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A comprehensive framework and multi-stakeholder approach

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Review

Smart, sustainable, and circular port maintenance: A comprehensive framework and multi-stakeholder approach

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A R T I C L E I N F O

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A B S T R A C T

Ports and waterways are key in supporting the waterborne supply chains that form the backbone of global trade. Maintaining adequate water depth is vital for accessibility and safe navigation. Port authorities and contractors are the key players in developing maintenance strategies, and they strive for a mutually beneficial compromise. Port authorities aim to optimize port performance while keeping costs and delays at acceptable levels. Contractors aim to optimize the use of equipment and execution strategies to achieve cost-effectiveness and time efficiency. While minimum cost and duration are common and simple decision criteria, there is growing societal pressure to incorporate smart, sustainable, and circular elements. However, these elements are less straightforward to interpret and there is a lack of a comprehensive framework to quantify smart, circular, and sustainable strategies. This lack of clarity presents significant challenges in balancing traditional and emerging objectives in port maintenance. Our study directly addresses this gap by providing a structured approach to decision-making that integrates these critical but complex elements. As a result, trade-offs on these important issues are harder to achieve reducing the contributions of port authorities and contractors. This study addresses this gap by applying the Frame of Reference (FoR) method to extract objectives and indicators for decision-making from both the port authorities' and contractors' perspectives. We fill in the prescribed elements of the basic FoR template through a systematic literature review (SLR), clarifying to what extent consensus exists on these topics. The SLR revealed 128 articles and identified common strategies, research methods, influential journals, and contributing countries. Projecting these findings onto the basic FoR template showed that the protection of marine ecosystems and sediment management has received considerable attention from researchers while mitigating emissions and adopting smart techniques are emerging subjects in the literature that need further investigations. As a result, this study offers theoretical and managerial insights to improve what can be achieved with smart, circular, and sustainable maintenance strategies, while identifying crucial remaining knowledge gaps.

1. Introduction

The growing demand for transportation in support of global waterborne trade has triggered competition among ports worldwide to attract new maritime traffic and shipping routes. The quality of port and waterway infrastructure affects the average waiting time of vessels and directly influences the tendency of shipping companies to favor a specific port or route within a region (UNCTAD, 2022). Consequently, port and waterway authorities are continuously engaged in extensive infrastructure investments and the exploration of maintenance strategies aimed at optimizing the efficiency and functionality of their operations.

Van Koningsveld et al. (2023) argued that ports and waterways should be viewed as parts of a coherent system that supports waterborne supply chains and that their integral design and operation are essential. Variations in waves, currents, and sediment transport cause sedimentation in ports and waterways. These sedimentation processes bear substantial consequences for port accessibility resulting in partial or complete obstruction of port operations (Bakker et al., 2024). The inaccessibility of a port means that vessels cannot (readily) access berth areas and delays in cargo handling cause significant economic losses. Consequently, such ports lose reliability in the eyes of shipping companies, which may opt for alternative, more reliable ports. To solve this

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problem, maintenance dredging and mitigation measures come into play to remove, mobilize, or bypass sediments, ensuring continued accessibility in ports and waterways (Wan et al., 2018).

Historically, cost and time have always been the main aspects to be controlled in port maintenance projects. During the last two decades, there has been societal pressure on both port authorities and contractors to pay more attention to other aspects of port maintenance such as smartness, sustainability, and circularity, but the lack of a clear framework inhibits their progress toward these concepts. Smartness can be implied as using digital technologies to increase the efficiency of port maintenance, e.g. by using intelligent navigation systems and devices that adjust the dredging job most efficiently by changing vessel settings (Mikac et al., 2022; Wang et al., 2022a, 2024). Sustainability can be addressed by mitigating greenhouse gas emissions, controlling the water turbidity caused by dredging works, minimizing carbon footprint, and avoiding the generation of underwater sound to protect the flora and fauna (Laboyrie et al., 2018; Han et al., 2022; Donázar-Aramendía et al., 2023; Sukri et al., 2023). Circularity can be seen by managing the dredged sediments, developing harmless methods for disposing of contaminated sediments, and beneficially re-using dredged material (Mills and Kemps, 2016; Crocetti et al., 2022; Nguyen et al., 2023b).

Increasing attention to these challenges in port maintenance leads port authorities and contractors to compromise on the quantification of these criteria. Finding trade-offs for cost and time can be easily quantified from the viewpoint of both port authorities and contractors; while there is unclarity when addressing smartness, sustainability, and circularity aspects. The vagueness of the context and application of these concepts, and the different driving factors of each stakeholder makes it difficult for port authorities and contractors to contribute. To improve this issue, this study investigates the mentioned gap by applying the Frame of Reference (FoR) method (Van Koningsveld and Mulder, 2004; de Vries et al., 2021) to define objectives and indicators for decision-making from both the port authorities and the contractors' perspective.

The increasing emphasis on incorporating smart, sustainable, and circular practices into port maintenance introduces complex challenges that go beyond traditional cost and time considerations. The absence of a clear framework for integrating these elements complicates the decision-making process, making it difficult for port authorities and contractors to achieve balanced and effective solutions (Hermawan et al., 2023). The main purpose of employing the FoR is to make the concepts of smartness, sustainability, and circularity in port maintenance explicit considering both port authorities' and contractors' viewpoints. The prescribed elements of the basic FoR template are filled through a Systematic Literature Review (SLR) to clarify the definition of smartness, circularity, and sustainability. Challenges are derived from an extensive literature review and driving factors of port authorities and contractors are described when addressing these three concepts.

The subsequent sections of this paper are organized as follows. Section 2 introduces common strategies for port maintenance, including dredging solutions and possible mitigation measures. Section 3 outlines the problem statement and research questions and describes how we will use the basic FoR template to address these questions. Section 4 describes the FoR and SLR approaches employed in this study. Section 5 discusses the articles extracted during the review and analyzes them thoroughly using the elements of the FoR approach for the three themes of smartness, circularity, and sustainability. Section 6 addresses the theoretical and managerial implications of the SLR findings and highlights knowledge gaps and future research directions. Section 7, summarizes the key insights and outcomes, providing a concise overview of the entire study.

2. Port maintenance strategies

This section introduces some key concepts that are important to understanding the difference between alternative dredging solutions and possible mitigation measures. Dredging can be categorized into mechanical and hydraulic dredging methods. Mechanical dredging physically collects the sediment in its in-situ form after which it is transported to its destination. Hydraulic dredging mixes the sediment with water after which this mixture is then re-allocated or remobilized. Given that maintenance dredging concentrates on loosely packed sediments that accumulated relatively recently, hydraulic dredging methods are often applied for the bulk of the sediment transport, while mechanical methods are incorporated for harder-to-reach spots and bed leveling details. Bianchini et al. (2019) distinguish the following primary strategies including sediment re-mobilization, anti-sedimentation structures, and pumps that are used along with sediment re-allocation as the most common approach for port maintenance. Each strategy involves its specific equipment and techniques.

2.1. Sediment re-allocation

Sediment re-allocation is an approach that includes the physical collection of sediments and their deposition in designated locations. Three main types of equipment are used to execute this job: Trailing Suction Hopper Dredgers (TSHDs), Grab Dredgers (GDs), and Backhoe Dredgers (BHDs) (Laboyrie et al., 2018). TSHDs are mobile hydraulic-type dredgers that collect the sediment while trailing, and transport it to the placement site in their onboard hoppers. They use three discharging methods: bottom door placement, rainbowing, and pipeline transport (Ban and Bebić, 2023). GDs and BHDs are mechanical-type dredgers. GDs are stationary equipment mounted on a pontoon that utilizes a grab or clamshell bucket that opens and closes to grab and lift sediments. The grab or bucket is attached to a crane and a wire is responsible for lowering or raising the bucket. BHDs use a large excavator arm to dig and scoop up sediments from the seabed. BHDs are also usually mounted on a pontoon. They can be moved to different locations and do the dredging but once in place, the excavator's arm is relatively stationary with a certain dredging range in the area. The sediments collected by GDs and BHDs are usually placed into separate barges that take care of the transport to the placement site (Chaabani, 2017; Xu et al., 2022). TSHDs can conveniently dredge sediments from locations that are in an easy trail path but the corners and the locations near quay walls are less accessible for these vessel types. GDs and BHDs, however, are better at reaching into difficult spaces, such as corners and near quay walls. Cleaning out the berth pockets, corners, and areas next to the quay walls is also done by bed-levelers and plows. These vessels flatten the peaks and troughs generated due to dredging. Therefore, different combinations of equipment are often required depending on the project's specifications.

2.2. Sediment re-mobilization

Remobilizing strategies fluidize the sediments to either transport them to a more favorable location or change their rheological properties. These strategies maintain the sediments in the same area instead of transporting them over significant distances. Water injection dredging is one of the re-mobilization techniques used to maintain the water depth by injecting water into fine sediment layers. This job is done by water injection dredgers (WIDs), small vessels equipped with plows that inject water into fine sediment layers and generate a fluid mud layer. The generated fluid mud layers might follow bed gradients or currents to move to a more favorable nearby location. In this case, the sediments stay close to the seabed but move horizontally in short distances (Ten Brummelhuis, 2021). Water Injection Dredging involves injecting large volumes of water into the sediment on the seabed or riverbed at low pressure and close to the sediment-water interface. The injected water fluidizes the sediment, creating a high-density mixture of water and sediment that becomes less dense than the surrounding sediment and rises upward. The fluidized sediment is then transported by natural currents to deeper parts of the waterway or designated areas (Kirichek et al., 2021). Re-circulation dredging involves the distribution of sediment within a waterway to maintain navigability without removing it. The process typically uses a dredger equipped with pumps that intake water and sediment and then reintroduce the mixture back into the water body through diffusers. This approach enhances sediment dispersion and fluid mud dynamics, promoting natural settling processes (van Rees et al., 2022). Bed leveling involves the use of specialized equipment, such as leveling blades or plows, to smooth out and level the seabed or riverbed. The equipment is dragged across the bottom surface, redistributing sediment from high spots to low spots, effectively creating a more uniform and even bed profile. Bed leveling is typically used to maintain navigation channels, ensuring a consistent depth and free of obstructions. This method does not remove sediment but rather redistributes it to achieve the desired seabed profile (O'Brien, 2015).

2.3. Mitigation measures

Numerous techniques and equipment can be used as mitigation measures to reduce the intrusion of sediments in the port area. Port accessibility is then ensured without a need for sediment removal. Sediment wash-out jet systems use jets to dislodge sediment and keep it in suspension, preventing accumulation and promoting natural dispersion by water currents (Bianchini et al., 2020). Hydraulic jet pumps use high-pressure water to fluidize and re-allocate sediments, making it easier to transport and reducing the need for mechanical excavation (Pellegrini et al., 2020b). Current deflecting walls are the structures that alter water flow patterns to prevent sediment deposition in critical areas, directing them toward open offshore locations (Wang et al., 2022b). Sediment traps involve over-depth dredging in a certain area to capture and retain sediment, preventing it from reaching navigational channels. This localized containment simplifies dredging by concentrating sediment in specific areas that are easier to be dredged more efficiently (Saichenthur et al., 2021). Stationary submersible pump systems can be installed at the bottom of sediment traps to continuously pump the accumulated sediments to designated disposal areas and reduce dredging frequency (Barth et al., 2016). Air bubble screens create a curtain of rising bubbles to redirect sediment, reduce deposition in designated areas, and leverage buoyancy and water flow to keep sediments in suspension (Vahaji et al., 2019). Utilizing the mentioned mitigation measures is dependent on sediment properties, project characteristics, and equipment availability.

Sediment re-allocation, sediment re-mobilization, and applying mitigation measures are not mutually exclusive in the port maintenance context, but each of these methods can be a part of a wider port maintenance strategy. Based on the local properties of ports and waterways, the best combination of these methods can be estimated considering their costs, execution time, etc.

3. Problem statement

Maintaining nautical accessibility and ensuring safe navigation of large-draught vessels requires careful design of potential port maintenance strategies. This design based on cost and time can be done in a relatively rational manner by carefully planning the execution process and assessing the number of required resources (i.e. number of days the equipment is needed on site, the estimated amount of energy/fuel required, the number of human full-time equivalents required). However, other aspects of port maintenance are gaining attention from both practitioners and researchers such as smartness, circularity, and sustainability. These concepts are still relatively undefined in the context of port maintenance in terms of their potential added value and objective evaluation criteria. It becomes even more challenging when these criteria are interpreted differently by port authorities and contractors. To shed light on these challenges, this study aims to investigate the following research questions.

- What is referred to in the scientific literature as smart, circular, and sustainable port maintenance concerning nautical accessibility?
- What quantitative criteria can be used to assess the smartness, circularity, and sustainability of port maintenance strategies?
- How do port authorities and contractors perceive the implementation of smart, circular, and sustainable port maintenance strategies differently?

To answer these questions, this study applies the Frame of Reference (FoR) approach to systematically define objectives, performance indicators, and evaluation criteria. An essential element of the FoR approach is a basic template that conveniently outlines the minimum number of elements that need to be made explicit when dealing with a decision problem. Elements that remain empty or undefined can be regarded as challenges for the decision problem at hand. To determine which challenges exist in the context of smart, circular, and sustainable port maintenance, an extensive literature review is required. Therefore, the FoR approach is coupled with a Systematic Literature Review (SLR) method to investigate the most relevant research papers published in this field, classify the main challenges, and identify the knowledge gaps. These two approaches not only highlight how the problem is viewed from both port authorities' and contractors' perspectives but also expose the driving factors in implementing each of these criteria in port maintenance. Furthermore, remaining challenges can be revealed and subjects that require further investigation can be identified.

4. Materials and methods

4.1. Frame of reference

The FoR approach was developed by Van Koningsveld and Mulder (2004) who analyzed the particularly successful policy of dynamic coastline preservation to extract the key components that are summarized as the basic FoR template. This template has proven to be a useful tool for structured analysis of existing approaches/policies and the development of new ones. The FoR approach has been applied successfully in multiple projects to gather insights from stakeholders with different backgrounds to improve their decision-making processes. Some examples of real-world projects where the FoR approach was applied successfully are the coastal sediment management policy in the Netherlands (Van Koningsveld and Mulder, 2004; Mulder et al., 2011), navigation channels design (Miedema et al., 2007), beach recreation planning (Jiménez et al., 2011), environmental monitoring of offshore renewable energy projects (Garel et al., 2014), and dredging project assessment (Laboyrie et al., 2018).

The FoR approach serves as a useful tool in quantifying the trade-offs between multiple, often conflicting objectives in port maintenance such as cost efficiency, environmental sustainability, and contribution to the circular economy. The application of FoR in real-world projects is achieved through defining clear objectives, selecting and quantifying indicators and metrics, and facilitating stakeholder communication. The basic template can be used both descriptively, to assess how well-specified existing policies are, and prescriptively, to guide the development of new policies. Every decision problem/policy requires the specification of:

- **A strategic objective:** The strategic objective represents the long-term vision of the desired state of the system under certain consideration. It serves as the overarching goal that the policies and strategies aim to achieve.
- **An operational objective:** Operational objectives are specific measurable objectives designed to execute the broader strategic goals in day-to-day operations. These objectives offer actionable steps to integrate solutions that exist for each relevant challenge.
- **A quantitative state concept:** For each operational objective, one or more quantifiable parameters are specified through the

Quantitative State Concept (QSC). These parameters provide the quantitative building blocks for decision-making. They are crucial for determining indicators, benchmarking, instating the intervention procedure, and assessing whether the objectives are met.
- **A benchmarking procedure:** The benchmarking process involves comparing the quantifiable parameters to established benchmarks or reference points. This step helps assess how well the system is performing concerning its objectives. The benchmarks are used to set performance standards and guide decision-making.
- **An intervention procedure:** Once the benchmarks are established, intervention procedures are put in place to address any gaps between the current state and the desired state. These interventions can be strategic actions, policy changes, or specific measures aimed at achieving the objectives. In any case, an intervention should be capable of achieving the desired state.
- **An evaluation procedure:** The evaluation procedure involves assessing whether the objectives have been met after implementing interventions. This step serves as a feedback loop to determine the effectiveness of the strategies and policies. It helps decision-makers to refine and adapt their approaches as needed.

Fig. 1 shows how the above elements together form the basic FoR template and how these elements are interconnected (Van Koningsveld et al., 2023).

Port authorities and contractors (e.g. dredging companies) can have different perceptions of the concepts of smartness, circularity, and sustainability in port maintenance. The FoR approach helps to make these differences explicit. The SLR is employed to extract the main perspectives from the literature and fill the basic FoR template as much as possible. The approach will reveal to what extent each of these concepts is addressed and what elements of the basic FoR template remain unspecified, or where authorities and contractors have diverging perspectives.

4.2. Systematic literature review (SLR)

SLR is an explicit and reproducible approach that helps to identify, collect, and analyze the existing literature on a specific subject (Lim et al., 2019; Filom et al., 2022). In this study, the following iterative steps are proposed to find and filter the data to make it helpful for practitioners (Theocharis et al., 2018; Sepehri et al., 2022; Nguyen et al., 2023a).

1. **Developing queries:** To find the relevant literature on the subjects of interest we need to develop appropriate queries. The queries typically consist of several synonymous keywords for each subject of study and several content-related keywords to focus the search. These keywords are combined with logical operators such as AND, OR, and NOT to form a query. During the search process, these queries are iteratively updated to include all relevant literature.
2. **Locating research articles:** A structured search strategy is required to ensure that data collection is comprehensive and that no relevant research papers are overlooked during data collection. Well-known academic data sources (e.g., Scopus, Web of Science, etc.) are used to search for related articles.
3. **Collecting the research articles:** When searching using queries, an initial pool of publications is obtained. To collect the most relevant and closely related publications, exclusion and inclusion criteria can be defined to restrict the publications obtained to a specific timeframe, subject, publisher, etc.
4. **Analyzing the articles:** After applying the exclusion and inclusion criteria the remaining articles should be analyzed to determine recent trends in the subject under study and knowledge gaps. In this step, descriptive graphs and charts are created to statistically analyze the collected articles.
5. **Interpreting the findings:** This step summarizes the findings and assesses the strength of the evidence presented in the articles, examining the practical applications of the articles, and identifying potential directions for future research development.
6. **Refining and updating:** With an iterative process, the SLR method repeats all of the above steps to continuously refine and update the collected articles, and provide the latest state of the review process.

The SLR approach can be applied to any subject. In this paper, insights into the subjects of smart, circular, and sustainable port maintenance are gained. The FoR approach is applied to contextualize the SLR steps. Search queries are developed to search for the most relevant studies that address each of these subjects. These queries consist of two parts connected by an "AND" operator: the first part is a combination of synonyms for each subject, and the second part is a combination of relevant port maintenance terms. The keywords are formulated so that they are most likely to return all relevant search results. For instance, using "smart" as a keyword includes search results for "smarter" or "smartness" and the same applies to using "circular", which includes search results for "circularity". The keywords and queries listed in Table 1 are used for the search in the Scopus database.

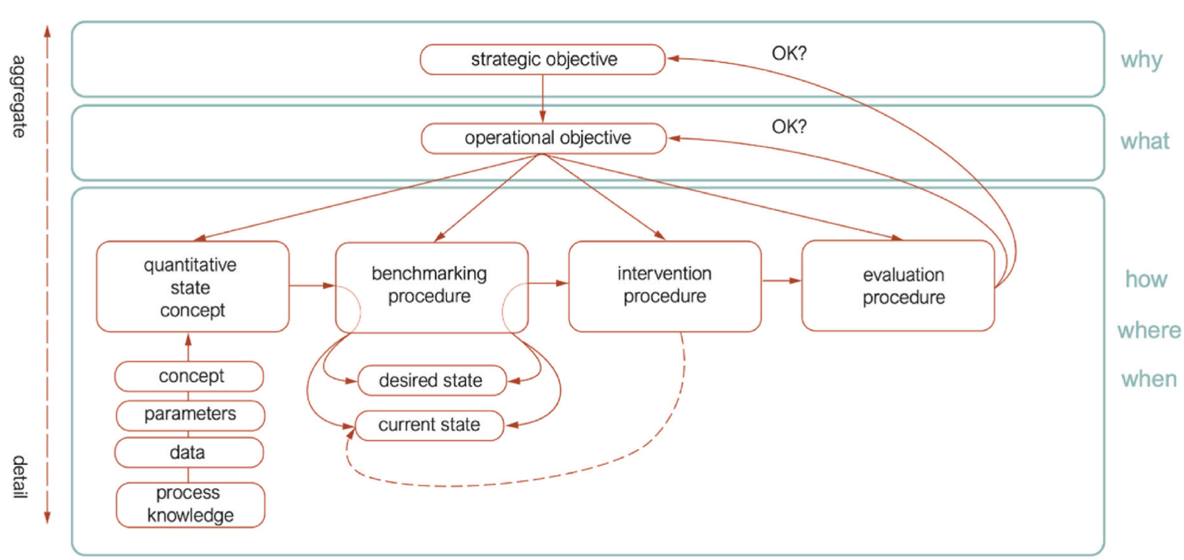

Fig. 1. Basic FoR template (Van Koningsveld et al., 2023).

Table 1
Selection of keywords and queries for SLR.

Port maintenance aspect	Query
Smartness	(smart OR intelligent OR simulation OR ai OR (artificial AND intelligence) OR (machine AND learning)) **AND** (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND remobilization) OR (sediment AND bypass) OR (prevent AND sediment))
Circularity	(circular OR (beneficial AND reuse) OR (nature-based AND solutions)) **AND** (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND remobilization) OR (sediment AND bypass) OR (prevent AND sediment))
Sustainability	(sustainable OR sustainability OR environment OR turbid OR emission OR (water AND quality) OR noise) **AND** (port AND ((maintenance AND dredging) OR (sediment AND reallocation) OR (sediment AND remobilization) OR (sediment AND bypass) OR (prevent AND sediment))

The search results showed that Scopus returns more relevant articles on the subjects of interest. Based on the query results, an initial pool of publications is created before they are filtered and analyzed. Inclusion and exclusion criteria are defined in Table 2 to find out which articles align with each subject and how the recent trend of research in each subject can be determined. The main aim is to limit the articles to English and accessible articles published since 2000. Review articles, conference reviews, and lecture notes are excluded from the search results to ensure that unique research papers are studied in the SLR. The search is focused on the research articles and conference proceedings that have contributed to the subject. Besides, a large piece of knowledge has been provided by industrial publishers (e.g. IADC, WODA, CEDA, and WODCON proceedings) that are included in the search separately.

The criteria listed in Table 2 are used to filter the search results and determine the final number of publications reviewed in each category. The results of SLR and the categorization of the problem based on the FoR approach are discussed in the next section.

5. Results

Section 5.1 provides a descriptive analysis of the literature retrieved after applying the queries and filtering steps. Once the final pool of studies to be reviewed has been found, the selected period is divided into two similar periods (2000–2011 and 2012–2024) and a statistical analysis is performed for each period. This approach helps to visualize the ongoing trend in the different subjects and to find out what subjects have been studied in recent years compared to the years before. Sections 5.2 to 5.4 describe the results of projecting these SLR findings onto the FoR template for the subjects of smart, sustainable, and circular port maintenance strategies, respectively. Each subject is considered from both the port authority's and the contractor's perspective. Separate tables are provided for each classification to identify any differences in perception and the significance of any knowledge gaps.

Table 2
Exclusion (EXC) and inclusion (INC) criteria for data filtering.

Criterion	Description
EXC1	Excluding the studies published before 2000
EXC2	Excluding the studies that are not accessible
EXC3	Excluding the studies that are not written in English
EXC4	Excluding the review articles, conference reviews, and lecture notes
EXC5	Excluding the studies that don't fit the context of smart, circular, and sustainable port maintenance
INC1	Including university theses and studies published by IADC, WODA, CEDA, and WODCON proceedings

5.1. Descriptive analysis

The search results include the publications found in the categories of smartness, sustainability, and circularity port maintenance strategies. Fig. 2 shows the data collection process and the number of articles (N) removed at each step when using the inclusion and exclusion criteria presented in Table 2. This data collection and screening process resulted in a final pool of articles aligned with the research's focus on strategies related to smartness, circularity, and sustainability in port maintenance. To make sure that the final selection of studies is consistent and content-wise relevant, the first pool of publications was extensively refined to ensure all included articles fit the context.

With the retrieved data from the SLR steps, 298 articles were obtained in the initial pool, and a total of 128 articles were studied in the SLR after implementing inclusion and exclusion criteria. The affiliation of the authors of the reviewed studies shows that the Netherlands is the leading country in the number of publications on smart, circular, and sustainable port maintenance. It is followed by the United States, China, Italy, and Spain showing a strong record of innovation in the field of maritime technology and a significant interest in addressing the challenges of sustainable port operations in these countries (see Fig. 3).

A total of 128 articles published between 2001 and 2024 shows that the number of publications has been steadily increasing over the past two decades, with a notable surge in the past five years (see Fig. 4).

This growing interest is driven by the increasing demand for sustainable and environmentally friendly practices in port operations. Fig. 5 shows the most studied challenges, including:

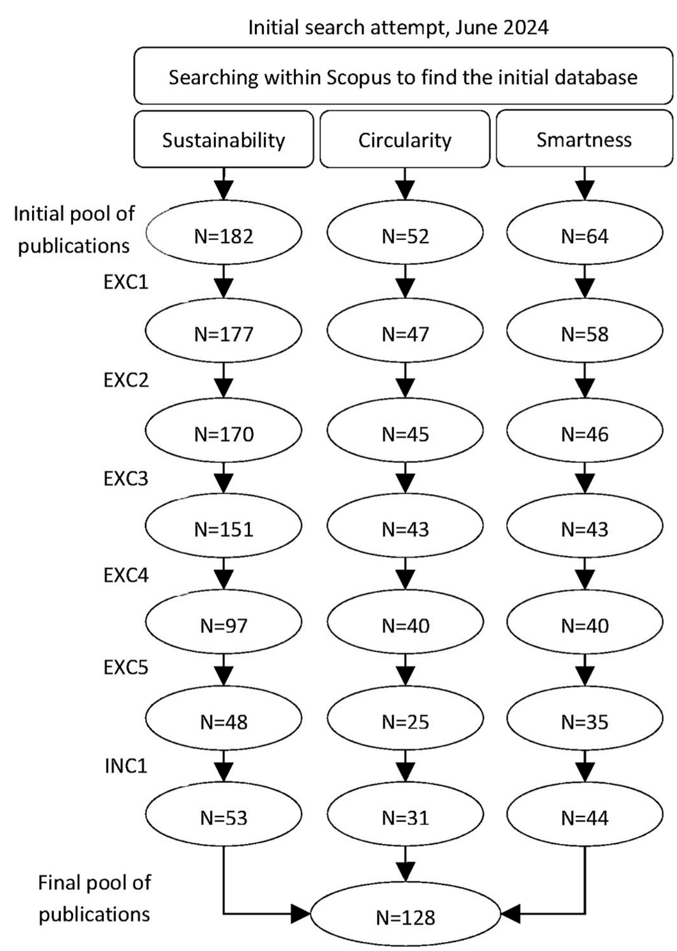

Fig. 2. Data collection process.

Fig. 3. Country-wise analysis of the reviewed studies.

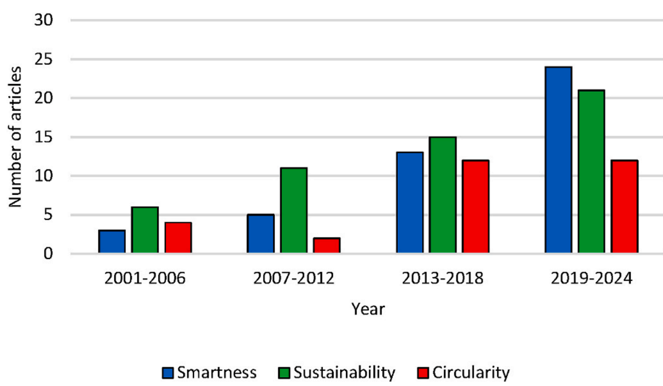

Fig. 4. Year-wise analysis of the reviewed studies.

- Water-related sustainability challenges (turbidity, underwater noise, contaminated sediments);
- Air-related sustainability challenges (greenhouse gas emissions, energy consumption, alternative fuels);
- Managing dredged sediments in an environmentally responsible manner;
- Enhancing the efficiency of port processes through smart technologies; and
- Implementing predictive maintenance strategies.

The frequency of articles addressing these challenges has evolved, with a significant increase in research on smartness and sediment management in recent years. This shift reflects the growing recognition of these topics as critical components of sustainable port maintenance.

Fig. 6 shows academic journals and industrial publishers that have published articles on port maintenance that specifically address the criteria of smartness, circularity, and sustainability. The distribution of different publishers separates the number of publications by two periods. During the first period (2000–2012), industrial publishers made the main contribution to this field of research, while a notable transition to academic journals was shown during the second period (2013–2024). In this regard, journals such as "The Journal of Environmental Management", "Ocean Engineering", "Journal of Soils and Sediments", and "Transportation Research Part E" have published a considerable number of articles, while "Marine Pollution Bulletin" remains an important journal in both intervals due to its focus on marine environmental challenges.

An analysis of keywords shown in Fig. 7 revealed a clear trend towards more focused research on port processes and smartness strategies in recent years. This emphasis is evident in the increasing use of keywords such as "maintenance dredging," "predictive maintenance," and "port efficiency." This transition shows that the recent studies not only focus on optimizing the dredging operations but also discuss the impact of dredging on port process efficiency.

Key findings from the SLR obtained from Figs. 3–7 show an increase in attention to the scope of this study. Older articles concentrated on the viewpoint of a single stakeholder, while recently published articles provide a more holistic view into the subjects of smartness, sustainability, and circularity. This transition is observed in the aim and scope of the journals that contributed to this subject recently and the main keywords used in the mentioned studies. In the next section, the Frame of Reference (FoR) approach is applied to gain a deeper understanding of the challenges identified in this section. Furthermore, the FoR framework provides a systematic way to identify relevant indicators and develop intervention procedures for addressing these challenges for developing new smart, sustainable, and circular port maintenance solutions.

5.2. Smart port maintenance

As global trade and shipping activities evolve, port maintenance

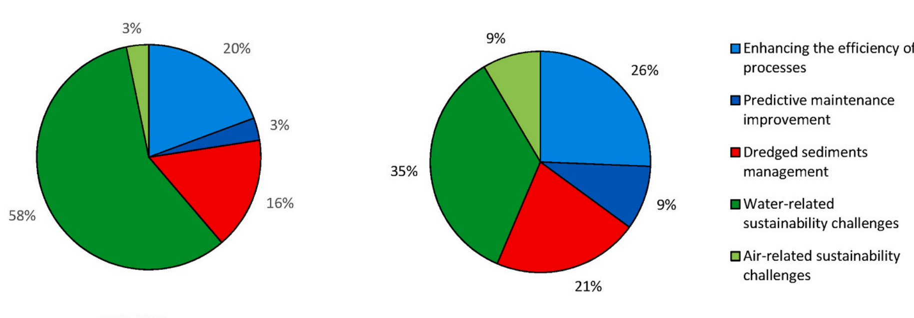

Fig. 5. Challenge-wise analysis of the reviewed studies.

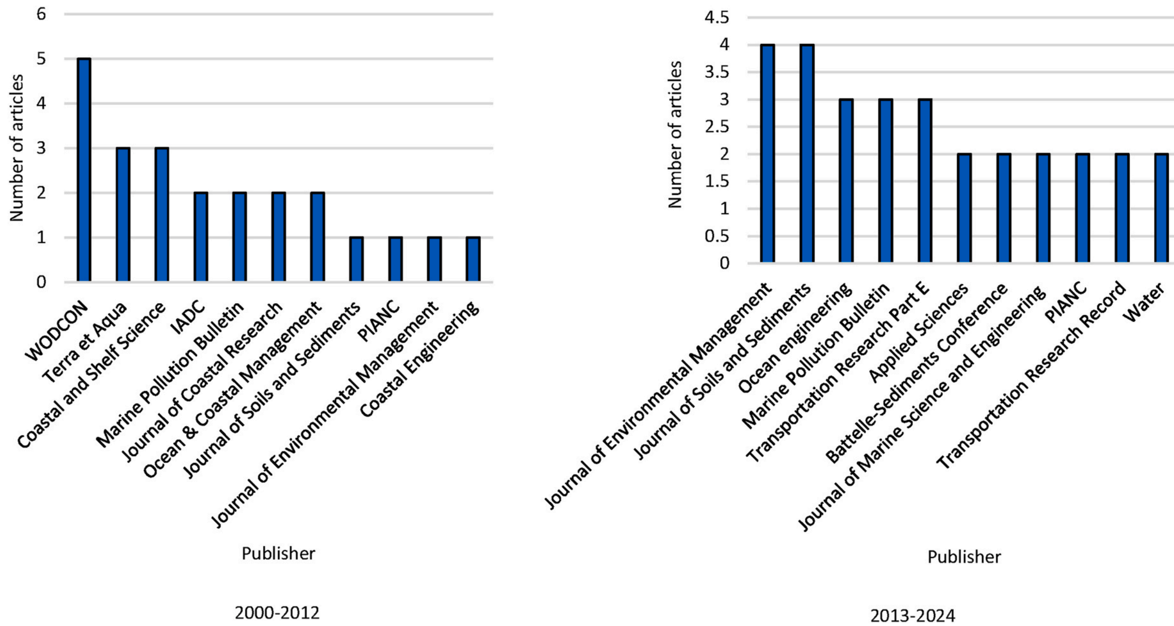

Fig. 6. Journal-wise analysis of the reviewed studies.

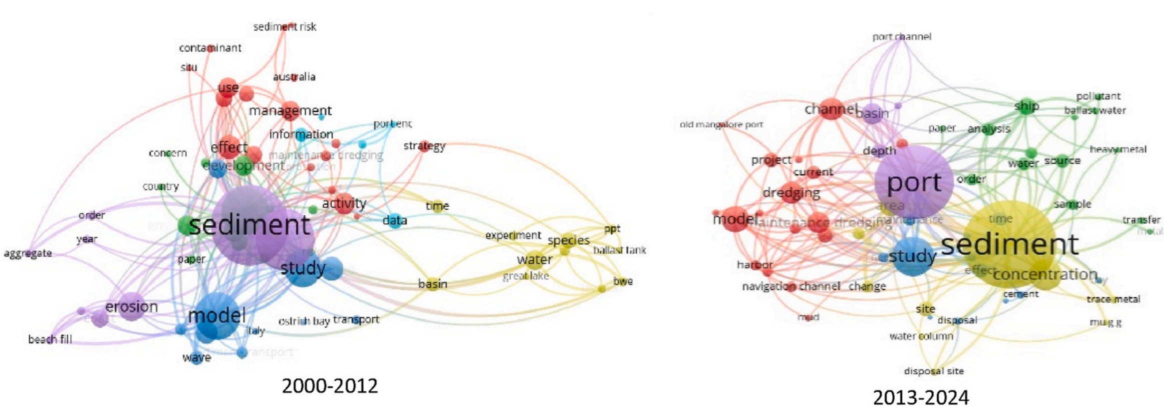

Fig. 7. Network map of keywords used in the reviewed studies.

becomes a critical factor in keeping the harbors and channels navigable and fostering sustainable practices. The integration of advanced technologies and methodologies into maintenance dredging processes offers various benefits including an increase in process efficiency, upskilling of the crew, and implementation of predictive measures. The implementation of these technologies in practice should align with the viewpoints of both contractors and port authorities.

5.2.1. *Contractors' perspective*

Smart port maintenance is viewed as a strategic approach by contractors to optimize the efficiency and effectiveness of dredging operations while minimizing costs and environmental impact. Employing smart port maintenance techniques helps contractors improve the planning of the equipment by employing advanced technologies.

Noteworthy examples from the literature review include the research works conducted by Mamunts et al. (2018) discussing GPS-guided dredging equipment, and Hayes et al. (2022) addressing the use of drones for surveying. Smart practices rely on data analysis to make informed decisions by collecting data on sedimentation rates, water depth, and dredging equipment properties.

Modern TSHDs equipped with automation systems can be controlled with integrated computer systems from the bridge (Brantjes, 2011). Braaksma et al. (2007) and Braaksma (2008) discussed a control system that helps the operators on the vessel's bridge to optimize the efficiency of the dredging process. Multiple scenarios considering different sediment properties are simulated to compare the dredged volumes per dredging cycle. Estimating the performance of excavation, sedimentation, pipeline transport, and discharge processes in a TSHD was discussed by Stano (2013) and Stano et al. (2014) who employed a nonlinear Bayesian algorithm to estimate the production parameters. Thereafter, they conducted multiple numerical simulations of the loading operation to achieve the highest efficiency for different setups. Similarly, Yue et al. (2015) adopted a quantitative classification model coupled with rough-set theory and conditional entropy to estimate the production efficiency of a TSHD considering the impact of sediment and underwater conditions. Estimating the production of a TSHD was further elaborated by Van Rhee (2002), Wangli et al. (2007), Su et al. (2017), Li et al. (2017), Sloof (2017), Tang and Fu (2020), Mao et al. (2022) and Hao et al. (2022) to achieve the optimal control strategy in the loading phase of a TSHD when real-time evaluation of the dredging performance is included. A production model for the draghead was then formulated by de Jonge (2017) who simulated different dredging scenarios by changing the physical parameters of the loading phase. Predicting the suction density of the sediments in a TSHD was discussed by Hao et al. (2020) who proposed a meta-heuristic algorithm to optimize extreme learning machine models and build an output simulator for suction density. Later, the quantitative relation between the performance of a TSHD and operational parameters was discussed by Tang et al. (2021) who coupled deep learning and human knowledge. They collected the big sensor data and quantified the mentioned relation by solving a sparse optimization problem. Estimating the production of a TSHD was further elaborated by Bai et al. (2021) by adopting the ReliefF-Granger algorithm for data analysis and artificial intelligence (AI) to extract the significant factors in calculating the production.

Applying data-driven methods in the dredging process can help contractors explore new opportunities to employ multiple soil, vessel, and site conditions along with environmental regulations. Mourik and Osnabrugge (2015) discussed the devices and sensors in the new vessels that can be used to measure the production of vessels. Bokuniewicz and Jang (2018) analyzed how the sensors and location-tracking systems can be used to monitor the real-time location of dredging vessels. These systems provide heatmaps in which various intensities of colors represent the frequency of vessel presence in each designated area. Evaluating the project duration, the beginning of the job, and risk probability is vital for contractors before submitting a tender. Chou and Lin (2020) employed Monte Carlo simulation coupled with a stochastic machine learning approach to assess the uncertainty of project duration in the initial phase of tendering. An agent-based simulation is another research method to connect numerous operational variables of a dredging process. De Boer et al. (2022) introduced an agent-based simulation package based on discrete events that define multiple objects that interact during the simulation process. This package is also applied by de Boer et al. (2023) to investigate the interaction of different dredging equipment when the number of each equipment and the total amount of dredged sediment is adjustable.

Upskilling the dredging crew using simulators is addressed by Mourik and Braadbaart (2003) and van Muijen et al. (2003). The goal of these simulators is to achieve the highest efficiency for dredging vessels and to mitigate the breakdowns and environmental impact of the dredging processes. Virtual 3D dredging sites in simulators provide trainees with hands-on experience in dredging techniques, automation systems, data analysis, and on-board diagnostics.

The mentioned literature described numerous examples from the literature that could be classified as smart port maintenance practices from a contractor's perspective. The strategic objective that encapsulates all of these examples can be formulated as "To execute port maintenance with the most efficient way of using the dredging equipment".

5.2.2. *Port authorities' perspective*

Port authorities aim to maintain efficient and safe navigation of seagoing vessels to facilitate port processes and prevent disruptions. To ensure this, berth areas, turning basins, and navigation channels should remain at the required depth to reduce the risk of groundings and delays. Meanwhile, port maintenance operations might interfere with the port processes and cause delays for seagoing vessels that intend to be served in a terminal. Smart practices are helpful in better planning maintenance works, improving the efficiency of port processes, mitigating the corresponding costs, and minimizing environmental impacts.

Skibniewski and Vecino (2012) introduced a web-based project management framework to improve the performance of port maintenance projects. This framework which is used to optimize the cycle time of processes can be aligned with the contractors' business rules by generating several scenarios and estimating the cost efficiency of each scenario. On the other hand, analyzing spatial and temporal data helps port authorities in the predictive maintenance of ports and waterways when it is coupled with monitoring the bathymetric data (Xin et al., 2022). The bathymetric data is further used by Hu et al. (2022) to monitor the impact of dredging on sedimentation patterns in the future and optimize the efficiency of dredging processes.

The budgeting problem for maintenance dredging projects is discussed by Mitchell et al. (2013) who determined an optimal budgeting scheme for multiple projects when the efficiency of port processes is also taken into account. A polynomial time heuristic algorithm is used to optimize the problem based on maximizing the amount of cargo throughput and potential dredging scenarios. Similar research was conducted by Khodakarami et al. (2014), who developed a budgeting model that optimizes the benefits of multiple maintenance projects in a multi-modal transportation network. Different maintenance dredging scenarios are analyzed in terms of the required financial resources and operational efficiency. They also included the capacity of ports and waterways network and depth restrictions in the model. The budgeting problem was coupled with the selection of maintenance dredging strategies by Ahadi et al. (2018), who incorporated budget uncertainty assigned to each port district. The genetic algorithm developed in this study aims to address the disrupted flow due to the lack of sufficient depth for the navigation of seagoing vessels.

The role of machine learning and AI in port maintenance was discussed by Liu et al. (2019) who employed multiple machine learning algorithms to estimate the sediment types considering bathymetry and backscatter. They proposed an efficient model that predicts the changes in sediment distribution which can be used to preserve the water quality and control the impact on benthos. Similarly, many other articles (Goldstein et al., 2019; Pham et al., 2019; Mateo-Pérez et al., 2021; Bashir, 2022; Houser et al., 2022) investigated the application of AI in analyzing the morphological data to determine sedimentation and hydrodynamic patterns and to propose novel strategies for port maintenance that has the lowest costs and minimum environmental impacts.

Analyzing the big data of pre and post-dredging surveys conducted by Sugrue (2021) and Rahman and Ali (2022) was used to evaluate the effectiveness of maintenance dredging processes. The authors considered the largest draught of seagoing vessels when selecting the port maintenance strategies to identify the navigation issues. In this regard, predicting the sedimentation process in berths and channels is also significant when monitoring the safe navigation of vessels and planning for regular maintenance dredging. Nakagawa et al. (2023) utilized the obtained data from bathymetric surveys to simulate the hydrodynamics, predict the sedimentation process, and ensure efficient port maintenance. Sepehri et al. (2023) applied agent-based simulation to identify the interference between dredging equipment and seagoing processes in terms of the waiting time that each vessel experiences before being served in a terminal. Determining these interactions can be used to improve the port processes planning and to select port maintenance strategies by quantifying trade-offs between different indicators (e.g., cost, energy consumption, emission, etc.). Analyzing the automatic identification system (AIS) by Sepehri et al. (2024b) demonstrated the interferences of seagoing processes and maintenance dredging operations when a TSHD aimed to dredge a terminal in multiple cycles. The waiting time of seagoing vessels due to the lack of required nautical accessibility was then quantified while monitoring the vessels' movements according to the AIS data.

The reviewed literature above elaborated on reported examples of smart practices of port maintenance from the viewpoint of port authorities. The strategic objective that encompasses all of the instances can be formulated as "To perform cost-effective port maintenance with the least interference with port processes".

5.2.3. *Synthesis*

The FoR approach used in this study elaborates on how the above-mentioned strategic objectives from the contractors' and port authorities' perspectives could be further operationalized. The obtained insights from the SLR when following the FoR template are used to develop a coherent perspective for all stakeholders. This approach helps us by (a) having more explicit perspectives on what could be considered "smart port maintenance"; and (b) showing how contractors and port authorities have different perceptions on this problem.

The results obtained from reviewing the literature show that both contractors and port authorities have different viewpoints that overlap at some points (see Table 3). Contractors address the efficiency of port maintenance based on the equipment's operational performance, while port authorities aim to connect it to the interaction with port processes. Outlining the downtime in both port maintenance operations and port processes can lead to a compromise between contractors and port authorities during the project implementation. Operational inefficiencies along with port hindrances during dredging both associate with the cost-effectiveness of port maintenance projects. Contractors aim to improve their cost-effectiveness by achieving a holistic view of project characteristics and equipment performance, while port authorities try to have accurate estimates of the required budget. The majority of research works are done from the perspective of contractors focusing on improving the performance of different steps of the project with a few research papers examining how port maintenance can affect the performance of port processes.

5.3. Sustainable port maintenance

Sustainable practices in port maintenance seek to harmonize social and economic considerations to safeguard long-term ecological health while maintaining efficient maritime operations. These practices involve strategies that minimize adverse aquatic environmental impact (e.g., hydrodynamic variations, turbidity increase, and wastewater discharge), ecological impact (e.g., loss of benthos and escape of aquatic animals), and other effects (e.g., vessel exhaust emission, vessel noise emission, and dispersion of contaminated sediments) (Han et al., 2022). These effects can be controlled by minimizing dredging frequency, utilizing eco-friendly equipment, and engaging stakeholders with different perspectives.

5.3.1. Contractors' perspective

Contractors aim to minimize the environmental impact of port maintenance operations by adopting eco-friendly equipment that leads to fewer sediment dispersions, lower exhaust emissions, and lower noise emissions. They actively engage with local communities and stakeholders to ensure that port maintenance aligns with community values. Transparent communication, consultation with stakeholders, and collaboration with environmental organizations help contractors to achieve these goals.

Noteworthy examples from the literature review include many research papers (e.g. Gilkinson et al. (2003), Hitchcock and Bell (2004), Erftemeijer and Lewis III (2006), and Erftemeijer et al. (2012)) discussing the impact of port maintenance operations on physical habitats, analyzing the effects of contaminated sediments on the marine environment (Guerra et al., 2009), monitoring the impact of heavy metals on local habitats (Donázar-Aramendía et al., 2023), and developing decision-support tools to mitigate these effects (Ramirez et al., 2017). Besides, contractors follow legislation posed by their governmental and non-governmental clients. el Mahdi Safhi et al. (2024) analyzed the sustainability limits of managing the dredged sediments in port development projects by introducing different real-world case studies. Innovative solutions proposed by dredging companies are also discussed to draw a conclusion on which environmentally-friendly approaches can be further developed for port infrastructure projects.

Dredged sediments released from dredging equipment, including TSHD overflows, disturbance in the area of dragheads and jetbars, and scouring of the seabed by propellers and bow-thrusters are the main sources of generating turbidity. By extracting real-time data on overflow losses in a TSHD, Kerssemakers (2004) and Babuska et al. (2006) discussed an estimation of the mixture density and flow rate. The performance of the TSHD in overflow losses was evaluated by simulating the processes with real measurements. A new Computational Fluid Dynamics (CFD) model was developed by Decrop (2015), Decrop et al. (2016, 2017), and Decrop et al. (2018) to understand the dynamics of sediment distribution in a designated marine environment and implement mitigation measures to minimize its impact on the local habitats. Furthermore, the CFD modeling was applied for the sediment diffusion characteristics and their influencing factors during the overflow stage of a TSHD to minimize the pollution impact of sediment disturbance (De Wit, 2010, 2015; Luo and Yu, 2019; Shao et al., 2020). Advanced technologies on board help the crew to monitor the performance of the dredging equipment in real-time and adopt control strategies where the dredging vessel has no overflow, has a certain amount of overflow, or has a controlled overflow. A trade-off analysis coupled with environmental risk assessment is proposed by Becker (2011), Dupuits (2012), and Becker et al. (2015) to determine how the overflows affect the vessel's production and the ecological health of the surrounding environment. Bai et al. (2022) discussed an optimization method for the loading cycle of a TSHD in which statistical analysis and machine learning methods are employed to predict the total amount of loaded sediments in the hopper bin and the rate of overflow loss.

Underwater sound is generated by dredging equipment, jet pumps, and air bubble screens, which can be harmful to marine fauna. De Jong et al. (2011) discussed this challenge by providing a framework applicable to port maintenance projects to analyze the possible effect of different types of sounds generated in different places or measured by different monitoring equipment. This research was tested by Reine et al. (2014) using regular surveys that determine the relation between the generated underwater sound and the total amount of dredged sediments within a certain period.

The relation between the amount of emissions and the fuel type in a TSHD was discussed by Ytsma et al. (2009) suggesting the dredging

Table 3
The FoR of smart port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	To execute port maintenance with the most efficient way of using the dredging equipment	(Brantjes, 2011; Bai et al., 2021; Tang et al., 2021)	To perform cost-effective port maintenance with the least interference with port processes	(Ahadi et al., 2018; Sepehri et al., 2023)
Operational objective	No deviation from the predicted cycle time of port maintenance processes due to inefficient performance of equipment and operators' errors	(Bokuniewicz and Jang, 2018; Chou and Lin, 2020)	No overrun from the estimated budget and no deviation from the predicted cycle time of port processes	–
Quantitative state concept	Duration of cycle time, operational and workability-related delay periods of equipment	Yue et al. (2015)	Estimated project budget and duration of interference between port maintenance and port processes	Nakagawa et al. (2023)
Benchmarking process	No equipment downtime due to inefficient performance of equipment and operators' errors	–	No exceeding budget and no waiting time for seagoing processes due to port maintenance	Hu et al. (2022)
Intervention process	Reschedule equipment processes based on smart and data-driven methods and upskill operators to achieve deliverables.	(de Boer et al., 2022, 2023)	Regulate a penalty cost for the requested extra budget and potential waiting time of port processes.	(Mitchell et al., 2013; Khodakarami et al., 2014)
Evaluation process	Real-time assessment of equipment efficiency, project characteristics, and operators' performance	(Li et al., 2017; Hao et al., 2020)	Regularly monitor the cost-efficiency of port maintenance operations and their interactions with port processes.	Sepehri et al. (2024b)

companies invest in the energy transition in their fleet. Understanding the behavior of energy systems in a TSHD for emissions reduction is discussed by Shi (2013), de Roode (2020), and de Roode et al. (2022). Thereafter, the vessel's operational performance can be optimized along with minimizing the total emissions. Automatic steering is a solution to minimizing emissions discussed by Noshahri (2016) when the vessel's operation is adjusted based on the highest efficiency and environmental restrictions. Van Ingen et al. (2021) classified the main energy-consuming phases of a TSHD into gathering, pumping, and transportation and compared the total emissions from these phases with the processes of WID.

The reviewed studies discussed some instances of sustainability criteria in port maintenance from the viewpoint of contractors. Varied problems addressed in sustainable port maintenance result in a broad strategic objective which can be formulated as "To promote the sustainability of port maintenance operations, by preserving coastal habitats, reducing sediment dispersion, underwater sound, and greenhouse gas". Regular assessment of sustainability practices' performance helps contractors achieve a trade-off between equipment efficiency and environmental damage mitigation strategies (Bianchini et al., 2019).

5.3.2. Port authorities' perspective

Port authorities aim to achieve a balance between economic development and environmental consequences of port maintenance operations. The initiative of port authorities is to maintain the required water depth with the least environmental impact on the local habitats when collaborating with environmental agencies and local communities. These practices also incorporate monitoring water quality, total greenhouse gas emissions, and underwater sound intensity.

Bray (2008) established a holistic view of the environmental impact of dredging projects and how it affects project planning and execution. Later, Sulaiman et al. (2011) emphasized the port authorities' requirements for maintaining the accessibility for large-draught vessels along with comparing the sustainability aspects of different dredging strategies. Scheffler et al. (2014) proposed a multi-criteria decision analysis (MCDA) model to analyze the sustainability of different dredging projects. A stochastic multi-criteria acceptability analysis is proposed to determine which project contributes to each economic, social, and environmental aspect of sustainability.

Sediment dispersion is a significant issue that causes ecological risks and was addressed in different studies. Mestres et al. (2014) studied the impact of sediment spills from the barges used for transporting the dredged material on the surrounding marine habitats. Pellegrini et al. (2020a) presented a technology based on a patented jet pump that maintains the water depth through continuous removal of sediments. The cost-effectiveness and environmental impact of this technology are then compared to the traditional maintenance dredging method. In another study (Mikac et al., 2022), the efficiency of jet pumps as sediment bypassing plants is analyzed by measuring the reduction of organic matter content in the sediment and the higher diversity of fish fauna in the local environment.

Short-term and long-term impacts of maintenance dredging operations on the aquatic environment were discussed by Thibodeaux and Duckworth (2001) concerning the dispersion of contaminated sediments. Monitoring of contaminated sediment dispersion was conducted when contamination of the remobilized sediments by TSHDs causes serious damage to flora and fauna, especially in the displacement location of a TSHD (Ponti et al., 2009; Torres et al., 2009). Wasserman et al. (2013) proposed a new planning approach for maintenance dredging where monitoring the contaminant concentration in the sediments is a part of the environmental impact assessment. A detailed mapping of contamination is shown in separated regions and limitations are established to avoid extra concentration of these sediments in each region. Donázar-Aramendía et al. (2018) and García-Oliva et al. (2019) employed a Before-After-Control-Impact (BACI) approach to determine the impact of port maintenance on the salt intrusion in estuaries. The authors assessed the impact of dredging on sediment and water characteristics, macrofaunal communities, and surrounding shallow water habitats. Moreover, the quality assessment of sediments was discussed by Birch et al. (2020) based on anthropogenic change (AC) and ecological risk (ER) in port estuaries. Miró et al. (2022) discussed multiple challenges such as the impact of port maintenance on the macrofauna of the water column in a turbid estuary. Establishing environmental limits that should be included in the port development plans is discussed by Suedel et al. (2024) to predict the potential adverse impacts of dredging on sensitive habitats. In this regard, the indirect effect of dredge plumes on surrounding coral habitats is assessed by developing a risk-based framework that applies preventive measures when the risk level surpasses a certain threshold.

The potential risks of underwater sound during maintenance dredging are addressed by developing a risk-based framework for different marine species (McQueen et al., 2023). The framework can be used by port authorities to regulate sound emission regulations during port maintenance. Underwater sound is further analyzed by Suedel et al. (2019) for different phases of maintenance dredging such as excavation, transit, and material placement. The developed risk-assessment framework in this study uses different site-specific information to evaluate the potential damage of generated sound by each dredging phase to the flora and fauna.

Port authorities seek to minimize the impact of port maintenance operations on air quality and greenhouse gas emissions as they recognize its importance on public health and surrounding ecosystems (ParisAgreement, 2015). When it comes to port maintenance, one of the ambitions of port authorities is to minimize the greenhouse gas emitted from both dredging and seagoing operations, while the required water depth is maintained and port processes are not disrupted. Energy transition in dredging equipment is an emerging subject that contributes to mitigating the total emissions of the system. Ban and Bebić (2023) analyzed the opportunities for using alternative fuels in a TSHD and how the type and amount of emissions can be reduced. Nooren (2023) investigated the initiatives of Dutch port authorities in reducing carbon emissions in the maintenance dredging operations when considering the expectations of different stakeholders such as environmental agencies.

The reviewed studies discussed how port authorities view sustainability aspects of port maintenance. Based on different issues elaborated in this scope, the strategic objective that encapsulates all of these issues can be formulated as "To promote the sustainability of port maintenance operations and port processes, by imposing operating limits on habitat protection, focusing on the emissions of sediment, underwater sound, and greenhouse gas".

5.3.3. Synthesis

The FoR approach is used to elaborate on how the mentioned strategic objectives could be further operationalized in Table 4. The insights obtained from the SLR coupled with the FoR template help us in (a) understanding the explicit definition of sustainable practices in port maintenance, and (b) how contractors and port authorities have different perspectives towards these practices.

The insights drawn from the literature show that similar to the smartness aspect, contractors and port authorities address the sustainability aspects from the perspective of equipment and port processes respectively. To ensure that sustainability criteria are followed during port maintenance projects, port authorities establish operating limits on the emissions of sediment, underwater sound, and greenhouse gases that might be harmful to local habitats. On the other hand, contractors assess their equipment performance regarding the mentioned emissions to make sure that they remain within acceptable limits and apply mitigation practices if they don't follow the regulations. The abovementioned emissions are more frequently addressed for dredging equipment of contractors and port authorities mainly outlined the environmental damages of these emissions on surrounding habitats.

Table 4
The FoR of sustainable port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	To promote the sustainability of port maintenance operations, by preserving coastal habitats, reducing sediment dispersion, underwater sound, and greenhouse gas emission	(van Ingen et al., 2021; Bai et al., 2022)	To promote the sustainability of port maintenance operations and port processes, while imposing operating limits on habitat protection, focusing on sediment dispersion, underwater sound, and greenhouse gas emission.	Sulaiman et al. (2011)
Operational objective	The total sediment dispersion, underwater sound, and greenhouse gas emission should remain within the limits imposed by regulators and clients.	(Noshahri, 2016; Shao et al., 2020)	The port accessibility is maintained by keeping sediment dispersion, underwater sound, and greenhouse gas emissions within the limits that avoid harm to local habitats.	–
Quantitative state concept	Sediment dispersion, underwater sound, and greenhouse gas emission as a function of space and time concerning the use of dredging equipment	Ramirez et al. (2017)	Acceptable limit values on the environmental stresses focused on sediment dispersion, underwater sound, and greenhouse gas emissions related to the resilience of nearby receptors.	McQueen et al. (2023)
Benchmarking process	Assess that the equipment dispersion of sediment, generation of underwater sound, and emission of greenhouse gas remain within acceptable limits, and if not, adopt emission mitigation practices.	–	Assess that the efficiency of existing limits guarantees the sustainable interaction between the port and environment and if not, adjust the limits.	Scheffler et al. (2014)
Intervention process	Establish separate sediment dispersion, underwater sound, and greenhouse gas emission reduction practices according to the existing limits.	(Decrop et al., 2018; de Roode et al., 2022)	Establish operating limits that result in a trade-off between the economic performance of port processes and environmental damages caused by port maintenance operations.	Pellegrini et al. (2020a)
Evaluation process	Evaluating how emission limits contribute to the sustainability aspect of port maintenance	Bianchini et al. (2019)	Evaluating how emission limits contribute to the sustainability aspect of port maintenance and ensures the port accessibility and efficiency of port processes	(Birch et al., 2020; Suedel et al., 2024)

5.4. *Circular port maintenance*

Circularity in port maintenance refers to adopting practices that minimize sediment waste and determine beneficial purposes for the collected materials. It involves dredging methods that instead of re-allocating the sediments in displacement areas, employ methods that re-use the dredged sediments in infrastructural projects. During the sediment handling, extra operations on the sediments might be required such as dewatering, treatment, and processing. Contractors and port authorities have different driving factors toward the circular practices in port maintenance which are elaborated as follows.

5.4.1. *Contractors' perspective*

Contractors contribute to the circular economy by re-designing the operational cycle of equipment. It includes using pipelines to transport the sediment in designated locations or rainbowing the sediment to the shoreline instead of re-allocating it in an offshore area. Meanwhile, the impact of these extra operations on the efficiency of the whole dredging cycle should be analyzed along with its environmental impact on the surrounding habitats (Mills and Kemps, 2016). Sediment transport for circular practices plays an important role in determining the efficiency of re-using the dredged material and contributing to port process facilitation. Karambas and Samaras (2014) developed a mathematical model that formulates the sediment transport in port maintenance projects to use the dredged sediments for shore protection and maximize the efficiency of dredging operations. The Kleirijperij project in the Netherlands is an instance of re-using the dredged sediments for beneficial purposes when a TSHD built a sediment trap in the location with the highest sediment concentration and transported the collected sediments to the dewatering units through the pipeline (Kleirijperij, 2018). During the project, contractors generated a closed-loop dredging cycle adopting different strategies to facilitate the clay production in the system which later can be used for dike reinforcement.

Besseling et al. (2021) discussed the beneficial re-use of sediments from the viewpoint of using dredging equipment by categorizing the whole process into dredging, transport, and application phases. Besides, the circularity aspect of implementing the projects is studied from the perspective of operational costs, emissions, impacts on surrounding natural systems, and the volume of dredged sediments being reused. Coulet et al. (2014) investigated the possibility of using geotextile tubes as a part of a retaining structure by Broads authority. Dredging was done by a grab dredger when using barges for transportation of the dredged sediments. The barges were emptied at the project site by a long-reach excavator and the sediment was pumped into the geotextile tubes and backfill areas. The dredging contractors conducted a soil investigation before project implementation and the stages of implementing the project were specified. Coulet et al. (2016) discussed the use of geotextile bags to be used as a breakwater when dredging the Waterside Marina for maintenance dredging. The breakwater was designed to perform stable based on the hydraulic conditions of the estuary and marina. The sediment was dredged by a backhoe dredger deployed on a pontoon and pumped into the geotextile bags mechanically. The efficiency of the dredging method was continuously monitored during the excavation phase.

The studied literature can be classified as circular port maintenance from the contractor's viewpoint who aims to justify the dredging processes in a way that can be used for circular projects. Also, integrating regular maintenance dredging with other strategies such as using sediment traps and sediment pipeline transport are interesting topics for contractors. The strategic objective encapsulates all of the circular practices and can be formulated as "To promote the circularity of port maintenance by optimizing the efficiency of sediment management". This objective can be operationalized further by adopting cost and time efficiency factors of the dredging project for contractors along with the importance of contributing to the circular economy and gaining a reputation in the competitive environment.

5.4.2. Port authorities' perspective

Port authorities consider the dredged sediments as port assets that should be maintained within the port environment not only to contribute to the circular economy but also to optimize the resource efficiency for construction projects. The final product is achieved when the local environment is preserved and the cost-efficiency of the project is optimized.

A study proposed by Hanson et al. (2002) discussed national information concerning beachfill operations for coastal protection by re-using the dredged sediments from port maintenance. Dean (2002) elaborated on beach nourishment by emphasizing the benefits of these projects such as damage reduction and environmental enhancement. In another research work, Paipai (2003) and Brandon and Price (2007) investigated different examples of beneficial re-use of sediments such as reclamation, building construction material, and habitat restoration. Habitat restoration as an application of reusing dredged materials was further analyzed by Yozzo et al. (2004) who analyzed the efficiency of using sediments for the construction of artificial reefs, oyster reef restoration, and wildlife island creation. They presented the pros and cons of adopting these strategies along with estimated costs and potential risks of the projects. Studds and Miller (2010) analyzed the re-using of dredged sediments from maintenance dredging for canal stabilization while considering a trade-off between maintaining the accessibility of navigation channels, de-contamination of the sediments, and the suitability of re-using the sediments for construction fill. Other applications of re-using sediments were presented by Temmerman et al. (2013), Tonneijck et al. (2015), Lunemann et al. (2017), and Laperche and Lemiere (2019) on coastal protection, Fuller (2015) and Baptist et al. (2019) on tidal marshes enhancement, and Bortali et al. (2022) and Nguyen et al. (2023b) on building construction material. The SURICATES project was also another example of nature-based solutions in coastal protection conducted by closed-loop dredging cycles to satisfy the port accessibility requirements and avoid the disturbing of contaminated sediments using a real-time monitoring system (Lemière et al., 2022; Masson et al., 2019).

Coastal erosion was discussed by Pranzini et al. (2015) by outlining the major management aspects and the potential strategies that can be used to re-use the dredged sediments for this purpose. Winterwerp et al. (2016) described building with nature as an innovative approach to restoring eroding mangrove-mud coasts. They analyzed the patterns of degrading coastlines before the start of the project and adopted sustainable aquaculture policies during the project implementation to prevent soil subsidence, hydrological disturbance, and damage to remaining ecosystems. Then, Pranzini et al. (2018) proposed a model that predicts the sediment distribution when being re-used in beach nourishment. Nature-based solutions were further discussed by Spearman and Benson (2022) and Spearman and Benson (2023) when connecting the potential solutions for habitat restoration and different dredging strategies. They concluded that instead of using TSHDs and discharging material in designated offshore areas, an agitation dredging approach using a WID can be adopted to remobilize the sediments. This approach reduces the carbon emission and dredging costs significantly and contributes to the circularity by providing the recycling of sediment within the estuarine system. Crocetti et al. (2022) and Dengate et al. (2022) reviewed the circular trends applied in re-using the contaminated dredged sediments by addressing the technical and socio-environmental aspects of sediment-based by-products. The relationship between sediment management and port maintenance was further developed by Bian et al. (2022) who aimed to maximize the amount of sediments being re-used and the navigability index in the port that guarantees the port is accessible for a certain period. Later, Sepehri et al. (2024a) connected the circular re-use of dredged sediments to different strategies of port maintenance and the efficiency of port processes.

The articles above discuss the circular port maintenance problem from the port authorities' point of view which can be encapsulated in a strategic objective as "To promote the circularity of port maintenance by developing practices for re-using the dredged sediments in the port as an asset". Operationalizing this objective requires multiple considerations such as determining the physical aspects of the project along with economic and environmental impacts on the local community.

5.4.3. Synthesis

The FoR approach is used to elaborate on how the mentioned strategic objectives could be further operationalized in Table 5. The insights obtained from the SLR coupled with the FoR template help us (a) understand the explicit definition of circular practices in port maintenance, and (b) how contractors and port authorities have different perspectives towards these practices.

The reviewed studies in the context of circularity show that the majority of articles discuss the challenges of circularity in port maintenance from the viewpoint of port authorities. Most of the studies were focused on different applications of sediment reuse for beneficial purposes such as reclamation, restoration, and building construction materials. These studies view the dredged sediments as port assets that can remain in the port's surrounding environment to contribute to the circular economy. Research on the circularity of port maintenance is rarely developed from the perspective of dredging contractors who focus on closed-loop dredging cycles and altering the equipment design to make it compatible with circular port maintenance operations.

6. Discussion

The effectiveness of implementing smart, sustainable, and circular practices in port maintenance is demonstrated in several case studies. Port of Rotterdam uses digital tools such as the PortXchange platform to optimize the traffic flow of vessels based on just-in-time arrivals, interactions with other neighboring vessels, and emission reductions (Suvadarshini and Dandapat, 2023). Circularity in this port is promoted by defining and implementing land reclamation and habitat restoration projects based on reusing dredged materials from maintenance (Broussard et al., 2023). Port of Antwerp uses real-time data monitoring systems to optimize the performance of maintenance dredging activities while reducing environmental impacts. Eco-friendly sediment disposal programs conducted by this port contribute to the circular economy (Vandekeybus et al., 2010). Port of Los Angeles aims to reduce emissions by developing electrified and energy-efficient equipment using alternative fuels. AI and real-time monitoring of air quality and equipment performance help the port achieve a collaborative approach between different stakeholders (Giuliano and Linder, 2014).

Investigating the relevant articles in the context of port maintenance with a detailed exploration of the adopted research objectives and

Table 5
The FoR of circular port maintenance.

Procedure	Contractor perspective	References	Port authority perspective	References
Strategic objective	To promote the circularity of port maintenance by optimizing the efficiency of sediment management	(Coulet et al., 2014, 2016)	To promote the circularity of port maintenance by developing practices for re-using the dredged sediments in the port as an asset	Bridges et al. (2018)
Operational objective	The design of equipment and processes allows for the required efficiency of sediment management in port maintenance.	–	The port infrastructure and local habitats are preserved by reusing the dredged sediments from port maintenance.	(Masson et al., 2019; Lemière et al., 2022)
Quantitative state concept	Mass of re-useable collected sediments by maintenance dredging equipment as a function of time, hydrodynamics, and location	–	Mass of collected sediments as port assets to be re-used in local habitat and port infrastructure preservation	Nguyen et al. (2023b)
Benchmarking process	Assess that the closed-loop port maintenance operations are compatible with the equipment performance limitations.	Besseling et al. (2021)	Assess that the required performance of preserving port infrastructure and local habitats remains within the operating limits.	–
Intervention process	Establish closed-loop port maintenance operations according to the equipment performance limitations.	Kleirijperij (2018)	Establish operating limits that result in a trade-off between the economic performance of port processes and the preservation of port infrastructure and local habitats.	Baptist et al. (2019)
Evaluation process	Evaluating how re-designing the equipment and processes enhances the efficiency of sediment management and contributes to the circularity aspect of port maintenance	–	Evaluating how different sediment re-using methods improves the efficiency of local habitat preservation and contributes to the circularity aspect of port maintenance	Hanson et al. (2002)

methodologies enabled us to (a) derive literature-based definitions of smartness, sustainability, and circularity in the context of port maintenance, and (b) recognize how different stakeholders may have slightly different perspectives on these themes. SLR revealed several emerging subjects that require additional research, particularly in the area of emission mitigation and the adoption of smart techniques. Future studies can focus on alternative fuels, electrification of equipment, and carbon capture methods. The key areas of investigation include autonomous dredgers, real-time project data analysis, and predictive maintenance based on the bathymetry patterns.

Implementing the proposed approach in real-world projects faces challenges such as technical restrictions, high initial costs, and regulatory constraints. To overcome these barriers, expanding the capacity of infrastructure (terminals, cranes, etc.) and training of experts is required which can be achieved through pilot projects. Lessons learned from such projects develop an insight into managing costs and risks, developing standardized guidelines, and fostering stakeholder engagement. The proposed approach in this study can be further improved by taking the following considerations into account:

- The SLR approach coupled with FoR used different queries of keywords to search for the most relevant publications for smartness, sustainability, and circularity. However, the size of obtained publication pools depends on different combinations of keywords. Furthermore, selecting Scopus as the main research dataset could lead to overlooking relevant literature on the subject that is available in Scopus, Scholar, etc. Therefore, the inclusion criterion used in the SLR encompasses the relevant studies that were overlooked in the paper collection stage.
- Both stakeholders in this study (dredging contractors and port authorities) are selected due to their greater influence on the regulation of policy and the implementation of operational constraints concerning smartness, sustainability, and circularity. To have a broad viewpoint on the problem, the conflicting interests of all key stakeholders (e.g. port operators, environmental organizations, etc.) should also be included in the analysis.
- Most studies are focused on how processes can be improved from the perspective of different stakeholders to contribute to these three themes. However, the possibility of selecting different strategies for addressing these themes is rarely discussed. For example, the changes in the sustainability aspect of dredging when choosing remobilization instead of re-allocation are rarely studied by researchers, while each dredging vessel has its environmental impact (emissions, turbidity, and underwater noise during a project.
- The viewpoints of the contractors and the port authorities on the challenges associated with classified with smartness, sustainability, and circularity are not always contradictory but overlap on some points, which provides opportunities to look for compromises between the parties involved in the implementation of the project. Clearly stating the expectations of stakeholders in the initial phases of a project can help them understand what requirements and limitations need to be considered during project implementation. Defining quantifiable KPIs can also help them predict how each strategy highlights the three themes and what innovative solutions can be used for collecting, analyzing, and reporting their data.

Theoretical and managerial insights obtained in this study enhance the implementation of smart, sustainable, and circular practices in port maintenance by providing a structured decision-making framework. This framework which can include the viewpoint of multiple stakeholders employs the FoR method to clarify and prioritize objectives and metrics used for more informed trade-off quantifications. On a practical level, this study offers a set of indicators and best practices identified through an SLR, guiding stakeholders in adopting advanced technologies, environmental practices, and circular economy principles. During the tendering phase or project implementation, the compromise between stakeholders can be adjusted by negotiating clear and quantifiable objectives, metrics, and evaluation measures.

The final compromise on strategy selection for port maintenance is achieved through an accurate quantification of different KPIs and comparing the strategies to determine which one fits in each theme. For instance, a smart approach such as data-driven decision-making might suggest the implementation of a strategy that is not sustainable enough. In this case, clearly defining the motivation and requirements of stakeholders can facilitate the decision-making process. The study identifies key knowledge gaps in the integration of smart technologies, environmental impact mitigation, and the application of circular economy principles in port maintenance. Some targeted research questions that could help fill this gap are proposed as follows.

- How emerging technologies and smart practices can help stakeholders in achieving a compromised plan in port maintenance to maximize the dredging efficiency and minimize the interferences between seagoing and dredging processes?
- How does minimizing the environmental impact of maintenance dredging result in decreasing the pollutants in the whole port environment?
- How closed-loop dredging methods can improve the efficiency of reusing the dredged sediments for beneficial purposes and what indicators exist in quantifying the contribution of such practices to the circular economy?

There is a need for comprehensive frameworks to effectively incorporate data-driven methods and eco-friendly techniques for reducing greenhouse gas emissions and managing pollutants during dredging. Additionally, practical applications of circular economy concepts, particularly in the reuse and disposal of dredged materials, are underexplored when contractors address the problem. Along with the results obtained from the descriptive analysis of the final pool of articles that highlighted the scarcity of research in various countries and less attention to certain objectives, a compromise between different stakeholders is lacking when selecting port maintenance strategies.

Quantifying smartness, sustainability, and circularity in port maintenance requires robust methodologies that use measurable indicators and standardized frameworks. For smartness, metrics like the level of automation, data analytics usage, and fuel consumption reductions can be quantified through data-driven approaches. Sustainability can be measured using Environmental Impact Assessments (EIAs), lifecycle assessments, greenhouse gas emissions, and biodiversity impact. Circularity is quantified through Material Flow Analysis (MFA) and circular economy metrics, which measure the reuse of dredged materials and resource efficiency. To standardize these methodologies, ports can adopt common frameworks aligned with international standards, use benchmarking tools for performance comparison, engage in collaborative platforms for knowledge sharing, and conduct pilot projects to refine and apply these approaches across different port contexts.

7. Conclusion

We presented a comprehensive framework to define the concepts of smartness, sustainability, and circularity in port maintenance. A systematic literature review (SLR) showed to what extent these topics have gained traction in recent years and identified the latest challenges in port maintenance. Next, we showed that different stakeholders, namely contractors and port authorities, can have distinct perspectives on the same themes. This distinction is crucial, as it demonstrates why it is often challenging to agree on these broad and sometimes vaguely defined concepts. By categorizing the studies using a frame of reference (FoR) approach, we structured these perspectives to highlight their unique objectives, quantifications, actions, and assessments.

The analysis also suggested that despite these different viewpoints, there are notable overlaps in the stakeholder's FoR. For example, both contractors and port authorities recognize the importance of improving process efficiency, albeit from different angles. Recognizing and understanding these overlaps can facilitate better stakeholder collaboration and agreement during project implementation. Finally, our findings suggest that integrating these different perspectives can lead to innovative approaches in port maintenance. Future research studies can focus on proposing a more accurate quantification of different KPIs on smartness, sustainability, and circularity. Also, including the perspectives of other stakeholders (e.g. port operators, environmental organizations, etc.) provides a holistic approach to addressing smartness, sustainability, and circularity while selecting strategies.

The SLR approach showed the emerging trends in smart, sustainable, and circular port maintenance by descriptively analyzing the authors' contributions from different countries, the number of publications in each year, and the frequency of addressed challenges. Different objectives, metrics, and evaluation measures are used to differentiate the viewpoints of contractors and port authorities toward each of these three themes. A structured FoR framework used in this study offers different stakeholders a clear idea of these concepts and how they can come up with a compromised perspective when selecting port maintenance strategies. This perspective not only incorporates cost and time factors along with these themes but also solves potential conflicts during the tendering phase or project implementation.

New literature-based definitions of smartness, sustainability, and circularity from the perspectives of contractors and port authorities helped us to identify important knowledge gaps for further research. A low number of research articles on circular port maintenance from the viewpoint of contractors is a considerable gap in the corresponding literature. Also, smart port maintenance is rarely addressed from the perspective of port authorities because smartness is mainly implied as a means of improving the efficiency of dredging equipment. Integrating port processes with different scenarios of port maintenance can help ports develop a more comprehensive insight into how this interference can be quantified.

Integrating perspectives from stakeholders can be effectively managed through structured engagement, transparent communication, and collaborative decision-making. To do so, tools such as Multi-Criteria Decision Analysis (MCDA) can be used to balance different interests and form stakeholder advisory committees for consultation. Digital collaboration platforms can facilitate real-time data sharing and feedback, while Public-Private Partnerships (PPPs) encourage joint decision-making and shared investment.

Future research could explore the socio-economic implications of port maintenance strategies, such as potential job creation and broader impact on local communities. Involving more stakeholders such as terminal operators and environmental organizations helps accurately quantify more trade-offs. Anticipated changes in the FoR approach include real-time decision-making for different phases of projects and expanding stakeholder engagement mechanisms to maintain the relevancy and alignment of decision-making during the process.

CRediT authorship contribution statement

Arash Sepehri: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alex Kirichek:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Marcel van den Heuvel:** Writing – review & editing, Supervision. **Mark van Koningsveld:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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