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Efficient, secure and green future scenarios: An application of foresight methodologies on seaports digitalisation

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A B S T R A C T

The relentless progression of digitalisation permeates every sector, including maritime and transport industries. This study explores the digitalisation landscape expected to evolve over the next decade, with a particular focus on its impact on ports. Employing a combination of Delphi and Roadmapping analyses, it seeks to identify the most probable, impactful, and desirable scenarios.

The findings give insight on two principal aspects: they identify the digitalisation trends most related and impactful to future ports, and they provide guidance on which technologies to prioritise, also providing their phased implementation to achieve specific scenarios over time.

The research is structured around three alternative scenarios: efficiency-driven, security-oriented, and green-centric, each with distinct implications for port development and management.

1. Introduction

Digitalisation is considered one of the most significant megatrends in contemporary society (Inkinen, Helminen, & Saarikoski, 2021) and one of the main drivers of the evolution of the maritime and transport industry (Voorspuij & Becha, 2020). Consequently, digitalisation is also pushing the maritime industry beyond its traditional boundaries and offering many opportunities to improve productivity, efficiency and sustainability (Heilig, Lalla-Ruiz, & Voß, 2017; Jović, Tijan, Brčić, & Pucihar, 2022). In this sector, ports are organisations that are significantly affected by these changes (Cepolina & Ghiara, 2013), which are expected to be rapid and extensive. The digitalisation of ports is expected to improve the efficiency and effectiveness of global logistics networks, cargo flow management, operations planning, berth allocation, human resource planning, route optimisation and information exchange (Jović et al., 2022). Port authorities are well aware of the benefits to be gained by digitalising ports; however, ports are complex systems to manage, and the implementation of new digital technologies requires not only operational changes but also the formulation of a long-term strategic plan.

Foresight practices, by systematically trying to describe future scenarios, are useful in defining a strategic plan. Indeed, they favour a future-oriented perspective - generally over a period of 5 to 10 years - and allow monitoring of weak signals of change, such as technological trends, within the organisation's context (Gordon, Ramic, Rohrbeck, & Spaniol, 2020), even in the presence of uncertainty (Ebolor, 2023; Schoemaker, 1995).

In a strategic technology implementation plan, anticipating technology trends is useful in prioritising decisions, determining which technologies to implement and deciding when to implement them, ensuring that the timing aligns with the maturity of the technology.

Future studies that have dealt with the digitalisation of ports have focused only on a specific technology (e.g., blockchain) (Nguyen, Chen, & Du, 2022) or have considered digitalisation a macro trend for ports (Attanasio et al., 2023). Other studies have analysed the potential future opportunities of digitalisation (Inkinen et al., 2021) and future implementation strategies (Seo, Lee, & Jeon, 2023). From a methodological point of view, existing studies on the future of port digitalisation have never used the Delphi method to identify trends and scenarios for port digitalisation, in combination with technology roadmapping to prioritise technologies to achieve the scenarios. Compared to other foresight methods, the Delphi method provides access to tacit and prospective knowledge of experts in the field. It builds scenarios based on iterative answers to questionnaires to reach a consensus of opinions on specific scenarios. In contrast, technology roadmapping provides guidelines on how to reach a desired future. Despite the recognised importance of digitalisation in ports, the literature lacks a comprehensive overview of technological trends impacting the port value chain and those that

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should be pursued to achieve specific outcomes.

To fill this gap, we formulated the following future-oriented research questions with a 10-year time horizon:

RQ1: What are the digitalisation trends that will affect ports in 10 years' time?

RQ2: What future scenarios are identifiable?

RQ3: How can these scenario be achieved?

To answer the research questions, two forecasting methodologies were used: the Delphi study for the first two and Technology Roadmapping for the third. Using the Delphi study, the opinions of experts in the fields of digitalisation and ports were gathered. Among these experts were academics, managers involved in digital technologies and port officials. Drawing on their expertise, the experts imagined the future of ports ten years from now. Based on the results of the Delphi method, technology roadmapping was applied to identify the paths and decisions needed to achieve the desired future goals.

To ensure a comprehensive view of the future of port digitalisation, we organised this study as follows. In section 2, the literature review presents the state of the art of port digitalisation and why a vision of the future is needed. Section 3 explains in detail the methodology used, while Section 4 presents the qualitative and quantitative results obtained and discusses their implications in ports. Finally, Section 5 discusses the main findings and Section 6 sets out considerations and future research.

2. Theoretical background

2.1. Port digitalisation and the need of a future vision

Over the years, organisations operating in the maritime sector have committed themselves to digitalisation projects and international organisations, such as the European Union, have worked to create favourable conditions for the development of digitalisation. For example, in 2017 and 2019, the European Union recommended the use of paperless procedures for customs processes, transport documents and documents between cargo owners and contract carriers (European Commission, 2017, 2019). Similarly, the International Maritime Organisation has emphasised its support for the adoption of electronic data exchange, both between ships and between ships and land, with the aim of improving the efficiency, safety and security of maritime transport.

The interest in supporting digitalisation in the maritime sector is driven by several factors, similar to those driving other sectors to pursue the digitalisation route. These include the ability to more effectively analyse and utilise data, often from disparate and dispersed sources, the improved communication and sharing of information, within the organisation and with stakeholders, and the consequent improved monitoring and reporting of various activities, enabling improved operational efficiency and better decision-making processes.

As logistics centres and connection points for several shipping companies, ports can benefit greatly from the digital transition. This became evident as early as the early 2000s, when many ports started to use the digital technologies available at the time to achieve specific objectives, such as changing their business model to gain a competitive advantage (Barnes & Oloruntoba, 2005; Shepherd, 2004), designing new processes to simplify cargo handling (Lee & Whang, 2005), and meeting legal requirements (Barnes & Oloruntoba, 2005). Over time, more and more advanced technologies have become available, and this progress is still ongoing. Technological innovations include artificial intelligence, the Internet of Things (IoT), advanced automation systems, new software platforms and communication tools. (Gölzer & Fritzsche, 2017; Herrero Càrcel, 2016; Zolich et al., 2019; Brümmerstedt et al., 2017).

However, the integration of these new technologies could generate conflicts and obstacles in operational processes. Such conflicts can be mitigated by implementing a long-term development plan or technology foresight process (Brümmerstedt et al., 2017; Cepolina & Ghiara, 2013; Fahim et al., 2021a, b; Inkinen et al., 2021; Sun, 2021).

2.2. Futures studies on ports and research gap

The literature highlights the pivotal role of digitalisation in shaping the future of the maritime sector and ports, both from an operational perspective (Attanasio, Battistella, & Chizzolini, 2023; Seo et al., 2023) and a strategic one (Attanasio et al., 2023; Inkinen et al., 2021; Nguyen et al., 2022). The adoption of digital technologies is expected to drive port growth and yield significant outcomes (Nguyen et al., 2022), positioning ports as increasingly critical nodes in multimodal transport networks and supply chains (Inkinen et al., 2021). Understanding how the digital transition will unfold is crucial for guiding efforts towards a strategically advantageous development. Anticipating new trends in port digitalisation is essential, as they are seen as key drivers (Attanasio et al., 2023).

In the literature, anticipating the future of ports is recognised as a successful strategy for advancing the maritime sector and shipping (Attanasio et al., 2023). However, the digital transformation of ports remains a complex issue that has not received as much research attention as other specific topics such as vessel navigation, route optimisation, or autonomous shipping (Inkinen et al., 2021). Consequently, ports are often not studied as single systems that benefit from digitalisation and possess a strategy for its diffusion and application. In addition, there is not a widely accepted common understanding of digitalisation strategies, and there is no common way to assess the level of digitalisation in ports (Seo et al., 2023).

Furthermore, there are only four articles that jointly address the digital transformation of ports, without limiting themselves to individual technologies, and the future forecast, as shown in Table 1. Among these articles, three focus on future investigations concerning the digitalisation of specific segments of the maritime sector. These segments include supply chain (Seo et al., 2023), energy management (Attanasio et al., 2023), and container shipping (Nguyen et al., 2022). It is worth noting that in the case of Nguyen et al. (2022) and Seo et al. (2023), the study is centred around blockchain and a single case study. Only Inkinen et al. (2021) focused on port digitalisation as a transition process not limited to a single technology. However, their study focused exclusively on Finnish ports. Moreover, their method is a workshop analysis thus lacking a more structured foresight methodology.

Therefore, there is a gap in structured and systematic foresight studies on the overall future of port digitalisation and this paper aims to fill this gap by attempting to identify the most important digitalisation trends and estimate their overall impact on European ports in a single paper.

3. Methodology

3.1. Introduction to the Delphi method

To answer to the first research question, Delphi method was employed. The Delphi method is a qualitative forecasting tool that facilitates communication between independent experts on a complex issue to be addressed. It brings together common knowledge to address ambiguous circumstances. By means of a multiple iteration questionnaire, this method makes it possible to reach a group-wide consensus on the future development regarding a certain topic (Loo, 2002). The Delphi method has distinctive features compared to other expert discussion methods such as workshops (Twin, 2022). Indeed, the use of an iterative questionnaire allows for asynchronous group communication. Thus, the questionnaire does not require experts to meet at a particular time and place but retains the effectiveness of traditional workshops. Furthermore, experts participate anonymously in the evaluation of the questionnaire, allowing them to express their opinions more freely without being influenced by the persuasive abilities of other participants, which can lead to the 'halo effect'. In conclusion, an important

Table 1
Synthesis of literature on port digitalisation and foresight.

Authors	Description	Industry	Foresight Method	Digitalisation focus	Topic	Gap on which the paper focuses
Nguyen et al., 2022	This study gives a comprehensive view of the potential failure modes of blockchain applications.	Maritime transport	Interviews and scenario planning	Yes	Container shipping	The study is limited to the blockchain applications thus lacking a more comprehensive view on the entire system of the smart port.
Inkinen et al., 2021	The aim is to identify potential opportunities for digitalisation in Finnish ports involved in international trade and transportation.	Maritime	Workshop	Yes	Digitalisation	The study is focused on Finnish ports thus lacking a European/international view. Then the method is a workshop analysis thus lacking a more structured and quantitative foresight methodology.
Attanasio et al., 2023	The study identifies the main trends in ports' energy management and provides three different scenarios about the future of ports.	Maritime	Delphi	No	Energy management	The study is focused on energy management and not digitalisation.
Seo et al., 2023	In this study, practical strategies for digitalising maritime container supply chains are put forward, along with robust evaluation criteria.	Maritime transport	Survey	Yes	Supply chain	This study is focused on digitalisation strategies that address real-world systems but it focuses on a single case study.

validation demonstrating the effectiveness of the Delphi methodology stems from the error theory, according to which the aggregated responses of the group can define a higher truth of solutions than those proposed by individual experts (Lund, 2020).

3.2. Steps of the Delphi method

Following the methodological steps suggested by Belton, MacDonald, Wright, & Hamlin (2019), the researchers applied this method systematically following the methodological steps shown in Fig. 1.

3.2.1. Conceptual framework and projection development

3.2.1.1. Literature review for finding the trends. As a first step, a time horizon of the study of 10 years was defined as appropriate. This was deemed a horizon that provided a fair balance between pure speculation and what could be applied.

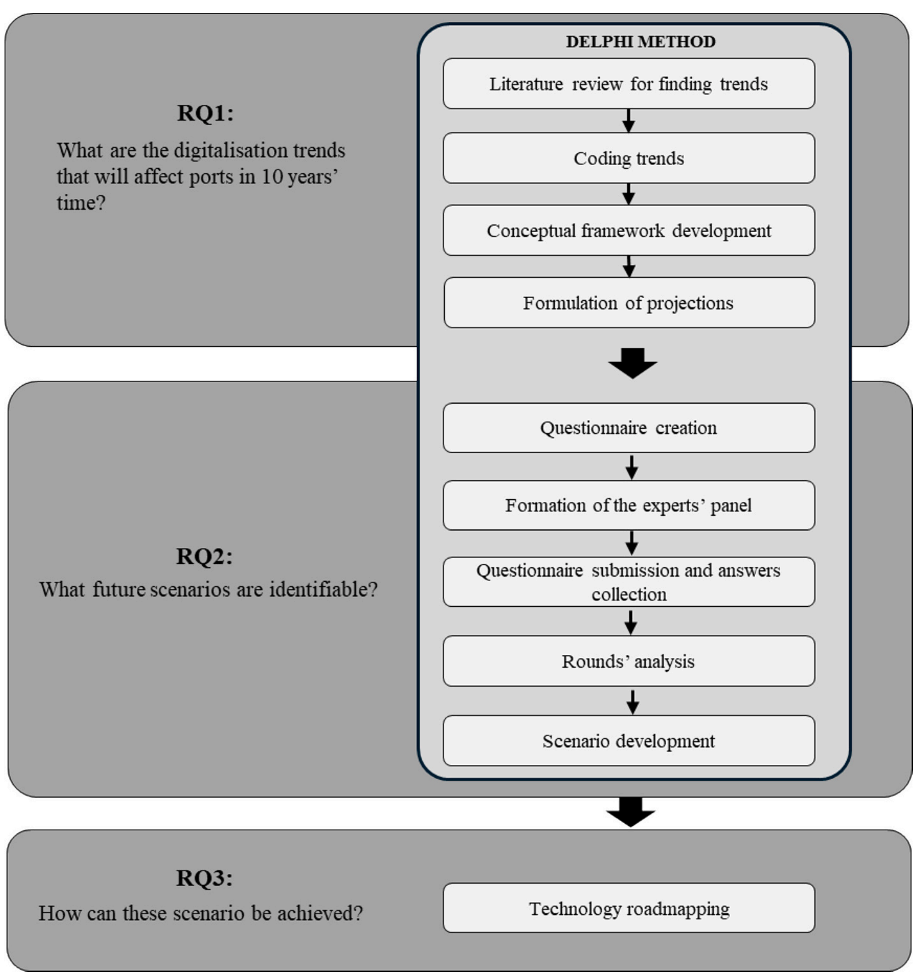

Fig. 1. Methodology.

Next, the literature review was carried out using Scopus's database. The purpose of this literature review was to identify which port technology trends are most discussed in the literature, on the basis of which to then develop the projections of the Delphi study to understand its future 10 years from now.

The string that was used to conduct the search on Scopus is the following: TITLE-ABS-KEY ((“port” OR “seaport” OR “sea port” OR “harbor” OR “dock” OR “haven”) AND (“digital*” OR “digitization” OR “4.0” OR “smart-port” OR “smart port”) AND (“techno*” OR “innovation” OR “addition” OR “transformation” OR “conversion” OR “technique*” OR “method*” OR “approach”)) AND (LIMIT-TO (SUBJAREA, “BUSI”)) AND (LIMIT-TO (LANGUAGE, “English”)). The search yielded 191 articles. These documents were then exported to Excel for further processing. The initial filtering involved reading the titles to eliminate clearly unrelated articles. A more detailed filtering was conducted by reading the abstracts, resulting in 56 of the initial 191 articles being deemed suitable for the purposes of this study.

3.2.1.2. Coding trends. The chosen articles were examined to identify trends associated with the digitalisation of ports. Then, the trends identified in the literature review were classified. The objective of the categorisation was to organise the identified trends coherently and to enhance information accessibility. Given the interdependence of the identified trends, it was essential to delineate them as distinctly as possible to avoid overlap and information contamination. Section 4.1 provides a succinct explanation of the trends.

3.2.1.3. Conceptual framework development. To determine the impact of digitalisation on ports, it was considered useful to analyse how the trends found from the literature review are related to the ports' value chain. For this purpose, the value chain's primary and secondary activities related to commercial ports to which reference is made are the ones identified by Attanasio et al. (2023), which are:

- Primary activities: infrastructure and superstructure development, port inbound and outbound logistics, port internal operations, port marketing, community and stakeholders' relations, and services.
- Secondary activities: port authority management, human resources management, technological development, regulatory and legal affairs.

To find the relations between trends and the value chain, a conceptual framework was developed. This framework allows to ensure that the questionnaire covers all topics related to the study of the future of port digitalisation. This framework relies on the use of a logic table (Table 2) that was created following a matrix structure characterised by the trends that have been identified as rows and the value chain's activities as columns.

The identification of influences between digitalisation trends and value chain activities was seen as the most effective method to achieve the fundamental characteristics of the questionnaire. The logical tables are characterised by 100 cells impacting on the primary activities and the secondary activities. Each cell represents a potential influence between trends and activities. For 49 of the 100 cells, an influence between trends and activities was identified, based on relationships clearly expressed in the literature.

The influence analysis started from the assumption that the port had not yet adopted any of the identified trends. Initially, the impact of value chain activities on trends was examined, and then the opposite influence, i.e. trends on activities, was analysed. Intersections were selected based on evidence from the literature review, which provided key information on the nature of trends (physical or digital), operation, port activities involved, relevance, personnel involved, level of preparedness and operational requirements (costs, materials, skills, technological prerequisites, etc.).

3.2.1.4. Formulation of projections and questionnaire creation. These 49 influences were subsequently converted into sentences with a forward-thinking prospective, called projections, aimed at generating the most appropriate sentences for the questionnaire. Once the sentences were formulated, they were grouped or merged by similarity of topic, lowering the final number of projections to 26. After the cells with influence between trend and value chain were identified, the relationship between them was made explicit with a sentence describing it. 26 sentences derived from the 17 most important intersections were written. With the execution of the procedure just described, it has been ensured that the 26 sentences covered all the topics to be addressed.

To create this questionnaire, the projections were divided into sections and ordered in a logical manner to facilitate and speed up the response from the experts. The sections are the following: “cost”, “risk”, “time”, “transparency”, “speed”, “standardisation”, “automation” and “sustainability”. These categories were created based on the explicit effects of the various projections, representing areas of impact for different trends and setting them as objectives achievable through specific technologies.

In addition, for five projections it was considered significant to

Table 2
Logical table for digitalisation in port value chain.

		Primary Activities						Secondary Activities			
		Infrastructure and superstructure development	Port authority and management	Port internal operations	Port marketing	Community and stakeholder relations	Services	Port authority and management	Human Resources Management	Technological development	Regulatory and legal affairs
1	Data	a1	b1	c1	d1	e1	f1	g1	h1	i1	l1
2	Digital Twin	a2	b2	c2	d2	e2	f2	g2	h2	i2	l2
3	Blockchain	a3	b3	c3	d3	e3	f3	g3	h3	i3	l3
4	Digital Platform	a4	b4	c4	d4	e4	f4	g4	h4	i4	l4
5	Electronic Trade	a5	b5	c5	d5	e5	f5	g5	h5	i5	l5
6	IOT	a6	b6	c6	d6	e6	f6	g6	h6	i6	l6
7	AI	a7	b7	c7	d7	e7	f7	g7	h7	i7	l7
8	Smart Port	a8	b8	c8	d8	e8	f8	g8	h8	i8	l8
9	Digital Container	a9	b9	c9	d9	e9	f9	g9	h9	i9	l9
10	Decision Support Tool	a0	b10	c10	d10	e10	f10	g10	h10	i10	l10

investigate the experts' opinion according to the size of the ports (small, medium and large), as it was recognised that responses could vary according to this parameter.

3.2.2. Questionnaire administration

3.2.2.1. Formation of the experts' panel. Two different fields of knowledge and experience were covered: digital technologies and/or port operations. For a Delphi survey, the inclusion of the highest possible degree of expertise is more important than the representativeness of the sample. As the representativeness of the sample is not a key factor, no limitations or specifications on the profession of the candidates were imposed in order to keep the views as diverse as possible and not to exclude the involvement of stakeholders not considered by the researchers. Therefore, the experts identified came from the following fields: academics, managers in the field of digital technologies and port officials. The aim was to form as diverse a sample of experts as possible, also considering the importance of the panel being international. The panel formation was done by selecting experts with years of experience in the field through various means: 1) direct contacts involving academics with expertise in digitalisation; 2) authors of articles identified in the initial literature review phase; 3) Online search, which allowed contacting port authorities in major ports;4) LinkedIn, used to expand the network of experts through targeted searches. It was decided to use only free channels such as messaging and the use of e-mail for sending the questionnaires to the experts. Even though these channels were cost-free, their use still made it possible to personalise the messages and communicate directly with each candidate in the attempt to increase the probability of response.

3.2.2.2. Questionnaire submission and answers collections. In the questionnaire created specifically for the study in analysis, three types of numerical evaluations were used for each of the 26 projections:

1. Probability of occurrence: it was chosen to allow the experts to respond with a percentage: 0 % indicates that the projection analysed will not occur and 100 % indicates that there is a certainty that it will occur.
2. Desirability of occurrence: for this evaluation, a Likert scale was used with values from 1 to 5 where respectively: 1 means that the projection is undesirable and 5 means that the projection is very desirable.
3. Impact on the future of ports digitalisation: as in the case of desirability, a Likert scale was used to assess impact with values from 1 to 5 where respectively: 1 means that the projection has no impact and 5 means that the projection is of great impact.

The questionnaire was administered between 2023 and 2024 in two rounds using the 'Google Form'. In addition to the projections, some questions were asked to obtain information on the profile of the participants, including an expertise self-assessment. The questionnaire collected the responses of 36 experts, all with a high level of expertise in their field. The respondents came from various countries, including Italy, Belgium, Brazil, Germany, Spain, and Sweden, and were mainly researchers or professors in digitalisation (30 %), experienced port researchers (20 %), logistics consultants (15 %), port safety officers (20 %), and project managers overseeing port-related innovation projects (15 %).

Between rounds, a statistical summary was generated and included in the questionnaire of the following round to allow the experts to see the aggregated responses and reconsider their evaluation for each projection based on this summary. It emerged that the experts were from different European countries. Regarding self-assessments concerning the level of expertise in digitalisation and port operations, the experts expressed advanced knowledge in these fields with an average of 24,6 years of experience.

3.2.3. Analyses

3.2.3.1. Analysis of rounds of Delphi. At the end of each round, a descriptive statistical analysis was made of the responses obtained for each individual projection. These statistics include the calculation of the mean value, median, standard deviation and interquartile range (IQR). These statistics make it possible to aggregate the overall opinion of the experts for each projection. What is obtained is a summary of the responses of the various experts, which is the key element in achieving the asynchronous exchange of opinions that characterises the Delphi method. The statistics obtained in the summary were analysed through a consensus analysis and a convergence analysis of opinions.

To define that a consensus has been reached, it was decided to establish a threshold value of the interquartile range, i.e., a value that if exceeded indicates that the responses are too scattered to define the presence of a shared opinion. The threshold for the probability ratings was set at 25, which means that 50 % of the participants must give a response that falls within a 25-point range (e.g., half of the participants must give a score between 60 % and 85 %). Since the desirability and impact ratings are between 1 and 5 (instead of 1 and 100), the threshold used is different, but the reasoning applied to determine it is very similar to the previous one. In fact, the Likert scale was converted to a percentage scale (where 1 equal 20 % and 5 equals 100 %), and as before it was determined that the interquartile range should not exceed 25 %. These percentages were then converted to a Likert scale, and since 25 % of 5 corresponds to 1.25, it was decided to adopt the latter value as the consensus threshold for these responses.

To obtain a representative value concerning the intensity of convergence, it is important to analyse the percentage variation in the value of the standard deviation obtained in the second round compared to the value of the first round. Among all, the probability-related standard deviation values are the most representative. In fact, probability, in comparison to desirability and impact, is the only parameter that was not evaluated using a Likert scale from 1 to 5, which is not an optimal measurement parameter for calculating the standard deviation. The negative percentage variation (NPV) in standard deviation was assessed across different ranges: NPV ≤ -20 % denoted high convergence, -20 % $<$ NPV < -10 % indicated medium convergence, and $-$ 10 % $\leq$ NPV $<$ 0 % represented low convergence. Conversely, positive percentage variation (PPV) in standard deviation for convergence was considered within the following ranges: PPV $\geq$ 20 % for high divergence, 10 % $<$ PPV $<$ 20 % for medium divergence, and 0 % $\leq$ PPV $\leq$ 10 % for low divergence.

Regarding the Delphi study, it can be stated that from round 1 to round 2, consensus decreased in only 8 out of 36 overall projections (i.e., in 22.22 % of the cases). This result suggests that a reasonable level of overall consensus has been reached in the two rounds, especially regarding the projections for the cost category, which turns out to be the only category in which there is no projection that presents dissent.

It can be said that a predominance of convergence of projections is present. Specifically, in numerical terms, of the 36 total cells, 1 has SD 2 = 0.00, 27 have SD variation ≤ -20 %, 3 have -20 % $<$ SD variation $<$ -10 %, 2 have 0 % $<$ SD variation $<$10 %, 2 have SD variation $\geq$ 20 % and finally 1 has SD 1* = 0.00. The fact that the percentage change in the standard deviation turns out to have a negative value in most of the projections means that a satisfactory result in terms of convergence of expert opinions was achieved. Once the second round and the respective summary of responses had been completed, the questionnaire administration phase ended.

In Appendix A the table with the results of the consensus and convergence analyses can be found.

3.2.3.2. Scenario development. Starting from the Delphi results, we conducted a probability – impact analysis to answer the second research question. This analysis aimed to convert the experts' numerical evaluations into concepts and organise them by area of impact. Essentially, this analysis translated the experts' quantitative assessments into a more comprehensible and unified representation. The evaluations were organised according to the questionnaire categories: "cost," "risk," "time," "transparency," "speed," "standardisation," "automation," and "sustainability", which also represent the objectives that can be achieved through the different technologies.

The analysis also identified which projections could most significantly shape the future of ports. To determine this, limits were set for probability and impact values. According to Belton et al. (2019), the projections with a probability value exceeding 65 % and an impact value greater than 3.5 were deemed highly influential for the future of ports. The higher these parameter values, the more impactful the projection and its related technology.

Desirability ratings were analysed separately to determine which projections and technologies were preferred by the experts. Projections with desirability values between 4 and 5 were considered highly desirable. Then, it was observed that the various objectives potentially achievable through the identified technologies - cost reduction, risk reduction, time efficiency and speed, transparency, standardisation, automation and sustainability - could be grouped according to their contribution to performance outcomes. By grouping the objectives according to performance outcomes, 3 scenarios (efficient, smart and green) emerged.

3.3. Technology roadmapping analysis

The third research question was to determine how to achieve the identified scenarios. To accomplish this, an additional foresight method was used: technology roadmapping. Technology roadmapping aids in the management and strategic planning of technology to achieve specified objectives by investigating the dynamic connections between technological resources and organisational goals (Phaal, Farrukh, & Probert, 2004). This approach is highly adaptable to various organisational objectives. Technology roadmapping yields multiple advantages (Garcia & Bray, 1997) as it facilitates consensus among decision-makers regarding a defined set of needs. It offers a mechanism for experts to foresee advancements in specific domains. Additionally, it establishes a framework to facilitate the planning and coordination of technological advancements at any level within an organisation, across an entire discipline or industry, and even at cross-sectoral, national, or international levels. Technology roadmapping is frequently employed alongside Delphi to provide direction on realising the scenarios identified through this methodology (e.g., da Silveira Junior, Vasconcellos, Guedes, Guedes, & Costa, 2018). The roadmapping methodology comprises two primary elements: the application procedure (consisting of the phase of defining future goals to be achieved and the prioritisation of technologies based on collected data) and the resultant output (typically a roadmap). Consequently, the term 'roadmap' signifies a synthesis of technological strategies, while the roadmapping process entails the formulation of this roadmap (Kostoff & Schaller, 2002).

In practice, beginning with the present, the technological roadmap outlines how to use technology to reach a future point. In this study, multiple technology levels are depicted in roadmaps, with time sliding towards the x axis. The various technology layers show:

- which technologies need to be implemented to achieve a future point,
- and their order of implementation over time.

The technologies to achieve the specific objective were chosen consequently to the projections' probability-impact analysis. With the aim of understanding what can be expected from the future of digitalisation in the port sector, the following sections will analyse the findings from the digitalisation trends point of view and from the three scenarios (efficient, smart and green) obtained by the goals ("cost", "risk", "time", "transparency", "speed", "standardisation", "automation" and "sustainability") and the three main states (uncertain, desirable, and critical state) obtained from the answers provided for each projection by the experts in terms of probability, desirability, and impact respectively.

4. Findings

4.1. Ports' digitalisation trends

Port digitalisation trends were identified and include: Data Digitalisation, Digital Twin, Blockchain, Digital Platform, Internet of Things, Artificial Intelligence, Digitalised Containers and Decision Support Tools. All eight trends are considered valuable technology domains that are expected to gain prominence both in the medium term (5 years) and in the long term (10 years), where their importance is expected to grow significantly. These technology domains are already integrated in the operations and management of ports considered as best practices. A brief explanation of each trend is given below.

4.1.1. Data digitalisation

The conversion of data from analogue to digital forms is a process that has enabled the introduction of digital platforms. This digital transformation has thus facilitated the management, transparency and sharing of data, while ensuring low uncertainty in the management of operations (Seo et al., 2023). However, the digitalisation of data and its analysis has also introduced new risks, especially in relation to information security. Given the fundamental role that data plays in the digitalisation process, its security is crucial, especially when referring to seaports, where the loss of data could create very serious consequences, as these areas are at the heart of world trade and their role is becoming increasingly important (Henesey, Lizneva, Philipp, Meyer, & Gerlitz, 2020).

4.1.2. Digital twin

The digital twin is a virtual technology capable of digitally simulating the life cycle of a physical object or system. This model is based on the real-time use of data sent by sensors on the object to simulate its behaviour and monitor its operations. In this way, reliable solutions for decision-making can be achieved through the interaction between physical and virtual objects (Gao, Chang, & Chen, 2023). Improvements in information technology have enabled the digital twin to support decision-making in various fields, including port operations, such as the scheduling of ship docking and cargo handling. Furthermore, this technology has been widely adopted as a practical tool to evaluate the performance of systems in expanding sectors such as the maritime industry (Zhou et al., 2021).

An example in the port of Rotterdam is the use of drones for parcel delivery and robots, the automation of data management, such as for the management of waste collection activities at the local level.

4.1.3. Blockchain

A blockchain is a decentralised and distributed digital ledger that records transactions across a network of computers. It is designed to be secure, transparent, and resistant to modification. Blockchain is not only an open, transparent, and decentralised technology but also a distributed computing information system capable of leveraging autonomy and anonymity. In recent years, blockchain technology has become widespread in large state-owned enterprises, utilities, and small businesses. This remarkable spread is due to blockchain being one of the most advanced technologies that has attracted the attention of governments, financial institutions, and investors (Shi & Fan, 2021). Furthermore, numerous studies suggest that blockchain can improve the digitalisation and resilience of supply chains by addressing risks and uncertainties (Senarak, 2020), including maritime supply chains where ports are key nodes.

An example of blockchain application is seen at the Port of Antwerp, where blockchain technology is used to simplify the cargo processing process, creating a paperless port.

4.1.4. Digital platform

A digital platform refers to a comprehensive and integrated set of technologies, tools, and infrastructure that facilitates the creation, delivery, and consumption of digital products, services, or experiences (Hein et al., 2020; Pagano, Antonelli, & Tardo, 2022). Digital platforms today can support a high level of data integration, sharing and security, which allows this technology to be used to create innovative services that aim to create added value. For this reason, many companies have introduced the use of digital platforms to facilitate business opportunities (Seo et al., 2023). Furthermore, many ports around the world are implementing digital platforms as integral parts of their transformation strategy. However, from a technological point of view, digital platforms are very complex as they are layered modular architectures with stable core components and flexible complementary modules. This technological complexity implies that there are many associated challenges that need to be understood (Senyo, Effah, & Osabutey, 2021). In the coming years, digital platforms will be the basis for achieving the goal of overcoming challenges involving all actors in the maritime supply chain. This is particularly challenging as maritime transport involves a wide variety of actors, which makes digitalisation approaches in the maritime sector more complex (Lange & Grafelmann, 2022).

The rapid pace of technological evolution is a phenomenon that has occurred in parallel with the increase in the volume of trade, especially international trade, thanks to e-commerce platforms (Henríquez, de Osés, & Marín, 2022).

An example in the port of Rotterdam the "deliver" platform used for logistics and energy efficiency.

4.1.5. Internet of things

The Internet of Things (IoT) is a network of physical objects. The Internet has evolved from being a simple computer network to becoming a connectivity hub for devices of various types and sizes. In a port, these include vehicles, cranes, trucks, ships, and other types of equipment. All these objects are interconnected, communicate, and share information according to predefined protocols. The primary goals are to achieve intelligent organisation, positioning, tracking, security, and control measures, as well as real-time online monitoring, online updates, process control, and administration (Fahim et al., 2021a, b; Patel, Patel, & Scholar, 2016). This allows for the capture of all key information for each port logistics unit, improving interaction between different port logistics resources, enabling intelligent decision-making, and reducing operating costs and lead times. IoT, workforce, sensors, and applications communicate and collaborate in real time, optimising logistics system operations. By operating in this manner, port operators can improve container loading and unloading times and reduce the risk of accidents. Additionally, the regulation of container stocking order can be enhanced, increasing the efficiency of main operations in port areas (Baştuğ, Arabelen, Vural, & Deveci, 2020). By implementing IoT at every system level (e.g., connecting operational assets in an organic and functionally holistic manner), traditional ports can be transformed into Smart Ports. An example is the Port of Shanghai, which incorporates IoT, including logistics information systems, shore management systems, IoT platforms, underwater data acquisition, and data transmission.

4.1.6. Artificial intelligence

Artificial intelligence (AI) refers to the capability of a digital computer or computer-controlled robot to perform tasks typically associated with intelligent beings. Practically, the term AI is used for projects aimed at developing systems with intellectual processes characteristic of human beings, such as reasoning, learning, and experiencing. Ports can utilise AI technologies to enhance ship routing, improve ship delivery times, optimise container dwell time, and bolster port security by analysing data from cameras to detect threats or prevent accidents.

AI also aids in real-time maritime traffic management by analysing traffic data and forecasting the demand for ships at a port. It can help optimise the use of port space for traffic planning and scheduling. Additionally, AI plays a crucial role in predictive maintenance management by analysing data from sensors and monitoring equipment (Kuo, Huang, & Chen, 2022).

An example is the Port of Rotterdam, which uses AI to address issues such as carbon dioxide emissions and port logistics.

4.1.7. Digitalised containers

Digitalisation has also transformed containers, revolutionising the way goods are transported. Digitalising containers involves using various technologies such as IoT, RFID, QR codes, and GPS to enhance container transport. Through IoT, data such as humidity and temperature can be collected in real-time, facilitating easier tracking and communication between different shipping companies (Siror, Huanye, & Dong, 2011; Zeng, Chan, & Pawar, 2021). RFID or QR codes on containers allow for quick retrieval of information about their contents and destinations (Shi, Tao, & Voß, 2011). GPS tracking technologies enable constant monitoring of container locations, and the adoption of electronic container reservation systems helps to prevent misplacement within ports (Sadri, Harsej, Hajiaghaei-Keshteli, & Siyahbalaii, 2022).

An example is the Port of Antwerp, which employs 600 digital cameras and automatic analysis for optical inspection and preventive maintenance.

4.1.8. Decision support tools

Thanks to advances in digitalisation in data storage, processing, and transmission, the digital transformation of business processes has become an increasingly utilised tool for improving decision-making processes. One of the primary decision support tools capable of validating or correcting proposed solutions is simulation. This tool allows for the study of the behaviour of selected processes through a model operating in a controlled artificial environment, which is easier to manage than the real context (Battilani et al., 2022). Specifically, software platforms and communication tools can serve as effective decision-support tools to facilitate port activities in a simple and efficient manner. However, these decision-making tools require the use of sensors and necessitate human-assisted application, as there are still significant challenges regarding the autonomy being sought (Inkinen et al., 2021). Thus, creating an efficient decision-making tool is essential for a long-term vision of the port system, relying on investment initiatives to meet port demand and anticipate future developments (Loukili & Elhaq, 2018).

An example is the Port of Shanghai, which utilises automatic identification systems and digital data platforms to support decision-making.

4.2. Delphi and technology roadmapping

The Delphi analysis revealed three scenarios: Efficiency-driven scenario, security-oriented scenario and green-centric scenario. These scenarios were created by grouping the categories from the questionnaire. The categories were grouped within the scenarios according to the primary effects that emerged during the Delphi method. The Technology roadmapping offers guidance on prioritising technologies and their phased implementation to realise specific scenarios over time.

4.2.1. Efficiency-driven scenario

Ports are positioned to play an increasingly important role as essential nodes in multimodal transportation networks and supply chains, utilising technological improvements to enhance efficiency and effectiveness. The efficiency-driven scenario (summarised in Table 3) is based on the premise that digitalisation will be deployed to meet cost, time, and standardisation goals. Digitalisation and the integration of

Table 3
Technology roadmap: Efficiency scenario.

	Efficiency Scenario		
	Cost	Time/speed	Standardisation
Data digitalisation	**Short Term:** Data digitalisation improves data efficiency, accessibility, and storage, acting as both a cost-cutting motivator and a tool for data analysis and sharing.	**Short Term:** Data digitalisation enables Digital Platforms to make data accessible to all stakeholders, thereby speeding up access to information.	**Short Term:** Data digitalisation enhances the accessibility and storage of data.
Digital platform	–	**Short Term:** Digital Platforms increase the degree of real-time information sharing between various stakeholders.	–
Decision support system	**Medium Term:** Decision support systems give data meaning by linking it to key performance measurements like cost indicators.	**Medium Term:** Decision Support systems need to be integrated into these digital platforms. This integration not only enhances access to information but also improves decision coordination among different parties and accelerates analysis through the dashboards provided by these systems.	**Medium Term:** Decision support systems facilitate a standardised exchange of information, which is vital for establishing standardised protocols and procedures in port operations.
IoT	–	**Medium Term:** IOT integrates information from operational activities, enabling goods to be tracked and monitored, thus improving time, planning and reducing waiting times for port authorities, shipping companies, and other stakeholders	–
Digital container	**Long Term:** Digital containers eliminate the need for resources and personnel to collect and communicate information, leading to the most significant reduction in costs achievable.	–	–
Digital twin	–	**Long Term:** Digital twin optimises the operation of cranes handling containers, thus speeding up operations.	–
AI	–	–	–
Blockchain	–	–	–

technological business models have the potential to considerably increase efficiency by allowing for a smoother flow of goods and more efficient port resource management. This digital transformation not only improves port operations but also creates new services and business prospects. Digitalisation has the potential to improve port efficacy and efficiency by streamlining port operations through process standardisation, improving service quality within ports, and facilitating efficient strategic planning.

One of the primary challenges for short-term port digitalisation is to enable more efficient information distribution across port community organisations, operators, and public-private partnerships in order to create efficiency improvements. That's why the first technological trend is data digitalisation and decision support systems.

4.2.1.1. Technology roadmap – Cost

4.2.1.1.1. Analysis. In terms of cost (intended to lower costs), the three states (uncertain, desirable, and critical) have similar probability, desirability, and impact, indicating a positive trend. The high probability and impact values indicate that cost reduction is almost inevitable and critical. Data analytics, decision support tools, and digital containers will help the port industry optimise processes, resource allocation, and operational efficiency, reducing costs. Desirability values, ranging from 1 to 5, are consistently high for all three projections, exceeding 4.5. Thus, implementing these technologies is desirable. As in other sectors, cost reduction is expected to drive technological development in this growing sector.

4.2.1.1.2. Effects on scenario. The findings indicate that in ten years, cost objectives can be met by utilising three technological trends: digitalisation, decision support tools, and digitalised containers.

It will be critical to start digitalising data in the near future. Data digitalisation, which improves data efficiency, accessibility, and storage, acts as both a cost-cutting motivator and a tool for data analysis and sharing. Data digitalisation must be consistent throughout time because it is a need for deploying decision support systems. Their implementation can be evaluated in the medium term, as digitalisation must become a standard procedure at ports. Decision support tools are important because they give data meaning by linking it to key performance measurements like cost indicators.

Over time, the use of decision support tools facilitates the implementation of digitalised containers. Implementing digitalised containers results in cost advantages, provided there is already an efficient system in place to collect and analyse container information. Digitalised containers can only be implemented in the long term due to their current lack of widespread use. Digital containers eliminate the need for resources and personnel to collect and communicate information, leading to the most significant reduction in costs achievable.

4.2.1.2. Technology roadmap – Time and speed

4.2.1.2.1. Analysis. The "time" category contains three projections. All the projections, with the exception of projection P4 for small ports, have a desirability value above 4.5. This means that the technologies involved in these projections – digital platforms and IoT technologies, but generally all digital technologies - will certainly reduce the time in port operations and decision-making thanks to rapid information sharing. This also translates into increased port performance. As with the risk section, a distribution between the port's dimension for projection P8 is present. Similarly, an increase in the assessments of probability, impact and desirability can be seen as the size of the port increases. This projection questions whether small ports need enough technological integration to be smart. Ports with large ship and cargo traffic benefit most from these systems; therefore, the question is understandable. System benefits and ports' ability to make significant investments to become smart ports increase as port size increases. Thus, experts believe that only medium-sized and large ports should implement this technology, while small ports may do so later than the time horizon explored in this survey. For speed category there are the projections P12, P13, P14, and P15 and projections P13 is subdivided by port size. Digital technologies speed up decision-making and operations, as is well known. In this regard, the projections and desirability values indicate that communication and operations speed should be increased. Digital platforms and decision support tools that, through integrated information systems (P12) and container dispatching systems (P15), have almost certain probability evaluations and impact evaluations higher than 4,5 are expected to increase speed the most. Digital twin increases speed (P14), but the lower ratings in probability and effects may be due to the higher implementation complexity compared to integrated information systems and container dispatching systems. P13 shows a similar scattering between small and large ports as the other size-divided projections. Small ports may impact other operations and revenue loss due to port freight volumes and traffic, making efficient and just-in-time operations less critical. Significant port information system investments may have a lower ROI than medium or large port investments.

4.2.1.2.2. Effects on scenario. To achieve time and speed objectives over the next ten years, four technological trends should be implemented sequentially: Data Digitalisation, Digital Platforms, Decision Support Tools, IoT, and Digital Twins. Initially, it is necessary to start with Data Digitalisation, followed by the implementation of Digital Platforms. Data Digitalisation enables Digital Platforms to make data accessible to all stakeholders, thereby speeding up access to information.

In the medium term, ports can integrate Decision Support systems into these digital platforms. This integration not only enhances access to information but also improves decision coordination among different parties and accelerates analysis through the dashboards provided by these systems. Digital Platforms increase the degree of real-time information sharing between various stakeholders. The implementation of these platforms must be sustained over time, as they are crucial for integrating IoT systems at the operational level.

IoT systems can only be implemented once the use of digital platforms has become standard practice within ports. These systems integrate information from operational activities, enabling goods to be tracked and monitored, thus improving time planning and reducing waiting times for port authorities, shipping companies, and other stakeholders. The most significant time benefits are achieved by extending IoT systems beyond operational activities (such as cargo handling) to include strategic (defining objectives) and tactical (creating action plans to implement strategies) levels.

Further increases in speed can be attained by implementing Digital Twin systems in the first half of the long term. Digital Twins can optimise the operation of cranes handling containers, thus speeding up operations.

Ultimately, these efforts will lead to the development of Smart Ports, where information at the strategic, tactical, and operational levels is continuously integrated. This integration provides all stakeholders, including the port itself, with a comprehensive overview of port activities. Smart Ports can only be realised in the long term, once IoT systems at the operational level are fully functional.

4.2.1.3. Technology roadmap – Standardisation

4.2.1.3.1. Analysis. The standardisation category has only two projections (P16 and P17). P16 concerns internal actions affecting one port reality, while P17 concerns external regulations that affect multiple port realities. Digital data and data elaboration techniques help identify inefficiencies and procedural standards, as shown in the first projection. Standardising operational processes enables and catalyses cost reduction and faster transaction times, which are closely related to cost and speed goals. Following projection P17, experts believe port system legislative interventions can facilitate technology implementation. Incentives and environmental, customs, and data protection regulations allow governing bodies to influence port strategic choices.

4.2.1.3.2. Effects on scenario. To achieve standardisation objectives over the next ten years, it is necessary to consider the technological trends of data digitalisation and decision support tools. Data digitalisation should begin in the medium term and continue over time. Data digitalisation enhances the accessibility and storage of data, which is essential for the effective implementation of decision support tools.

Decision support tools can be introduced at the beginning of the medium term, as they are crucial for achieving standardisation objectives. These tools facilitate a standardised exchange of information, which is vital for establishing standardised protocols and procedures in port operations. Through the use of decision support tools, ports can streamline their operations and ensure consistent, efficient practices.

4.2.2. Security-oriented scenario

In a security-oriented scenario (summarised in Table 4), prioritising safety becomes paramount as advanced technologies are adopted to improve port safety measures and mitigate potential risks to both personnel and cargo. The action plan aims primarily to enhance maritime safety by fostering a comprehensive understanding of the broader operational environment onboard vessels. Digitalised navigation systems and standardised protocols are designed to streamline ship operations, both during voyages and while docked at ports. Ensuring compatibility between port information systems and e-navigation standards is crucial, although the action plan primarily focuses on advancing ship-based systems rather than specifically targeting port infrastructures.

4.2.2.1. Technology roadmap – Risk

4.2.2.1.1. Analysis. In risk category, projections using decision support tools to predict port congestion show the three states (uncertain, desirable, and critical) differing based on port dimensions. According to experts, decision support tools to optimise land use and harbor basin traffic are not very effective for small ports because their surface areas are small enough to be managed almost optimally without them. As the port grows, it becomes clear that finding the optimal use of this surface area becomes increasingly difficult without dedicated technologies that allow detailed analysis of all operations involving these surfaces.

Consequently, the impact of these tools is increasing as the area and freight volumes to be managed are larger and larger. It is logical that the increase in volumes handled is linked to an increase in port traffic, which translates into a greater risk of congestion and accidents. Therefore, it is reasonable to conclude that the adoption of decision support tools, by improving traffic and volume management, also has a positive influence on reducing the risk of congestion and accidents within the port. As ports' dimensions grow and as decision support tools' impact increases also the probability of occurrence and desirability for this projection increases, becoming almost certain for big ports. Also, data analysis and data exchange are very important to improve navigation security inside or in proximity of the port, which could limit damages and revenue losses.

4.2.2.1.2. Effects on scenario. Risk objectives can be achieved within ten years by leveraging the technological trends of digitalisation and decision support tools. Like cost objectives, data digitalisation should commence in the short term and continue over time. Data digitalisation supports the achievement of risk objectives by ensuring constantly updated and accessible data, complemented by the use of decision support tools. For instance, decision support tools in ports enable the monitoring of navigation data to prevent collisions, ensuring the safe movement of vessels. Additionally, providing real-time information to ship operators helps to prevent congestion and improve navigation. By integrating weather data, potential hazards in port operations and navigation can also be mitigated.

The implementation of decision support tools should occur at different time horizons based on the size of the ports. For large ports, implementation can start in the first half of the medium term; for medium ports, in the second half of the medium term; and for small ports, at the beginning of the long term. These varied timeframes reflect expert opinions and the cost investments required for these systems. In large

Table 4
Technology roadmap: security scenario.

	Security Scenario		
	Risk	Transparency	Automation
Data digitalisation	**Short Term:** Data digitalisation supports the achievement of risk objectives by ensuring constantly updated and accessible data, complemented by the use of decision support tools.	–	–
Digital platform	–	–	–
Decision support system	**Medium Term/Long Term:** Decision support tools in ports enable the monitoring of navigation data to prevent collisions, ensuring the safe movement of vessels. Additionally, providing real-time information to ship operators helps to prevent congestion and improve navigation	–	–
IoT	–	**Short Term:** IoT enables real-time tracking of all resources within the port.	–
Digital container	–	**Medium Term:** Digital containers allow to track containers and have detailed information on their location even when they are far from the ports.	–
Digital twin	–	–	**Shor Term:** Digital twin makes it possible to design and test automation systems before they are physically implemented in the port.
AI	–	–	**Medium Term:** Artificial intelligence can improve human-machine interaction by making most operations (including those related to container handling) and enhance automation through intelligent systems capable of learning, adapting and improving over time.
Blockchain	–	**Long Term:** Blockchain tracks all information of a specific container from loading to arrival is possible, ensuring transparency and accessibility for all stakeholders involved.	**Long Term:** Blockchain automates information gathering and stakeholder transactions.

ports, the risk reduction benefits are clear, justifying the significant costs. In contrast, for small ports, the benefits are less obvious, making the high investment costs harder to justify. For medium-sized ports, the risk reduction benefits are apparent, but not sufficient to warrant substantial investment.

4.2.2.2. Technology roadmap – Transparency

4.2.2.2.1. Analysis. Analysis of these projections in the transparency category reveals the importance of information retrieval and sharing and the high likelihood that technologies facilitating communication will be adopted. IoT systems (P11) are considered by experts as one of the best ways to collect and share operational information within the port. Similarly, electronic container reservation systems (P10) are also considered interesting. On the other hand, the implementation of blockchain for transparency and horizontal collaboration (P9), although has high probability and impact ratings, is not as secure compared to P10 and P11 despite being a well-known technology for information transparency and traceability. To conclude, in a 10-year timeframe, transparency will be a key element that will characterise the port sector.

4.2.2.2.2. Effects on scenario. Transparency objectives 10 years from now can be achieved by considering three technological trends, namely IoT, Digitalised Container and Blockchain. To achieve transparency, the IoT is the first system that needs to be implemented in the short term to enable, e.g., real-time tracking of all resources within the port. The IoT is, therefore, the basis for implementing Digitalised Containers in the medium term. Indeed, thanks to these systems, it is possible to track containers and have detailed information on their location even when they are far from the ports. The two technology layers of IoT and Digital Container enable the long-term implementation of blockchain. Thanks to the blockchain, tracing all information of a specific container from loading to arrival is possible, ensuring transparency and accessibility for all stakeholders involved.

4.2.2.3. Technology roadmap – Automation

4.2.2.3.1. Analysis. The category automation is the most populous of all eight categories into which the projections of the questionnaire were divided. In fact, this category contains five projections (P18, P19, P20, P21 and P22) of which P22 was subdivided according to port size. The popularity of this category is given by the fact that the automation topic has been found very relevant in the literature and, by the experts' answers this relevance has been confirmed. In fact, all but one of the projections (P18) have a high probability of occurrence and a high impact and have rather high values in terms of desirability. Experts believe simulators can train personnel by testing them with simulated problems in the virtual port, as P21 received the highest probability rating in this category. The results of these training tests may be used for interventions or strategic planning to boost technology output. About equal in assessment are projections P19 and P20. Artificial intelligence and digital twin technologies may change naval and operational security. In addition to P21, another digital twin application is highlighted, demonstrating its flexibility and strategic importance. As seen today, artificial intelligence applications are among the most diverse and coupling them with simulators can be crucial in many areas, not just port security. Projection P18 is less optimistic about blockchain. This result was unexpected given projection P9's positive evaluations of blockchain for information transparency. Information transparency and trade facilitation are intuitively linked. The low score may be due to two factors:1) free trade is transparent enough for blockchain to not significantly benefit it; 2) the integration of this technology for this purpose is complex, involving human factors as well as technology. In the P22 projection, there is always a noticeable gap between the evaluations for small ports compared to those for medium-sized or large ports. However, the difference between the evaluations, in this case, does not follow a proportional decrease between medium and large ports, and this is assumed to result from the presence of slight dissent in the average probability evaluations for P22 for medium ports and P22 for big ports. Despite this dissent, the ratings for the latter two projections remains clearly positive, indicating that automation is a trend to be pursued for this type of port. P22 for small ports has decent ratings, although with significantly lower probability, impact and desirability ratings. This difference is again judged to be attributable to the lower return on investment for the implementation of this technology in smaller ports.

4.2.2.3.2. Effects on scenario. Automation enhances security by minimising human error through the automation of repetitive tasks prone to negligence. It also enables constant monitoring of conditions, allowing for rapid response to any anomalies or emergencies while limiting damage. Automation objectives over the next ten years can be achieved by considering the technological trends of digital twins and artificial intelligence. Unlike other objectives that require layered technology implementation, these three technologies operate independently for automation. Ports will be able to choose which technology to implement, taking into account the varying adoption times due to the current maturity of the technology.

The implementation of digital twins can be considered as a short-term intervention, as their use is already spreading in many industrial applications. Consequently, automation systems can be designed and tested within the digital twin before being physically implemented in the port. In the medium term, artificial intelligence will be widely used. Artificial intelligence can improve human-machine interaction by making most operations (including those related to container handling) and enhance automation through intelligent systems capable of learning, adapting and improving over time. In the long term, blockchain will be widely used to automate information gathering and stakeholder transactions.

4.2.3. Green-centric scenario

In a green-centric scenario (summarised in Table 5), the focus shifts towards prioritising sustainability, emphasising the adoption of eco-friendly port practices and the integration of sustainable technologies to mitigate the ecological footprint of maritime transportation. Ports are the vital lifeline of global trade, acting as the nexus that connects nations and drives economic expansion. However, this pivotal role presents a significant challenge: ports contribute substantially to carbon emissions. Addressing this issue requires the implementation of various sustainable strategies, from adopting renewable energy sources and cleaner propulsion systems for vessels to embracing digitalisation and smart technologies. By leveraging sensors and AI-based solutions, ports can enhance efficiency while simultaneously reducing their environmental impact.

Human behaviour, including port staff engagement, is also crucial. Train staff and optimise work processes with ergonomics to boost port efficiency and safety. Human involvement is vital to digitalisation, especially cybersecurity. As demand for high-skilled jobs rises, digitalisation and automation present new challenges and threats to port labour. Workers need specialised training and certifications to meet these demands.

Table 5
Technology roadmap: Green Scenario.

	Green Scenario
	Sustainability
Data digitalisation	–
Digital platform	–
Decision support system	–
IoT	**Short Term:** IoT monitors air quality and water health via sensors.
Digital container	–
Digital twin	–
AI	**Medium Term:** Artificial Intelligence can respond to critical air and water pollution levels by implementing emergency containment strategies based on sensor data.
Blockchain	–

4.2.3.1. Technology roadmap – Sustainability

4.2.3.1.1. Analysis. Sustainability is a very topical issue that must therefore also be analysed carefully in the case of the port sector. In this category, another capability of digital twinning simulators is highlighted: along with speeding up operations (P14), it is also able to optimise resources (P23) - tangible but not limited to - and thus positively impact the port's environmental sustainability. An example would be a detailed planning of quayside handling equipment paths, which could considerably reduce the amount of diesel used, thereby also reducing carbon dioxide emissions. However, the desirability for this projection is limited. Artificial intelligence (P24) is also expected to be used for environmental awareness. Its use in this field could derive from the optimisation of consumption, as well as to the efficient integration of the various energy sources that a port can access.

Very closely related to P23 and P24 is P26, which predicts a positive impact of IoT technologies on sustainability. This is because IoT technologies enable the construction of smart grids, which can effectively control and manage the incoming sources of energy but also its distribution and consumption. However, it can be said that experts find it uninteresting to adopt this solution for small ports. It can be deduced from the P25 projection that it is of great interest to stakeholders that digital technologies are also used for their environmental sustainability benefits. A motivation for this is that it increases the attractiveness for environmentally aware customers.

4.2.3.1.2. Effects on scenario. The findings indicate that sustainability goals for the next decade can be attained by leveraging IoT, Digital Twins, and Artificial Intelligence technologies. IoT emerges as the initial technological layer to be deployed, necessitating short-term implementation due to its capability to monitor air quality and water health via sensors. Additionally, IoT forms the foundation for introducing Digital Twins in the first half of the medium term, facilitating real-time data utilisation from sensors to monitor emissions. Moreover, IoT serves as a precursor for integrating Artificial Intelligence in the latter half of the medium term. Artificial Intelligence can respond to critical air and water pollution levels by implementing emergency containment strategies based on sensor data.

Environmental awareness and concerns drive megatrends in modern society. Transportation is scrutinised and policy-focused due to environmental issues. These dynamics show how environmental, transportation, and technological policies interact. Numerous international agreements govern port and maritime transportation environmental goals, highlighting the International Maritime Organisation (IMO)'s role in establishing regulatory frameworks. Digitalisation can provide solutions and strategic insights to transport sector carbon neutrality and environmental regulation. In optimising waste management across multiple ports serving a region through collaborative agreements facilitated by digital solutions, environmental sustainability is becoming a key competitive advantage.

5. Discussion and conclusions

Our findings underline the critical role of digitalisation in ports and highlight the importance of predicting future digitalisation trends. Compared to other studies that focus only on a technological trend (Nguyen et al., 2022), we identified several key trends shaping the digitalisation of ports, including 'data digitalisation', 'digital twin', 'blockchain', 'digital platform', 'internet of things', 'artificial intelligence', 'digital containers' and 'decision support tools'. These trends were found to impact various organisational objectives such as 'cost', 'risk', 'time', 'transparency', 'speed', 'standardisation', 'automation' and 'sustainability'.

Our Delphi analysis revealed three distinct scenarios: an efficiency-oriented scenario, a security-oriented scenario and an environment-oriented scenario. This result represents a novelty in literature, as no study on the future of ports has ever identified scenarios. In addition, we developed roadmaps describing how and when to implement these trends to align with each scenario. Technology roadmapping is a valuable tool for prioritising technologies and planning their gradual implementation to realise specific scenarios over time. The methodology of technology roadmapping represents a novelty in the literature on the future of ports, as no study has ever provided guidance on which technologies to prioritise to achieve goals and scenarios. In fact, previous literature focused on future investigations regarding the digitalisation of specific segments of the maritime sector (Attanasio et al., 2023; Nguyen et al., 2022; Seo et al., 2023) and did not offer a general analysis and guidelines applicable to all ports on the implementation of these trends. Indeed, several studies on the future of ports have focused only on the macro-trend of sustainability (Attanasio, Battistella, & Chizzolini, 2024; Gabrielii et al., 2025), leaving out that of digitalisation, or in the context of digitalisation have only considered small ports (Klein & Spychalska-Wojtkiewicz, 2023). In fact, in this study the key elements of each digitalisation trend are selected, combined and ordered based on the aggregated expert opinion, which is then used to identify the most likely, impactful and desirable elements of each trend to define technology roadmaps, providing a practical implication for this study. Due to the nature of the method used, our study identifies trends that are likely to affect all ports, unlike other forecasting studies specific to individual ports (e.g., Seo et al., 2023, focuses only on the port of Busan) or regions (e.g. Inkinen et al., 2021, focuses only on Finnish ports). This research aims to expand the knowledge of port digitalisation by considering the future vision. Experts believe that, 10 years from now, ports will be significantly more digitalised and advanced than they are today, mainly due to decision support tools, digital twins and IoT.

This research has a twofold contribution. Firstly, the research contributes to the literature on port digitalisation by identifying and collecting in one document the trends affecting port activities and determining the probability, impact and desirability based on the Delphi questionnaire evaluations. Furthermore, it combines two foresight methods - the Delphi method and Technology Roadmapping - not yet used in the literature for this topic. Secondly, the research has practical implications: the roadmaps were identified to show three different paths to be followed to achieve the objectives of cost, risk, time, transparency, speed, standardisation, automation and sustainability, i.e., the three scenarios of efficiency, security and green. Practically, identified scenarios can help decision-makers create shared visions of future strategy among all stakeholders. Moreover, scenario building helps decision-makers assess policies and investments ex-ante, simulating different choices and attempting to mitigate risks. Furthermore, the scenarios identified describe the future and act as tools for cultural and organisational change, representing a goal the entire organisation must strive for.

The roadmaps delineated for each scenario in the study offer a systematic overview of the technologies the experts deem most probable, impactful, and desirable for achieving the strategic objectives linked to each scenario. These roadmaps specify the relevant technologies and guide the technological levels to prioritise, specifically the intermediate steps necessary for the progressive adoption of technological solutions, thereby proposing a temporal sequence (short, medium, and long term) for implementation.

This methodology enables the adaptation of technological planning to the varying maturity levels of the technologies alongside the capabilities of the ports and institutions to facilitate the associated investments, infrastructures, and organisational processes. The research contains some limitations. Methodologically, the Delphi method is significantly influenced by the composition of the panels; future research could incorporate experts from various professions, countries, and backgrounds to compare results with those identified in this study. Moreover, it is essential to highlight that some biases (e.g., preconceptions, personal experiences, and areas of expertise) affect the experts' responses. Additionally, technology roadmapping often defines future visions over extended timeframes, even as the technological and market landscape changes rapidly. Furthermore, the data used to formulate roadmaps may be based on assumptions presented by experts. Future research may employ alternative foresight methodologies to ascertain which technologies, within each scenario, facilitate the attainment of specific objectives.

CRediT authorship contribution statement

Giovanna Attanasio: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Cinzia Battistella:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Elia Chizzolini:** Conceptualization, Formal analysis, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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