Cardone 2020). As well as process-based use cases, drones are another example of a URLLC use case, and are often being used for safety and security applications (Inkinen, Helminen, and Saarikoski 2021). Again, 5G is being used to enable these cases with trials in Riga (Port Technology International 2019) and Bristol (WECA 2022).

There are a variety of Smart Port use cases that require high rates of data transfer that characterize eMBB scenarios. Some use cases are based around the communication of video data, both directly and as virtual or augmented reality (VR/AR) (Parola et al. 2021), while there are also use cases dependent upon data sharing and/or decision support systems (Heilig, Lalla-Ruiz, and Voβ 2017; Pavlić Skender, Ribarić, and Jović 2020; Yau et al. 2020). Examples where 5G is being trialled include at Antwerp, with video streaming from tugboats, allowing safer movement of vessels within the confines of the port (O'Halloran 2020). In Hamburg, 5G is being used to control traffic

Table 1. Smart port use cases (adapted from Heilig, Lalla-Ruiz, and Voβ 2017; Inkinen, Helminen, and Saarikoski 2021; Molavi, Lim, and Race 2020; Parola et al. 2021; Pavlić Skender, Ribarić, and Jović 2020; Y. Yang et al. 2018; Yau et al. 2020).

Type of 5G application	Port waters	Sea/land transfer	Internal port movement	Port storage	Port arrival and departure	Other
mMTC = Massive Machine-Type Communications	• Tracking and sensor measurement on barges and tugs* • Trajectory estimation	• Sensors to monitor cargo* • Monitoring and managing equipment* • Container cone detection	• Sensors to monitor cargo* • Monitoring and managing equipment • Container and cargo location detection* • Vehicle tracking and locating	• Sensors to monitor cargo* • Monitoring and managing equipment • Container and cargo location detection* • Vehicle tracking and locating	• Container and cargo tracking and locating* • Vehicle tracking and locating	• Monitoring environmental impacts* • Energy management
URLLC = Ultra-reliable low latency communication	• Autonomous ships	• Robotics • Remote control of cranes*	• Robotics • Remote control of cranes* • AGV navigation*	• Robotisation		• Drones*
eMBB = enhanced Mobile Broadband	• Streaming video from tugboats* • Dredging optimization	• Artificial intelligence-based resource allocation, planning and scheduling	• Traffic control centres*	• Augmented reality		• Information sharing platforms • Data inter-change for paperless customs • Remote site support using VR/AR*

*= Examples found of 5G enabled use cases.

flows around the port, to avoid delays and improve air quality, as well as to support VR and AR applications for on-site maintenance support (Rost et al. 2018).

While there has been an increase in digitization during the past 20 years, Parola et al. (2021) highlights that there are trends within this development. Sensor-based technologies (effectively mMTC-type use cases) have featured for the longest period, with automation (URLLC) becoming more prevalent throughout the 2010s. eMBB-related use cases have emerged from the late 2010s, although use cases using technologies like AR remain scarce. In terms of where applications occur, Anwar, Henesey, and Casalicchio (2019) emphasise the greatest focus is on intra-port and quayside activities

As well as understanding what technological solutions are being developed for Smart Ports, it is also important for use cases to have a purpose—in effect, the performance measure attributes discussed by Yau et al. (2020). Through their systematic literature review of the use of digital technologies in maritime supply chains, Parola et al. (2021) identify three main categories of benefits—efficiency within operations, better customer service, and improved decision-making—and these are reflected in many of the studies covered in this paper. However, there are other benefits that Smart Port use cases can bring. As noted when describing the cases, safety and security can improved, through improved monitoring capabilities and automation of processes (Carlan et al. 2017; Chu et al. 2018; Yau et al. 2020). Finally, a number of authors highlight the opportunities for improving environmental performance (Del Giudice et al. 2022; Inkinen, Helminen, and Saarikoski 2021; Molavi, Lim, and Race 2020) through energy efficiency measures as well as monitoring and controlling the discharge of harmful substances.

2.2. Barriers and enablers to digitization

We now summarize the main factors that act as barriers or enablers to digitization, drawing both from port literature and more widely. In doing so, we acknowledge the observation in Carlan et al. (2017), 89) that there is 'no unique "recipe" for innovation success.' A wide variety of factors have been identified in the literature and are clustered here into some key themes—government, strategic alignment, knowledge capabilities, technology, costs and benefits, and cooperation. We do not explicitly separate barriers and enablers because the themes often contain conflicting factors. However, a feature of the literature, which is also reflected in Tijan et al. (2021) is there is a stronger emphasis on enablers compared to barriers.

Looking outside the firm, a key enabler is for the government to encourage digitization. Ports can play a significant role in their local economy, and therefore policy-makers look to maintain competitiveness through various measures including digitization (Inkinen, Helminen, and Saarikoski 2021). There may also be a role for government in supporting the implementation of standards (Chu et al. 2018) although this has been questioned by Carlan et al. (2017). Customer demand can also be an important enabler for digitization (Tijan et al. 2021). This may be through identifying use cases which can lead to market opportunities (Neokosmidis et al. 2017) or where the market requires port operators to have particular technologies (Carlan et al. 2017; Grover and Goslar 1993).

Several authors highlight the importance of strategic alignment between the overall strategy of the firm and its digital strategy as an enabler (Carlan et al. 2017; Heilig, Lalla-Ruiz, and Voβ 2017; Won and Park 2020). A prerequisite to this is having a digitization strategy to start with, and this is not always the case in the port sector (Tijan et al. 2021). Where a strategy exists, alignment means that organisational support can be easier to achieve as investment in digitization matches overall company goals. However, ports can often be characterized by functional silos between different parts of the organization (Chu et al. 2018), and this can then lead to misaligned objectives, hence acting as a barrier to change.

An organization's digital strategy will often reflect the knowledge capabilities of the firm in relation to digitization. In the telecommunications domain, several authors have highlighted the importance of having this capability as an enabler for deployment (Boullauazan, Sys, and Vanelslander 2023; Neokosmidis et al. 2017; O'Connell, Moore, and Newe 2020). This has also been observed in the port digitization literature (Carlan et al. 2017) and can be a challenge to address. In terms of barriers, Chu et al. (2018) noted that ports can face difficulties in recruiting the specialized technical engineers required to support digitization, notwithstanding that demand for these engineers often outstrips supply. There can also be resistance to change within the workforce, either reflecting cognitive issues associated with a lack of knowledge or an emotional response due to perceptions and assumptions (Raza et al. 2023; Tijan et al. 2021).

Technology can also act as an enabler and barrier to digitization within the port sector. New technologies are considered by some authors to be a driver of digitization (Tijan et al. 2021). For example, C. S. Yang and Lin (2023) demonstrate that being a member of a digital logistics platform can enable digitization. There are barriers, however, with a lack of standardization within the sector coupled with the frequent use of legacy systems that may not be compatible with newer technologies (Inkinen, Helminen, and Saarikoski 2021; Raza et al. 2023).

The costs and benefits of an investment decision are also frequently considered in terms of barriers and enablers (Lin et al. 2014; O'Connell, Moore, and Newe 2020). In terms of costs, entry costs are particularly identified as a barrier in the port sector (Chu et al. 2018), given the narrow margins of operators (Carlan et al. 2017). In the context of the port industry, a major barrier is the uncertainty around the benefits from digitization and this then reduces the confidence of the port operator to invest in the enabling technologies (Chu et al. 2018; Heilig, Lalla-Ruiz, and Voβ 2017). This is despite reported benefits including improved efficiency, cost savings, and environmental gains and enhanced security as a result of digitization (Neokosmidis et al. 2017; Surucu-Balci, Iris, and Balci 2024).

A further theme that comes through in terms of barriers and enablers is cooperation between actors involved in the deployment of technology. Several studies highlight that to enable the successful deployment of digital technologies in the port sector requires actors to cooperate rather than work individually (Carlan et al. 2017; Heilig, Lalla-Ruiz, and Voβ 2017; Inkinen, Helminen, and Saarikoski 2021). Heikkilä, Saarni, and Saurama (2022) highlight the importance of co-creation in innovation, extending this beyond the port boundaries and into the supply chain. However, it is also important to have a leader who can coordinate between the actors (Acciaro et al. 2018).

Summarising the literature review, existing research on Smart Ports has emphasized the use cases which are enabled by the components of the information system, and the performance benefits that accrue from using these. The use cases depend upon the effectiveness of the information system components and, with wireless data communication increasingly important, 5G networks have been demonstrated as a viable alternative to traditional Wifi or 4G networks. However, the willingness to invest in 5G networks by port operators has not been researched and therefore represents a gap in the literature. In addressing this gap, there is the opportunity to learn from wider literature on the barriers and enablers to digitization. Consequently, we develop two research questions:

RQ1 - What are the 5G use cases being considered by the UK port sector?

RQ2 - What are the enablers and barriers to scale up 5G adoption in ports?

The first research question recognises that 5G adoption is nested within wider use cases. Understanding the Smart Port cases that could be adopted, and their expected benefits help contextualise discussions around barriers and enablers in the second research question.

3. Method

The context for the research is the UK port industry. In 2022, UK ports handled 458.9 million tonnes of cargo, with 98% handled by the 53 major ports (Department for

Transport 2023). Major ports are those handling over 1 million tonnes per year. Following privatisation during the 1980s, there are three types of ownership model for ports—private, municipal, and trust (Tyers and Brione 2022). Private ports largely emerged as a result of privatisation and represent the majority of the largest ports in the UK. Often these are port groups, owning and operating a number of terminals across the UK as well as international operations. Municipal ports are owned by local authorities and tend to be smaller operations within the UK. Trust ports are independently managed and do not have shareholders or owners; any profits are re-invested into the port. More detail on the UK port sector can be found in Monios (2017). Considering the use of technology within the sector, there is no uniform level of deployment across the UK. The UK Government's Maritime 2050 strategy (Department for Transport 2019) emphasises the importance of technology, including smart ports for improving landside efficiency, while Connected Places Catapult (2021) provides a wider technology deployment within ports. However, there is no consistent level of technology use across the UK—some terminals have adopted automation, while others retain largely manual processes.

Given the early stages of 5G adoption within the UK port sector, we adopted a qualitative and explorative research approach. Primary data was collected from senior representatives from the UK port sector (ports, port groups and trade bodies) through a focus group ($n = 6$) and interviews ($n = 6$). Participants were contacted through three main approaches: an invitation circulated through a trade body to the Head of IT for 14 ports/port groups, attendance at a multimodal trade show to obtain contacts for the Head of IT with a subsequent email invitation, and email to publicly available contact addresses for UK major ports not contacted by the other approaches, again requesting a response from the Head of IT. While the participant count may ostensibly appear modest at 12, it is imperative to underscore the substantive representativeness of this cohort. Collectively they represent eight different port operators in the UK, with operations in approximately one-half of all major ports in the UK. Moreover, our sample incorporates a logistics provider who serves many of these ports as well as running inland terminals, two participants from 5G network technology providers and one representative from a UK port trade body. Insights from different players in the 5G ecosystem provide us sufficient insights about the current state of 5G deployment in the UK port industry. Only one UK port with known interest in 5G technology did not participate in the research.

A summary of participant characteristics is shown in Table 2. Most representatives were responsible for IT within the port although those from smaller ports had a wider range of responsibilities. In terms of experience with 5G, some participants were well along the path towards investing, either undertaking trials or having taken a decision to invest. However, many were still exploring potential opportunities, and some were more cautious, knowing a little about 5G without fully considering whether it offered opportunities for their organisation.

In the focus group, a short presentation was given summarising the current use of 5G in the port sector globally and highlighting some of the potential opportunities that were provided. An open discussion session was then held, addressing the following questions:

- What are the key operational challenges your organization faces that you believe 5G could help with? And how? (related to RQ1)
- What are the enablers and barriers to investment in 5G? (related to RQ2)

When discussing the operational challenges for 5G adoption, much of the focus was on potential use cases to improve existing port operations. In total, the focus group lasted approximately 2 h. For the interviews, a similar approach was taken, although the presentation element was adjusted to reflect the current experiences of the interviewee with 5G deployment in their organisation, based on information gleaned from secondary sources. An initial question was also asked to interviewees to confirm the current level of 5G implementation in their organisation. Interviews typically lasted

Table 2. Summary of research participants.

Participant	Port Ownership	Interviewee Role(s)	Time in position	Time with organisation	5G status at time of data collection
Port Group 1 (PG1)	Private	Head of IT IT Business Partner	4-7 years	Over 10 years	Started to explore opportunities
Port Group 2 (PG2)	Private	IT Director	0-3 years	4-7 years	Started to explore opportunities
Port Group 3 (PG3)	Private	Head of IT	0-3 years	0-3 years	Started to explore opportunities
Port Group 4 (PG4)	Private	Head of IT	0-3 years	0-3 years	Invested in trials and/or deployment
Port Group 5 (PG5)	Private	Head of IT IT Business Partner	0-3 years 0-3 years	4-7 years 0-3 years	Invested in trials and/or deployment
Port Operator 1 (PO1)	Trust	Head of IT	0-3 years	Over 10 years	Decision to invest
Port Operator 2 (PO2)	Private	Head of Projects	Over 10 years	Over 10 years	Invested in trials and/or deployment
Port Operator 3 (PO3)	Municipal	Business Development Manager	0-3 years	0-3 years	Not investigating 5G
Logistics Provider 1 (LP1)	n/a	IT Director	0-3 years	Over 10 years	Invested in trials and/or deployment
Network Provider 1 (NP1)	n/a	Business Development Manager Business Development Manager	0-3 years 0-3 years	4-7 years 0-3 years	Providing network to UK port(s)
Network Provider 2 (NP2)	n/a	Commercial Director Business Development Manager	0-3 years 0-3 years	0-3 years 0-3 years	Providing network to UK port(s)
Trade Body (TB1)	n/a	Chief Executive	4-7 years	4-7 years	n/a

45–60 min and were conducted online. Notes were taken by at least two members of the research team during the focus group and interviews.

To analyse the data, thematic coding was used. A largely inductive approach was used, with initial coding of the notes used to identify themes. These were then reviewed and clustered into higher-order thematic areas. For the potential use cases, two elements were coded from the data—the type of technology (for example, drones) and the value delivered from the use case (such as for health and safety). This distinction recognised that some technologies may have a range of applications, and equally some respondents knew about the potential technologies but had not considered possible applications for them at the time of the interview. One member of the research team undertook the coding, with verification by two other team members. Once complete, comparisons were made to existing literature on digitization within the ports sector. In the results below, quotes are attributed to participants using the abbreviations shown in Table 2.

4. Findings

4.1. RQ1: use cases

Table 3 presents the findings relating to potential use case applications. In terms of the types of technology that could be enabled by 5G, the three most common responses were tracking and monitoring, automation, and drones. The first of these involves putting sensors on '. . . everything that moves' [PO1] – equipment, cargo, and people—as well as providing telemetry data. Such technology takes advantage of the mMTC capabilities of 5G, allowing a large number of sensors within a small geographic area. By contrast, automation and drones require URLLC capabilities, with continuous data streams between the operator and the machine. Suggested equipment for automation included cranes and vehicles. Two respondents identified opportunities for communication, reflecting eMMB capabilities, with the opportunity to make high-speed broadband connectivity available through private networks:

Table 3. Use cases being considered for UK Ports.

Category	Theme	Summary	Thematic mentions
Type of technology ($n = 10$)	Tracking and monitoring	Use cases that allow ports to know where things are around the port (cargo, people, visitors)	9
	Automation	Use cases associated with automated processes/activities	6
	Drone	Use cases specifically associated with the application of drones	6
	Communication	Providing enhanced communication around the port	2
	Other	Other examples (VR, AI, etc)	1
Value delivery ($n = 11$)	Health and Safety	Use cases that may address concerns around injuries and accidents	9
	Process Improvement	Using data gathered by 5G to be more efficient/effective	5
	Data driven decision making	Use cases based around using data for decision making	5
	Environment	Use cases for monitoring environmental impacts	4
	Customer Use Cases	Uses cases focused on port customers	4
	Asset Monitoring	Use cases monitoring the condition of assets	4

n = number of mentions at category level

> [We] see connectivity as a utility. When looking at the broad landscape, public network operators don't have access to port site [for installation] and so we can then fast track connectivity as a utility. To do so, we make the network 'plug and play' for customers . . . it takes 1–2 days to plug in to the network rather than weeks. [PG5]

Turning to use case applications, health and safety benefits were identified by nine of the twelve responding organizations. In many cases, this related to improving the safety of workers—one participant noted the opportunity to ' . . . take people out of dangerous places and make things safer' [PO2]. Other related examples included monitoring the impact of accidents (such as oil spills) or for providing remote surveillance to improve security around the port site. While in a popular use case, it was also said that 'Safety is a high priority for the business . . . but not necessarily a full justification for 5G' [PG1].

After health and safety, there are a broad range of potential use cases are identified with the suggestions often reflecting the diverse operating environments at the ports. Process improvements particularly emphasised the handling of cargo more efficiently, although one respondent also highlighted opportunities for servicing ships moored away from the quayside. Data driven decision-making focused on providing enhanced information, with 5G ensuring this data is available in a timely manner when required: 'there is a challenge to turn that data into information but we need infrastructure to pull data so it [data availability] isn't a barrier to [data driven decision making]' [PG2]. Again, much of the focus was on land-based activities, but one respondent saw opportunities relating to hydrography data to enable modelling to inform dredging activities.

Use cases that involved monitoring could also benefit from 5G deployment, either on assets or on the environment. Asset monitoring could be through aiding visual inspections of buildings or telematics on machinery within the port, and for both reactive and proactive responses (e.g. to facilitate preventative maintenance). With the environment, the focus would be on emissions. Despite being mentioned a number of times, the consensus amongst participants was that there was ' . . . not much thinking about 5G use cases and environmental benefits yet.' [PG3]

Some participants identified use cases focused on customers. In some instances, these are applications offered by the port, with examples including virtual experiences for cruise passengers or dashboards for cargo owners. However, 5G capabilities are also seen as supporting port-based use cases provided independently from the port owner, for example, relating to offshore energy supply.

Finally, we look at how the types of technology enabled by 5G combine with the use case applications, as shown in Figure 1. This clearly shows that tracking and monitoring technologies have the widest range of potential uses, being linked to all the applications identified through the interviews. Automation and drones were both particularly seen as supporting

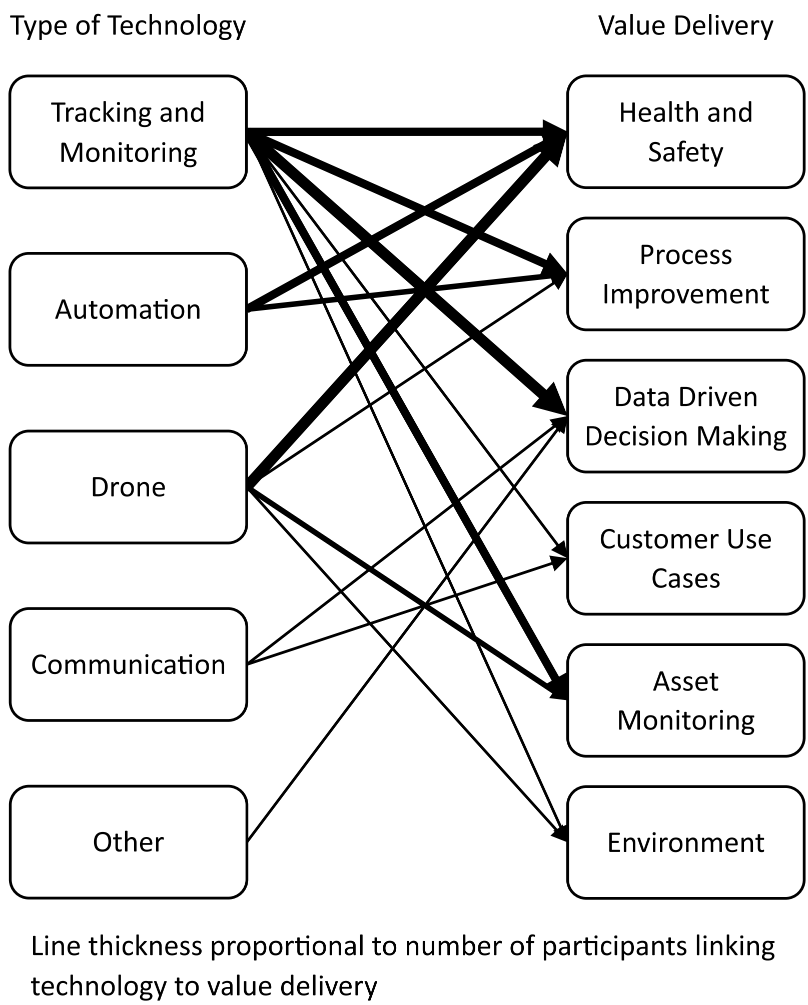

Figure 1. Connections between smart port technologies and applications for potential UK port use cases.

health and safety use cases. This reflects the view that safety can be improved by removing workers from dangerous situations, with automation of process activities (such as crane operations) and drones to carry out remote inspections, especially those at height or on the water.

4.2. RQ2: barriers and enablers

Table 4 summarises the main findings from the research relating to barriers and enablers for 5G deployment in the UK port industry. Both overall clusters and specific themes are described.

The most commonly mentioned themes were overall strategy and investment decision-making. The ports sector in the UK was acknowledged as being quite traditional in its outlook and are not leaders in innovation. Where digitization had occurred, participants stated that 4G and Wi-Fi networks were sufficient to support this. However, there was also recognition that ports need to embrace digitization to improve operational efficiency and productivity, increase safety, and progress sustainability. Therefore, the digital strategy of a port operator was seen as significant, and the development of these was seeing this move from being a barrier to an enabler. Ultimately,

Table 4. Barriers and enablers to 5G deployment in UK ports.

Theme	Sub-theme	Summary	Sub-theme mentions
Investment ($n = 12$)	Business case	General statements about making a business case	11
	Existing investment in telecoms	Current telecoms (& devices) means that its harder to justify 5G	7
	Cost/availability of funding	Comments on cost of 5G technology	6
	Tie in with new investment	Easier to incorporate 5G into new build investments	6
Overall Strategy ($n = 11$)	Innovation	Brief comments related to innovation	8
	Strategic justification	Firm/industry level perspectives on need for 5G	8
Workforce ($n = 9$)	Recruitment	Challenges in recruiting and retaining appropriate staff	9
	Workforce skills	Docker skills in using technology	6
	Workforce attitudes	Perceptions of technology use within ports	5
Use cases ($n = 9$)	Use case benefits	General comments on use cases and their benefits	9
	Future use cases	What the future direction for use cases might be	5
	Data sharing	Specific comments on data sharing in use cases	4
	Freeports	Specific comments on Freeport related applications of use cases	2
Government & Regulation ($n = 9$)	Government financial support	Role of government funding in enabling the move to 5G	9
	Spectrum availability	Comments on issues around 5G spectrum regulation	4
	Other government support	Other ways in which government can support the move to 5G	4
Technology ($n = 8$)	5G Coverage	Issues related to providing 5G coverage	6
	Problems with existing tech	Challenges faced with 4G and Wi-Fi	5
	Technology readiness	Can 5G technology currently do what port operators want it to do?	4
Implementation ($n = 7$)	Working with others	Observations on organisations working together for implementation	7

n = number of total mentions at thematic level

however, 'ports need to be flexible and so changes in procedures and systems are a part of life.' [PO2]

The business case for 5G was also seen as a barrier to investment. Any decision needs the investment cost to be compared with quantifiable benefits and, currently, there are challenges with both of these. With the port sector often not leading on innovation, these uncertainties represent a barrier, especially for the more corporate port groups where there is pressure to deliver a return on investment. Funding can also be a barrier for 5G implementation. Ports have finite resources, and it may be that other areas of the business are deemed more important for investment, particularly if they directly benefit the movement of cargo. Related to this, some participants directly identified the cost of 5G provision as a barrier. It was noted that it was 'often larger ports and port groups that invest as they have the financial backing and staff resource' [PO2]. This was one area of difference for respondents between the port groups with multiple terminals across the UK and port operators with just one facility.

Existing investments in telecommunications also represented a barrier, with participants already having these networks in place. Therefore, it is 'difficult to move from Wi-Fi to 5G due to large investment already made in Wi-Fi' [PG3], leading to a more incremental approach. However, the incremental approach can also then reduce some of the benefits that can be achieved. Alternatively, ports may adopt a hybrid approach, whereby radio masts support both 4G and 5G, with a switch towards the latter over time as required. Another participant noted '... [the] economic case is easier if 5G is part of an existing asset renewal cycle.' [TB1] Port infrastructure often predates the internet era and therefore telecommunications equipment needs to be retrofitted, which can be costly and disruptive. By contrast, new build facilities can include the physical infrastructure for 5G connectivity.

While much of the above focuses on cost, participants also highlighted barriers and enablers from use case introduction. Although many participants believed ports would benefit from 5G deployment, there remained uncertainty on the benefits because of the early stage of deployment: 'Currently, ports are more trials/testbeds than routinised. They are developing capability and evaluating use cases, devices, and applications.' [NP2] With many use cases being similar to existing systems, participants questioned what 5G offered that was different. It is likely that the biggest monetizable benefits will occur in use cases that improve processes within the ports, and these then support health and safety and environmental use cases where compliance is more important. Most participants thought that multiple use cases were likely to be needed for 5G to be a viable commercial proposition for an individual port.

Seeing the opportunities and benefits that may emerge from future use cases was considered an enabler in the UK port sector. As one participant commented, 5G investment is about 'building for the future rather than today' [PO1]. As current trials scale up and current use cases are implemented, new opportunities will emerge.

Turning to use case specifics, the use case results highlighted data driven decision-making and customer use cases as opportunities. These are likely to need data sharing, and it was highlighted that current mindsets may limit the extent to which this can happen—'we are still in the "data is power" zone which is so common in so many industries' [PG4] – although this situation is gradually shifting.

Government and regulation were another area raised by participants in affecting 5G implementation. The most commonly discussed issue was financial support through grants and project funding to reduce the financial risks associated with innovation. Government funding can support use cases implementation in a test environment, enabling them to reach a technology maturity level from where commercial adoption can take place. Beyond this, several other areas were identified where government support would enable the deployment of 5G. In the UK, licensing is government controlled and participants saw the availability of 5G spectrum licences as an important factor. Other issues raised included standardisation and skills. The former enables use cases to integrate with each other and existing systems. While government can play a supporting role here, there are also opportunities for port industry bodies to facilitate this. With skills development, workforce issues are a challenge, and government can support training and recruitment initiatives.

The remaining barriers and enablers are more related to the Implementation stage of 5G deployment. The most frequently mentioned theme, and particularly as a barrier, was the workforce in terms of recruitment skills, and attitudes.

Recruitment to support digitization has created new challenges. As with other areas of logistics, ports have an ageing workforce and one with a high turnover of people. However, attracting new and younger workers to the industry can be challenging as it is perceived as a traditional and manual sector. Port operators struggle more than the port groups because they have smaller IT departments that need to deal with day-to-day issues rather than projects like 5G implementation. Participants felt that opportunities created by 5G, such as automation and virtual reality, may change this perception. The nature of jobs is also changing, with roles such as developers now being sought by ports. As one participant noted, '[Recruitment] for IT talent is fierce—will an IT person want to work for a port or in FinTech? Historically, ports have not had to fish in that employment market.' [TB1] Ports are adapting to these new labour markets and some participants noted that changes accelerated by the pandemic, such as hybrid working, have helped facilitate this.

Digitization within ports has changed the workforce skills requirements throughout the port, from offices to the quayside. A substantial proportion of that workforce would not be considered early adopters of new technology, and therefore barriers exist in introducing digital working practices. As an example:

> For remote control cranes, one of the benefits is that technology can do the pick up and movement [of cargo] . . . For someone who used to be in a crane driving, it can be difficult to adapt by sitting in a remote control room. [PG4]

From the discussions, some ports have been more successful in this transition than others, providing opportunities for shared learning.

Participants also noted that digitization required not just new skills but also changes in workforce attitudes towards technology. Existing working practices are embedded, and organisational inertia was described as a barrier to digital innovations. Some also noted that nervousness about the use of technology might be increased by the use of terminology that was poorly understood and fears of job losses—'People see technology replacing jobs. The tangible cost savings mostly come from labour savings.' [PO1] Participants also noted that ports can be highly unionised, and therefore trade unions can play an important role in supporting deployment.

Turning to technology-related barriers and enablers, the most common theme related to 5G coverage. Private networks mean that ports can ensure the right level of coverage, although this has an associated investment cost and so some ports were also considering public networks. However, these need comprehensive coverage and, as several participants noted, rural areas where ports can be located are often the last to receive the latest generation of mobile communications.

There is also a trade-off between the capabilities of existing wireless communications and what 5G offers. Where ports use Wi-Fi and 4G mobile, issues identified include the available bandwidth for handling increasing amounts of data, security concerns, and the reliability of connections, with equipment and containers effectively forming Faraday cages and creating dead-spots. Despite this, for many participant, the existing Wi-Fi and 4G networks were sufficient for current operations and may have redundancy to accommodate further growth. As noted earlier, this creates a challenge for justifying further investigations into 5G deployment.

A common observation was that the readiness of 5G technology was a barrier to wider adoption —'I cannot say that I can set up a 5G network to do what I need to do today.' [PG4]. Off the shelf solutions were not widely available, and given the complexities of 5G deployment, operators lack confidence that a network can be set up to deliver what is expected. There are also issues with the availability of devices able to connect to 5G networks—'There are issues with the availability of ruggedised 5G devices . . . [Suppliers have] only really caught up in the past 6–9 months' [PG5]. As this quote highlights, the port environment requires devices used on the quayside to withstand bad weather, yet with few 5G use cases, most technology is configured for 4G or Wi-Fi connectivity. Over time, this barrier should reduce as availability improves.

Finally, participants identified that collaborative working between a wide range of stakeholders was seen as an enabler for 5G deployment—'Need to partner with someone you can trust . . . not able to do it all in house' [PG4]. This includes network providers, use case developers, government (both national and local), and the local community. In doing so, a better understanding of 5G capabilities and opportunities can be developed, increasing the likelihood of successful deployment.

5. Discussion

We now reflect upon how the findings address the two research questions posed. RQ1 asks, 'What are the 5G use cases being considered by the UK port sector?' Like the literature, there is a stronger focus on mMTC and URLLC type applications, with increased monitoring of cargo, vehicles, and equipment through widespread sensor deployment as well as automation. Although some mention was made of eMBB use cases such as AR, these are lower on the priority list for UK port operators. One technology that featured strongly in the research was the potential for drones, yet the smart ports academic literature to date has had less of an emphasis on this (Parola et al. 2021). Therefore, drones are likely to be a fast-emerging technology that port operators need to consider as part of digitization.

The predominant focus of applications in the UK port sector is for activities within the port boundary, with a focus on process improvement for port operations. These use cases are likely to bring direct benefits to the operating costs of ports and therefore underpin any business case for investment. Process-based applications are also a strong feature of the wider smart ports literature (Inkinen, Helminen, and Saarikoski 2021). However, the most identified area for the potential application of 5G enabled use cases was in health and safety, something that is addressed less in the previous research—for example, the maturity model in Boullauazan, Sys, and Vanelslander (2023) mentions safety and security, but more in the context of resilience to significant events rather than routine health and safety activities. As smart port literature develops further, there is the opportunity to integrate health and safety more strongly into wider evaluations of port digitization.

Some ports did consider more customer-focused use cases, and these were often ports where passenger traffic, and especially cruise passengers, makes a significant contribution to overall activity. By contrast, definitions of smart ports are frequently framed in the context of freight and supply chains (Li et al. 2023) and therefore opportunities exist to broaden this body of the literature to also reflect on passenger operations, building on the improved wireless communications offered by 5G.

RQ2 considers 'What are the enablers and barriers to scale up 5G adoption in ports?' Given the relatively early stage of adoption amongst participants, most of the focus was on more strategic issues relating to digitization strategy, investment decisions, use cases and government support. These findings are reflective of the wider literature around the enablers and barriers to digitization (Heilig, Lalla-Ruiz, and Voβ 2017), including the reluctance to adopt new technology (Acciaro et al. 2018), although there was a stronger emphasis in this research on government support and less focus on customer demand. The former may reflect the early-stage level of development for 5G-enabled use cases in the port sector, leading to a higher risk and therefore the need for government to facilitate investment. With customer pressure, any process improvement should enable shipping lines or inland transport operators to pass through the port more efficiently, and these operational gains then contribute to continued competitiveness. Therefore, the lack of customer pressure being a significant factor in this research is surprising.

Of the more tactical and operational-level factors, only collaboration featured consistently between this research and the academic literature (for example, Carlan et al. 2017). Ports are having to adapt to implement digitization, drawing on a broader range of expertise and knowledge. Obtaining this within their organisations is difficult for many port operators, and therefore engaging with a range of different stakeholders to facilitate digitization is essential. The larger port groups often have more capability to engage in collaboration, although they also have more pressure to deliver a positive return on investment which means investing in innovative technology like 5G can be perceived as riskier. While collaboration is often framed in the context of organisations involved in the cargo movement (Heikkilä, Saarni, and Saurama 2022), the research emphasises the importance of technology providers in this process.

By contrast, the technology-related enablers and barriers are less commonly discussed in the smart ports literature. With technology, many of the issue relate to the availability of 5G networks, as well as devices that connect to these. Therefore, it may be that this technology is more immature than other technologies examined in the literature, reflecting the dearth of studies in the systematic review of Taboada and Shee (2021). Another possibility is that there is less focus on technology barriers and enablers generally in the smart port literature and a greater emphasis on the general trend in technology use within the sector. Regardless, it is important to note that there is almost a vicious circle here, with a lack of technology that uses 5G hindering investment, yet without investment in 5G, there is no incentive to develop the technology. This further highlights the role government can play in breaking this cycle.

One aspect largely missing from the academic literature reviewed on smart ports is the human aspects, something discussed by almost all participants. Therefore, this research provides some key insights into the human challenges faced for smart port adoption in the port sector. The port workforce is often made up of individuals who are not digital natives, and therefore there can be resistance to new technology being introduced. Another important point is that ports need to recruit people who can support digital deployment, a different employment market to one they are familiar with. Further, there are challenges as port roles are often in more remote areas and may not be seen to be as attractive as working in, for example, retail or consultancy. While Tijan et al. (2021) and Boullauazan, Sys, and Vanelslander (2023) do identify these issues, the research enhances the depth of understanding.

6. Conclusions

The deployment of use cases within smart ports is reliant upon communication technologies, and increasingly these need to transmit data wirelessly. This research examines the adoption of 5G mobile technology as enabler for smart ports. In doing so, there is a focus on the UK market, with insights obtained from a broad range of port operators and technology providers. As an emergent technology, 5G is not widely used in the sector and so the opportunity existed to look at how 5G could impact into the future.

The research found that a wide variety of use cases were identified as having potential within the sector, enabled by automation, drones, or increased levels of remote monitoring and tracking. In terms of applications, the most important area was health and safety, an aspect not commonly mentioned in the wider smart port literature. Process improvements within the port are also important and contribute to the operational performance of the port. However, to deploy 5G requires several challenges to be overcome. Ports have historically been reluctant to innovate and embrace technology, but while this is being overcome through digitization strategies, there remain barriers. The newness of 5G and use cases also make it difficult for ports to identify benefits and therefore build a business case for investment. However, adopting a phased approach where 5G is available in conjunction with existing wireless technologies offers a route for ports to adopt and build experience with 5G.

The paper offers several contributions to the academic literature. Existing research on smart ports tends to focus on the use cases themselves and their adoption, rather than the supporting infrastructure to enable them. However, this infrastructure is important, especially for wireless communications. 5G is an emergent technology in this field, yet with the potential to impact ports significantly. This study provides insights into how this may become more widely adopted, taking opinions from a variety of stakeholders, many of whom are currently not deploying 5G within their operations.

Looking more generally, research on 5G in logistics focuses on the potential use cases that could emerge, rather than the business implications. This reflects the early-stage development of the technology. The research in this paper explores these business implications in depth, highlighting some that are particularly significant, such as the availability of compatible hardware that can also cope with the operating conditions found in logistics. For ports, this is through the provision of ruggedised hardware that is weather and impact proof.

More specific contributions include recognition that smart ports can not only offer process improvements but also wider environmental and social benefits. This last aspect particularly lacks coverage in the smart ports research, but comes through strongly in this study with the emphasis on health and safety. Workforce issues were also more strongly emphasized by participants in this study, adding to a wider understanding of how to deliver the technology for smart ports and recognising that change affects both processes and people. Different aspects related to the workforce include attitudes, skills, and the need to recruit people who might not traditionally work in ports, such as software developers.

There are also several managerial implications that arise from this research:

- For ports looking to deploy 5G, this should be embedded as part of a wider digitization strategy. As part of this, ports need to identify a portfolio of use cases to adopt over time, where the value that they will deliver is linked to their overall business strategy. Any investment needs this portfolio to build a business case.
- Ports need to be flexible in deploying 5G networks. The research identified that switching solely to 5G is challenging to justify for ports, and therefore a progressive evolution using technology with both Wi-Fi/4G and 5G capabilities is needed. This applies to both the radio network and the hardware, especially as the latter was identified as a constraint on adoption.
- 5G adoption requires a collaborative approach that focuses on processes, technology, and people. The latter is particularly challenging, with the need to change workforce attitudes and provide an upskilling of digital literacy. More generally, the port sector needs to work together to share experiences, best practices, and learning from 5G deployment. This will overcome the identified barrier of unclear business benefits.
- There currently remains a role for government support. Financial support through grants and applied research projects can offset the risks and encourage collaborative working. Schemes to develop skills, such as apprenticeships, can help enhance the workforce. Beyond financial support, government frequently provides licences for spectrum access and these should be provided in a manner to support use in industrial applications such as ports.

Future research would benefit from broadening the range of operating environments studied, considering ports in other countries globally. This will further enhance the generalisability of the findings and recognises that the UK focus could be a limitation. There is also an opportunity to undertake longitudinal research as 5G becomes deployed more widely, to observe how use cases, barriers and enablers are changing over time. It would be expected that, as more applications in ports are reported, so the business cases become easier to develop. Equally, there should be more hardware available, eliminating this as a barrier. From a technology perspective, there are opportunities to focus upon future generations of use cases that can fully exploit 5G capabilities. This will require inter-disciplinary research to understand both the technology and the port context.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Department for Media, Culture and Sport under the 5G Trials and Testbeds programme.

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References

Acciaro, M., C. Ferrari, J. S. L. Lam, R. Macario, A. Roumboutsos, C. Sys, A. Tei, and T. Vanelslander. 2018. “Are the Innovation Processes in Seaport Terminal Operations Successful?” *Maritime Policy & Management* 45 (6): 787–802. https://doi.org/10.1080/03088839.2018.1466062.

Anwar, M., L. Henesey, and E. Casalicchio. 2019. “Digitalization in Container Terminal Logistics: A Literature Review.” In *Proceedings of the 27th Annual Conference of International Association of Maritime Economists*, 1–25. Athens.

Bittner, K., and I. Spence. 2003. *Use Case Modeling*. Boston, MA: Addison-Wesley.
Björklund, M., and H. Forslund. 2018. "Exploring the Sustainable Logistics Innovation Process." *Industrial Management & Data Systems* 118 (1): 204–271. https://doi.org/10.1108/IMDS-02-2017-0058.
Boullauazan, Y., C. Sys, and T. Vanelslander. 2023. "Developing and Demonstrating a Maturity Model for Smart Ports." *Maritime Policy & Management* 50 (4): 447–465. https://doi.org/10.1080/03088839.2022.2074161.
Cardone, R. 2020. "The 5G Port of the Future." *Ericsson Blog (Blog)*. November 27, 2020. https://www.ericsson.com/en/blog/2020/7/the-5g-port-of-the-future.
Carlan, V., C. Sys, T. Vanelslander, and A. Roumboutsos. 2017. "Digital Innovation in the Port Sector: Barriers and Facilitators." *Competition and Regulation in Network Industries* 18 (1–2): 71–93. https://doi.org/10.1177/1783591717734793.
Chu, F., S. Gailus, L. Liu, and L. Ni. 2018. *The Future of Automated Ports*. McKinsey & Company. https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/the-future-of-automated-ports.
Connected Places Catapult. 2021. *UK Ports of the Future: A Vision and Roadmap*. https://cp.catapult.org.uk/document/uk-ports-of-the-future/.
de la Peña Zarzuelo I. (2021). "Cybersecurity in ports and maritime industry: Reasons for raising awareness on this issue." *Transport Policy*, 100: 1–4. https://doi.org/10.1016/j.tranpol.2020.10.001.
Del Giudice, M., A. Di Vaio, R. Hassan, and R. Palladino. 2022. "Digitalization and New Technologies for Sustainable Business Models at the Ship–Port Interface: A Bibliometric Analysis." *Maritime Policy & Management* 49 (3): 410–446. https://doi.org/10.1080/03088839.2021.1903600.
Department for Transport. 2019. *Maritime 2050: Navigating the Future*, Department for Transport. https://www.gov.uk/government/publications/maritime-2050-navigating-the-future.
Department for Transport. 2023. "Port Freight Annual Statistics 2022: Overview of Port Freight Statistics and Useful Information." *Department for Transport*. https://www.gov.uk/government/statistics/port-freight-annual-statistics-2022/port-freight-annual-statistics-2022-overview-of-port-freight-statistics-and-useful-information.
DHL. 2020. *Next-Generation Wireless in Logistics*. https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/next-generation-wireless-in-logistics.pdf.
Ericsson. 2021. Ericsson Report Charts Smarter Ports with 5G Private Networks. *Ericsson*. https://www.ericsson.com/en/news/2021/2/connected-ports-report.
Grover, V., and M. D. Goslar. 1993. "The Initiation, Adoption, and Implementation of Telecommunications Technologies in U.S. Organizations." *Journal of Management Information Systems* 10 (1): 141–163. https://doi.org/10.1080/07421222.1993.11517994.
Hazen, B., and T. Byrd. 2012. "Toward Creating Competitive Advantage with Logistics Information Technology." *International Journal of Physical Distribution & Logistics Management* 42 (1): 8–35. https://doi.org/10.1108/09600031211202454.
Heikkilä, M., J. Saarni, and A. Saurama. 2022. "Innovation in Smart Ports: Future Directions of Digitalization in Container Ports." *Journal of Marine Science and Engineering* 10 (12): 1925. https://doi.org/10.3390/jmse10121925.
Heilig, L., E. Lalla-Ruiz, and S. Voβ. 2017. "Digital Transformation in Maritime Ports: Analysis and a Game Theoretic Framework." *Netnomics* 18 (2–3): 227–254. https://doi.org/10.1007/s11066-017-9122-x.
Hofman, H. 2023. "The Game-Changing Potential of 5G in Logistics." *Maersk*. https://www.maersk.com/insights/growth/2023/01/17/the-potential-of-5g-in-logistics.
Inkinen, T., R. Helminen, and J. Saarikoski. 2021. "Technological Trajectories and Scenarios in Seaport Digitalization." *Research in Transportation Business & Management* 41:100633. https://doi.org/10.1016/j.rtbm.2021.100633.
Kwak, D.-W., Y.-J. Seo, and R. J. Mason. 2018. "Investigating the Relationship Between Supply Chain Innovation, Risk Management Capabilities and Competitive Advantage in Global Supply Chains." *International Journal of Operations & Production Management* 38 (1): 2–21. https://doi.org/10.1108/IJOPM-06-2015-0390.
Li, K. X., M. Li, Y. Zhu, K. F. Yuen, H. Tong, and H. Zhou. 2023. "Smart Port: A Bibliometric Review and Future Research Directions." *Transportation Research Part E: Logistics & Transportation Review* 174:103098. https://doi.org/10.1016/j.tre.2023.103098.
Lin, S.-C., S.-W. Lin, P. S. Chen, and Y.-K. Liu. 2014. "Adoption of 4G Wireless Services Under Consideration of Technology and Economic Perspectives." *International Journal of Mobile Communications* 13 (1): 71–91. https://doi.org/10.1504/IJMC.2015.065891.
Molavi, A., G. J. Lim, and B. Race. 2020. "A Framework for Building a Smart Port and Smart Port Index." *International Journal of Sustainable Transportation* 14 (9): 686–700. https://doi.org/10.1080/15568318.2019.1610919.
Monios, J. 2017. "Port Governance in the UK: Planning without Policy." *Research in Transportation Business & Management* 22:78–88. https://doi.org/10.1016/j.rtbm.2016.10.006.
Neokosmidis, I., T. Rokkas, M. C. Parker, G. Koczian, S. D. Walker, M. S. Siddqui, and E. Escalona. 2017. "Assessment of Socio-Techno-Economic Factors Affecting the Market Adoption and Evolution of 5G Networks: Evidence from the 5G-PPP CHARISMA Project." *Telematics and Informatics* 34 (5): 572–589. https://doi.org/10.1016/j.tele.2016.11.007.

O'Connell, E., D. Moore, and T. Newe. 2020. "Challenges Associated with Implementing 5G in Manufacturing." *Telecom* 1 (1): 48–67. https://doi.org/10.3390/telecom1010005.

O'Halloran, J. 2020. "Orange Belgium Reveals First 5G Innovations in Port of Antwerp." *Computer Weekly*. October 22, 2020. https://www.computerweekly.com/news/252490968/Orange-Belgium-reveals-first-5G-innovations-in-Port-of-Antwerp.

Parola, F., G. Satta, N. Buratti, and F. Vitellaro. 2021. "Digital Technologies and Business Opportunities for Logistics Centres in Maritime Supply Chains." *Maritime Policy & Management* 48 (4): 461–477. https://doi.org/10.1080/03088839.2020.1802784.

Pavlić Skender, H. P., E. Ribarić, and M. Jović. 2020. "An Overview of Modern Technologies in Leading Global Seaports." *Pomorski zbornik* 59 (1): 35–49. https://doi.org/10.18048/2020.59.02.

Port of Antwerp Bruges. 2020. "With Its Own 5G Network, Zeebrugge is Ready for the Future." *Port of Antwerp Bruges*. https://www.portofantwerpbruges.com/en/news/its-own-5g-network-zeebrugge-ready-future.

Port of Felixstowe. 2021. *Port of Felixstowe Selected for UK Government 5G Trial*, Port of Felixstowe. https://www.portoffelixstowe.co.uk/press/news-archive/port-of-felixstowe-selected-for-uk-government-5g-trial/.

Port Technology International. 2019. "European Port Tests 5G Solution." September 4, 2019. https://www.porttechnology.org/news/european-port-tests-5g-solution/.

Port Technology International. 2021. "Busan Port Authority to Integrate 5G-Enabled Computing into Yard Operations." May 21, 2021. https://www.porttechnology.org/news/busan-port-authority-to-integrate-5g-enabled-computing-into-yard-operations/.

Raza, Z., J. Woxenius, C. Altunas Vural, and M. Lind. 2023. "Digital Transformation of Maritime Logistics: Exploring Trends in the Liner Shipping Segment." *Computers in Industry* 145:103811. https://doi.org/10.1016/j.compind.2022.103811.

Reuters Events. 2021. *Logistics and Supply Chain Technology Report 2021*. https://media.chinatelecomeurope.com/view/480938548/.

Rost, P., M. Breitbach, H. Roreger, B. Erman, C. Mannweiler, R. Miller, and I. Viering. 2018. "Customized Industrial Networks: Network Slicing Trial at Hamburg Seaport." *IEEE Wireless Communications* 25 (5): 48–55. https://doi.org/10.1109/MWC.2018.1800045.

Surucu-Balci, E., Ç. Iris, and G. Balci. 2024. "Digital Information in Maritime Supply Chains with Blockchain and Cloud Platforms: Supply Chain Capabilities, Barriers, and Research Opportunities." *Technological Forecasting & Social Change* 198:122978. https://doi.org/10.1016/j.techfore.2023.122978.

Taboada, I., and H. Shee. 2021. "Understanding 5G Technology for Future Supply Chain Management." *International Journal of Logistics: Research & Applications* 24 (4): 392–406. https://doi.org/10.1080/13675567.2020.1762850.

Tijan, E., M. Jović, S. Aksentijević, and A. Pucihar. 2021. "Digital Transformation in the Maritime Transport Sector." *Technological Forecasting & Social Change* 170:120879. https://doi.org/10.1016/j.techfore.2021.120879.

Tyers, R., and P. Brione. 2022. *House of Commons Library: Ports and Shipping FAQs*. https://researchbriefings.files.parliament.uk/documents/CBP-9576/CBP-9576.pdf.

Verma, L., and M. Lalwani. 2019. "Digital Transformation: Impact of 5G Technology in Supply Chain Industry." In *Technology Optimization and Change Management for Successful Digital Supply Chains*, edited by E. Sabri, 256–274. Dallas, TX: IGI Global.

Wang, Y., A. Potter, M. Naim, A. Vafeas, A. Mavromatis, and D. Simeonidou. 2022. "5G Enabled Freeports: A Conceptual Framework." *Institute of Electrical and Electronics Engineers Access* 10:91871–91887. https://doi.org/10.1109/ACCESS.2022.3201889.

WECA (West of England Combined Authority). 2022. *5G Logistics: Increasing Efficiency and Productivity with 5G Technology*, West of England Combined Authority. https://www.westofengland-ca.gov.uk/what-we-do/innovation/5g-logistics/.

Won, J. Y., and M. J. Park. 2020. "Smart Factory Adoption in Small and Medium-Sized Enterprises: Empirical Evidence of Manufacturing Industry in Korea." *Technological Forecasting & Social Change* 157:120117. https://doi.org/10.1016/j.techfore.2020.120117.

Yang, C. S., and M. S. M. Lin. 2023. "The Impact of Digitalization and Digital Logistics Platform Adoption on Organizational Performance in Maritime Logistics of Taiwan." *Maritime Policy & Management*: 1–18. https://doi.org/10.1080/03088839.2023.2234911.

Yang, Y., M. Zhong, H. Yao, F. Yu, X. Fu, and O. Postolache. 2018. "Internet of Things for Smart Ports: Technologies and Challenges." *IEEE Instrumentation & Measurement Magazine* 21 (1): 34–43. https://doi.org/10.1109/MIM.2018.8278808.

Yau, K.-L. A., S. Peng, J. Qadir, Y.-C. Low, and M. H. LimLing. 2020. "Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology." *Institute of Electrical and Electronics Engineers Access* 8:83387–83404. https://doi.org/10.1109/ACCESS.2020.2990961.