A framework for PCO models in different port governance structures

A roadmap for PCO tool implementation

Master Thesis

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by

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Preface

This thesis marks the culmination of a challenging and enlightening journey, one that would not have been possible without the support and guidance of several key individuals and groups. First and foremost, I extend my deepest gratitude to my thesis chair, Lori, whose unwavering motivation and innovative ideas have been instrumental in shaping this work. Lori's encouragement and insights have been a constant source of inspiration throughout this process.

I am also profoundly thankful to Frederik for his steadfast support and to the OptiPort team, including Patrick, Myron, and Rares, who have been a daily source of support and clarity. Their collective expertise and willingness to assist with any problem I encountered have been invaluable, especially given the steep learning curve associated with this new topic.

On a personal note, I am eternally grateful to my parents, whose continuous support and reassurance of my capabilities have been my anchor. Their belief in me has been a driving force behind my perseverance. I also wish to thank my friends, who have been there for me during these challenging months, offering their time to discuss ideas and help clear my mind. It is clear to me that I would not have achieved this without their unwavering support.

This thesis is a testament to the collaborative effort of all these individuals, and I am sincerely thankful for each contribution that has made this work possible.

John Antony Kuttikat
Delft, August 2024

Summary

Seaports are crucial components of the global supply chain. As globalization expands, maritime trade is expected to grow, leading to more frequent port visits by vessels. This trend exacerbates inefficiencies in the port call process and increases the waiting times for ships. Therefore, to maintain a competitive edge and reduce environmental emissions, it is essential to enhance the port call process. This research aims to support this goal by developing a framework for Port Call Optimization (PCO) models and designing a roadmap for implementing a PCO tool.

The research focuses on optimizing the nautical chain, which includes tugs, pilots, mooring teams, and terminals. This area is often overlooked in PCO discussions but is heavily reliant on the berthing schedule provided by terminals. However, as ports evolve to adapt to changing conditions, designing and implementing a PCO tool becomes more complex. Thus, this study examines ports and their stakeholders in detail to propose an effective roadmap for designing an implementation tool. The research seeks to close the gap in fragmented PCO studies by offering a scientific approach to analyze port settings and establish a model that fosters collaboration and decision-making.

This study aims to provide a detailed and reproducible analysis of ports and the development of a PCO tool adaptable to various port governance structures. It employs a Design Science Research (DSR) approach, which outlines a clear process for creating a PCO tool roadmap. The research starts with a Systematic Literature Review (SLR) of PCO models and their environment, offering an extensive understanding of PCO, port governance structures, the role of the Port Authority (PA), port reform theory, stakeholder collaboration, and resource scheduling optimization models. After gathering this knowledge, a co-design process is proposed as part of the DSR methodology. This process involves user participation in design to ensure alignment with client needs, objectives, and future trends. The co-design process begins by defining trends that impact the PCO tool's design, ensuring it remains relevant. These trends are discussed with clients to align their expectations and experiences. Converged trends, along with brainstorming, interviews, and abstraction, help define the requirements shaping the design artifact. Previous research on the TOEI framework, closely related to PortCDM—a concept promoting collaboration among internal and external actors—was crucial in defining the design artifact's constraints and objectives. These requirements evaluate solutions backed by literature to determine their suitability for different port governance structures. Finally, a conceptual framework assesses the ports for factors affecting prerequisites, and steps to develop a roadmap are proposed.

This study conducts a case study of the Port of Rotterdam (PoR) to apply the roadmap development steps in creating a roadmap for OptiPort, a tugboat scheduling software aimed at achieving PCO functionality that includes stakeholders in the nautical chain and terminals. It is noteworthy to consider the factors influencing decisions on various aspects of the tool during its implementation phases. Interviews with the PoR and Portbase (port community system) was conducted to validate the role of PA and the maturity level of the technology available in Rotterdam. Finally, impact of different governance structures on the development of the PCO roadmap is analyzed to understand how optimization strategies and integration sequence of stakeholders differ from each other.

It is essential to recognize that the PCO tool, developed using the roadmap, helps optimize berth allocation and related nautical services within the port environment. By integrating user experiences and the new relationships formed among stakeholders due to the tool's implementation, the DSR environment is updated and improved. Additionally, the conceptual framework for roadmap development identifies the factors that affect the prerequisites for the PCO tool and outlines the steps for its implementation. This framework enhances the knowledge base, paving the way for future research and further improvements.

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Nomenclature

Abbreviations

Abbreviation	Definition
AIS	Automatic Identification System
BAP	Berth Allocation Problem
DSR	Design Science research
ETA	Estimated Time of Arrival
FCFS	First Come First Served
HCC	Harbor Coordination Center
HM	Marbor Master
ICT	Information Technology and Technology
JIT	Just In Time
NC	Nautical Chain
NGO	Non Governmental Organization
PA	Port Authority
PCO	Port Call Optimization
PCS	Port Community System
PoR	Port of Rotterdam
QC	Quay Crane
QCAP	Quay Crane Allocation Problem
QCSP	quay crane scheduling problem
STM	Sea Traffic Management
SLR	Systematic Literature Review
VTS	Vessel Traffic Service

1

Introduction

1.1. Background and Motivation

Background

Seaports serve as vital nodes in the global supply chain, facilitating the movement of approximately 80% of global trade [51]. They play a critical role in ensuring the smooth transition of goods between maritime routes and inland areas [149]. Despite facing significant challenges such as the COVID-19 pandemic and geopolitical conflicts like the Ukraine crisis, the shipping industry has demonstrated resilience. Projections suggest that maritime trade is expected to grow by 2.4% in 2023 and by over 2% annually from 2024 to 2028 [112]. Therefore, optimizing port performance is essential for maintaining competitiveness.

Research indicates that inefficiencies, such as limited opening hours, crew availability, administrative procedures, and delayed service provider arrivals, contribute to vessels spending half of their time in ports ineffectively [97]. Prolonged waiting periods at anchorage not only incur higher costs for shipowners but also result in increased CO_2 emissions [102]. Furthermore, ports engage in competitive strategies aimed at increasing vessel visits, as this directly impacts regional economic growth and development [2]. Thus, there is a pressing need for optimization tools to streamline port operations and ensure timely vessel service.

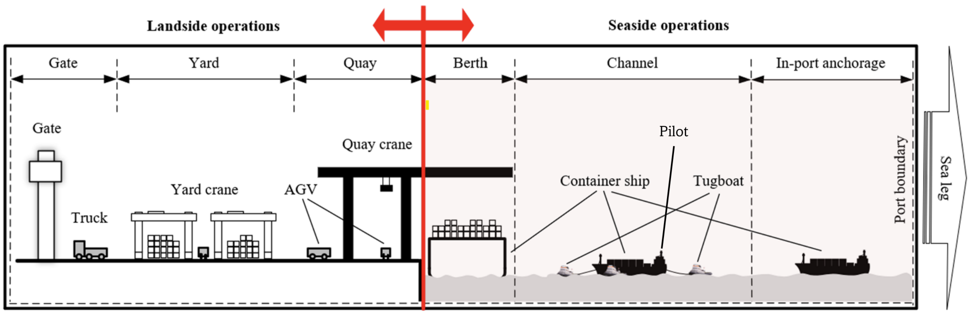

Figure 1.1: seaside and landside operations in container ports [128]

Figure 1.1 shows the seaside and the landside operations in a container port. In this research, the focus is on the port call optimization specific to the seaside operations. This includes operations including pilotage, towage and mooring services also called the nautical services while also considering berth allocation.

The port call process encompasses three key stages: arrival, which includes pre-arrival preparations such as documentation for customs and clearance and actual arrival at the port; the port visit, during which all necessary services are rendered to the visiting vessel, whether it is anchored or berthed; and departure, encompassing both the departure phase and post-departure activities [77]. Therefore, port

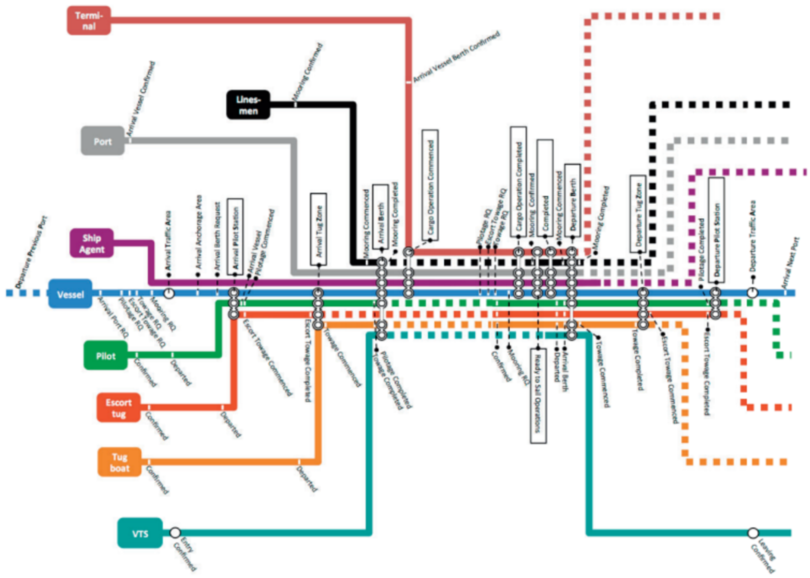

Figure 1.2: Core events and engaged actors in the port call process [77]

call operations involve a substantial number of actors. Upon arrival in the coastal area, several entities become involved in the port operations. Pilots, tug operators, and additional nautical service providers assist in navigating the ship to its berth. Mooring personnel secure the ship in place, while terminal operators and stevedores manage the loading and unloading of cargo. Other service providers handle tasks such as waste management and security. Vessel agents coordinate and ensure that all activities proceed as planned. These stakeholders collaborate to prepare the ship for departure from the berth, exiting the port area, and returning to the open sea as well. The complexity of port call operations can be seen in Figure 1.2 [77].

When vessels enter or depart from seaports, it's crucial for them to navigate safely through designated waterways. Pilotage services ensure safety, smooth navigation, and environmental protection, making it vital for this purpose [67]. Pilotage organizations operate under a safety management system to oversee the quality, safety, and environmental sustainability of the pilotage process [60]. These systems, tailored to each port, influence the execution of pilotage operations, reflecting varying criteria and standards across different ports.

During port reform initiatives, pilots frequently advocate for privatization as a primary measure. Pilots may operate independently as self-employed individuals, subject to regulation and licensing by a maritime authority, or they may opt to form private companies [94]. Governance structures vary between ports, influencing the responsibilities associated with pilotage, including training, supervision, office management, service provision, and fee collection [111].

Ships rely on towage services to safely navigate through narrow and shallow water passages [57]. The quantity and duration of tugboat assistance needed are decided by the onboard pilot overseeing vessel navigation [82]. Therefore, efficient scheduling of tugboats is vital for the smooth execution of port calls.

Towage operations are usually handled by private companies because privatization policies have been found to increase port efficiency and competitiveness. Ideally, having multiple towage firms competing actively within a port is advantageous. In such a scenario, port authorities would not need to regulate tariffs. However, certain aspects of towage operations, such as staffing, may still be subject to regulation by port authorities, contingent upon the specific circumstances and needs of the port [94].

The mooring service is essential for safely securing vessels, and allowing cargo operations to commence. In smaller ports, this service may be handled by local stevedores, while larger ports typically rely on specialized private firms for mooring assistance. Particularly in complex maritime scenarios, such as those experiencing significant tidal variations, mooring tasks demand specialized skills and equipment [94]. Port authorities may opt to regulate staffing, allocation and characteristics of mooring boats, and operational tariffs if there is only one specialized firm for mooring services [94]. This helps in maintaining operational efficiency and limiting monopolistic behavior.

Port operations face several uncertainties, including delays in vessel readiness, fluctuations in arrival and departure times, varying service durations, and specific requirements [82]. One possible solution to address these challenges is to increase resource capacity, but this option is limited by the substantial capital investment needed. Tugboats require significant upfront investment and ongoing maintenance, while pilots, who are generally highly experienced, demand high salaries [2]. As a result, improving the existing performance of the port is considered a more practical approach.

Port call optimization (PCO) refers to the systematic process aimed at maximizing the efficiency of port call processes in accordance with the requirements of stakeholders within the maritime transport value chain, thereby contributing to the optimization of the broader transportation system [70]. However, the scope for PCO is too broad involving various aspects of improvements. This is described in section 3.1. The PCO models identified in existing literature predominantly concentrate on enhancing specific aspects of port operations such as optimizing vessel arrival schedules, coordinating tugboat and pilot scheduling, or streamlining individual processes in isolation rather than addressing the entire port call process comprehensively.

Practical Motivation

IAPH's Managing Director commented: *"Whilst it is not the ultimate game-changer, Port Call Optimisation definitely is one of the low-hanging fruits that will help decarbonising the maritime sector. Its multiple advantages include increased safety and efficiency, so there is really no excuse for stakeholders in the nautical chain why they should not to get involved and make it happen."* [92]

Seaports are essential hubs in the global supply chain, handling around 80% of worldwide trade. As maritime trade continues to grow, this directly impacts the capacity of port services [112]. The resulting longer wait times for vessels lead to higher fuel consumption, increased $CO2$ emissions, and a greater risk of collisions [82], highlighting the need for improvements in port operations [112]. Moreover, vessel operators can incur costs of up to $4,000 per hour while waiting at ports. Seaport operators also face significant expenses related to berth construction, resource procurement, and operating costs. Therefore, optimizing seaport operations is crucial for the efficiency and cost-effectiveness of both vessel and port operators [1].

The landscape of port governance structures is undergoing significant transformation. The globalization of production and distribution, coupled with advancements in technology, has disrupted traditional state-controlled models. Various strategies, including privatization, commercialization, decentralization, and corporatization, have been employed to foster private sector involvement and adapt to evolving market demands [108].

Amidst these changes, the concept of PCO has emerged as a crucial mechanism to streamline the port call process and minimize vessel waiting times [70]. PCO tools, designed to schedule vessel services such as pilots, tugboats, and linesmen, have demonstrated their effectiveness in optimizing asset utilization and reducing service delays.

While PCO models are gaining traction within the marine industry, their full potential can only be realized by integrating all stakeholders within the nautical chain. Expanding PCO tools to encompass the diverse stakeholders involved in port operations represents a critical step towards enhancing overall port efficiencies. However, such expansion necessitates careful consideration of specific port governance structures and evolving trends in marine logistics. While optimization models focusing on individual service providers exist, there is a lack of holistic approaches that address the entire port call process within the context of varying governance frameworks.

The effectiveness of a PCO tool extends beyond efficient service scheduling; it must also comprehend the underlying objectives and dynamics of stakeholder interactions. This entails mirroring real-life relationships and preferences among stakeholders across various objectives. Moreover, the PCO tool must account for the evolving relationships dictated by specific governance structures within ports, adapting to the changing dynamics as ports evolve to meet societal and economic needs. Additionally, it is crucial to consider evolving trends in the marine industry, ensuring that the PCO tool remains adaptable and future-proof to effectively optimize the port call process.

1.2. Research Gap and Aim

Much research on port call optimization has been done for individual stakeholders [13] [129] [121] [134] [54]. While initial research on optimization models included strong assumptions on the service operations, trailing studies have improved upon them to make models as realistic as possible while trying different objective functions to find improvements in the port call performance. However, these studies focus on the optimization of an individual service provider without considering other stakeholders in the nautical chain. While studies have been conducted considering the multiple stakeholders of the nautical chain, namely pilots, tugboats and linesmen, a single objective optimization is considered without taking the differences in stakeholder objectives into account [83].

The diverse objectives of individual stakeholders often prompt them to act in accordance with their own self-interests, potentially leading to outcomes that are sub-optimal for the overall system. In order to address this challenge and achieve the shared objective of maximizing throughput efficiency, collaboration among stakeholders becomes imperative [70]. A study by Lokin [72] tends to oversimplify stakeholder objectives, particularly in the context of vessel service providers, by focusing solely on optimizing asset use and allocation without accounting for the nuances introduced by varying governance structures.

The aim of this research is to explore the modelling of the Port Call Optimization (PCO) tool to effectively incorporate various stakeholders, taking into account the complexities of their relationships within varying port governance structures to provide a comprehensive understanding from the fragmented nature of this subject. By achieving this, the research aims to enhance the feasibility of implementing PCO tools in real port environments, ensuring stakeholder satisfaction while optimizing overall port performance. Additionally, this study seeks to address the oversight of future trends in the optimization of nautical services. For instance, research conducted by Nikghadam et al. [82] demonstrates how optimization strategies can be leveraged to advise vessels on optimal service start times, facilitating Just-in-Time operations by encouraging vessel deceleration.

In essence, this study aims to facilitate the evolution of partial Port Call Optimization (PCO) tools towards achieving an optimal functionality level that is tailored to specific port contexts. This will be achieved through the development of a comprehensive roadmap outlining the requirements of multiple stakeholders and the dynamics of their relationships. Such a roadmap will serve as a valuable analytical tool, enabling the assessment of existing PCO models and the identification of necessary considerations for implementation within a particular port setting.

Throughout this thesis, terms like optimization solution, optimization tool, and optimization model have been frequently used in relation to PCO. However, these terms might be misunderstood due to the complexity of PCO, so it is important to clarify their meaning within the context of this project. The term ”optimization solution” refers to a specific approach to addressing the PCO problem by coordinating the schedules of various stakeholders in the nautical chain and terminals, aiming to reduce vessel waiting times and enhance throughput. This solution can be implemented through the development of a tool with advanced technological capabilities that facilitate communication and data sharing, thereby supporting resource planning. The ”optimization model” refers to a mathematical framework that aids in decision-making among different stakeholders under various port governance structures.

1.3. Research Questions

The research objective is to gain clarity on how partial PCO models can evolve into a full PCO support model, including multiple actors, and to provide directions on adapting them to different port governance contexts. To achieve this, the research will develop a framework to help map requirements from different actors and port structures so that models can be adopted to answer PCO questions of growing complexity. The main research question is as follows:

How can partial Port Call Optimization (PCO) models be transformed into desired levels of functionality to address full PCO questions, within the context of a certain port governance structure?

This main question is answered by the following sub-questions:

1. What are the requirements for effective implementation and deployment of the PCO solution?
2. What are the various model alternatives that can be used to serve PCO requirements?
3. How can model alternatives be evaluated to ensure that they perform effectively as a PCO solution for a given port?
4. What is the logical development roadmap for PCO tools from limited to high complexity, in different port governance contexts?

1.4. Problem Statement

Optimization of a port call process has been seen as a complex problem due to the large number of stakeholders that take part in the process. These stakeholders can be part of a centralised entity allowing a centralised flow of information and control or part of a decentralised system. Stakeholders part of a decentralised system can have objectives of their own making it difficult for a general optimization model to solve. Moreover, Future trends towards sustainable operations and advanced performance also play a significant role in the decisions made by the stakeholders.

Therefore, guidance on how a model can be adapted to serve any given port of a specific governance structure is required.

1.5. Thesis Organization

Table 1.1: Thesis outline

Chapter	Outline	Research Question
Chapter 1	Introduction	-
Chapter 2	Methodology	-
Chapter 3	Systematic Literature Review	SRQ1, SRQ2
Chapter 4	Conceptual Design	SRQ1, SRQ2, SRQ3, SRQ4
Chapter 5	Roadmap development Case Study: Port of Rotterdam	SRQ4
Chapter 6	Impact of governance structures on PCO roadmap	SRQ4
Chapter 7	Discussion and Limitations	-
Chapter 8	Conclusion	-

Table 1.1 shows the structure of the thesis, including where the research questions are addressed. Chapter 1 provides an introduction to the research and the research gap. Chapter 2 explains the research methodology used to discover the related research and a scientific approach to build the roadmap for PCO tool implementation. Chapter 3 contains the systematic literature review performed to obtain necessary information regarding the topic. Chapter 4 develops the conceptual design for roadmap development. Chapter 5 develops the roadmap for the Port of Rotterdam (PoR) as case study. Chapter 6 discusses the impacts on the PCO roadmap due to difference governance structures. Chapter 7 and 8 concludes the thesis.

2
Methodology

This chapter discusses the scientific methodology that is used for the design of a roadmap for PCO implementation. Following sections show how the Design Science Research (DSR) approach is used as a scientific approach to design a roadmap that is backed up by literature.

2.1. Design Science Research

This section details the methodology used to develop a roadmap for assessing existing partial PCO models and identifying the key considerations required for their implementation in specific port environments. The process involves understanding various port settings, stakeholder relationships, interactions, and operational dynamics. Multiple models must be analyzed to build a comprehensive knowledge base applicable to different port environments. Based on this understanding, a design artifact will be created to outline the requirements and considerations needed to accommodate the unique characteristics of various governance structures within port settings. This design will then be evaluated to determine its feasibility. Given the project's scope and the iterative nature of the design process, a Design Science Research (DSR) approach is employed. The design process will be guided by a DSR cycle, as illustrated in Figure 2.1.

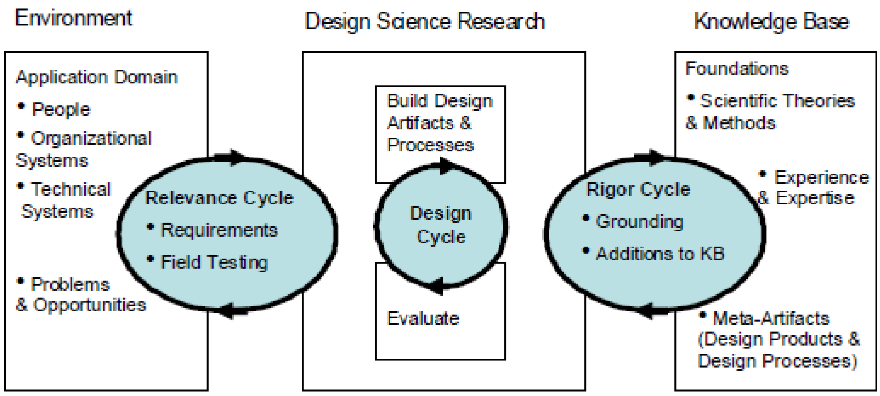

Figure 2.1: Design Science Research Cycles [49]

Relevance Cycle

The Design Science Research (DSR) framework aims to enhance the environment through innovative designs [49]. The application domain shown in Figure 2.2 consists of the governance structure and all port stakeholders that benefit from the goal. The relevance cycle initiates the DSR by providing the requirements of the application domain and the acceptance criteria for the evaluation of the framework. Governance models differ significantly, and their impact on service providers can vary depending on the policies enforced by the port authority. This is captured within the environment and transferred through the relevance cycle.

The developed roadmap is implemented in this environment, enhancing existing technologies and methodologies. Additionally, it guides the evolution of current PCO tools, helping to improve the environment for future updates.

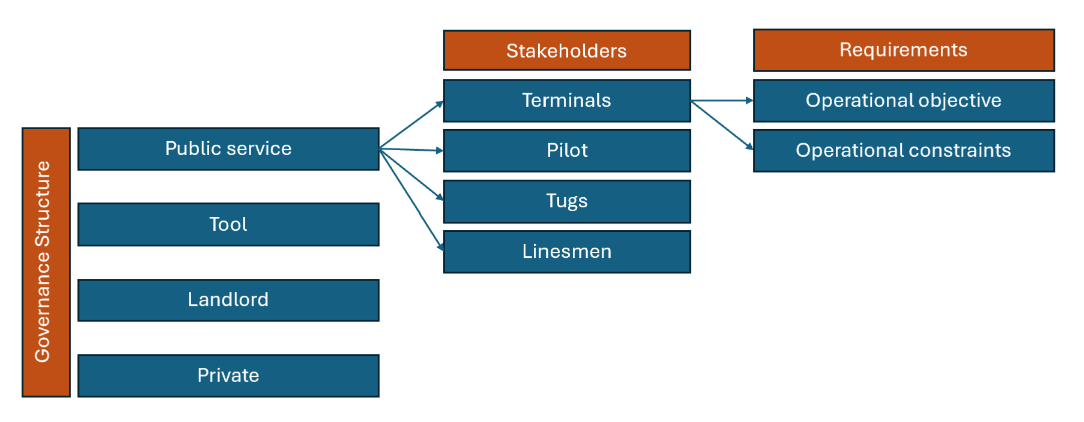

Figure 2.2: Application domain

Rigor Cycle
The rigor cycle serves as a foundation for crafting and assessing the framework, drawing upon existing knowledge. The knowledge base provides various scientific methods, experiences and expertise to deal with the various aspects of PCO. With a good knowledge base, it becomes easier to build the design artifact that provides the right solution for the environment.

This research aims to introduce new concepts, a conceptual framework for roadmap development, and a specifically designed roadmap for landlord ports like the Port of Rotterdam (PoR), thereby enhancing the existing knowledge on the subject. It seeks to bridge the gap between fragmented research from various stakeholders in the nautical chain, providing a comprehensive understanding of stakeholder interactions within different port governance structures for the implementation of PCO.

Design Cycle
This cycle includes the creation and evaluation of the design artifact. The artifact is developed to meet the environment's requirements, utilizing knowledge from the knowledge base. This iterative process of evaluation and redesign ensures satisfactory results for stakeholders. In this case, the roadmap serves as the artifact, designed according to the environment's requirements and refined based on feedback from the evaluation committee. However, due to the project's timeframe and scope, only one iteration is planned for this project. The design process follows a co-design process detailed in section 4.2 which involves the participation of stakeholders for which the roadmap is designed for. This co-design process enhances the quality and applicability of the solution.

By adopting Design Science Research as the overarching methodology, the approach to execute it can be done in two phases as described below.

2.2. Phase 1: Discovery Phase

During the discovery phase, the environment and knowledge base depicted in Figure 2.1 are studied via a systematic literature review. This comprehensive review illuminates various aspects of the environment, encompassing diverse governance structures, disparities in their operations and objectives, policies, the array of stakeholders involved, and their operational interrelations. Furthermore, this phase identifies existing models and methodologies devised to address various challenges within Port Call Optimization (PCO). By conducting a systematic literature review, a discernible, reproducible body of information is amassed, and subsequently subjected to analysis and integration into the design phase.

Systematic literature review

The systematic literature review serves to define both the environment and the knowledge base essential for the subsequent design phase. Within the environment, details regarding diverse organizational structures, their requirements, objectives, and their correlations with port size and location are elucidated. Concurrently, the knowledge base is tasked with furnishing information on methodologies to address these requirements under varying conditions. These data are systematically gathered to ensure reproducibility, with rigorous verification to ascertain that the collected information is adequate for generating comprehensive results covering the breadth of topics surrounding PCO.

Papers were sourced from the Scopus database spanning from April 3rd to April 24th, 2024. Search queries were formulated based on the research question at hand. Illustrated in Figure 2.3, a PRISMA flow diagram delineates the keywords, decision criteria, and the number of reports selected for inclusion in this study.

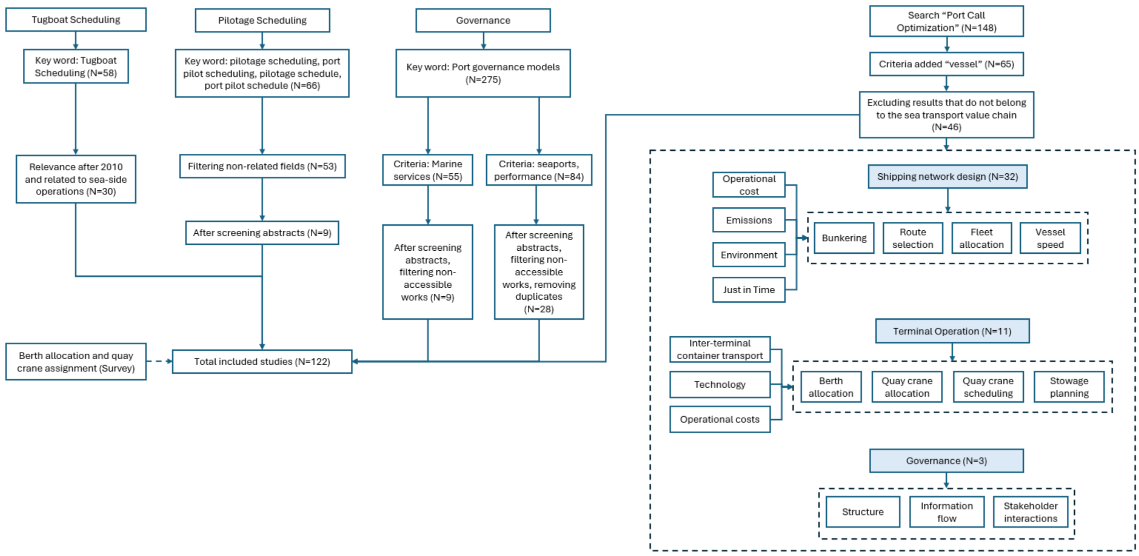

Figure 2.3: Flow diagram for systematic review

To encompass the broad scope of understanding various components of port call optimization, the literature review was categorized into five main parts based on their relevance to PCO. These categories are Port call optimization, governance, tugboat scheduling, pilotage scheduling, and berth allocation. While another important stakeholder, the linesmen, was recognized within the scope of this research, their impact on vessel turn-around time is limited, and there is limited existing study on this aspect. Therefore, linesmen were not included in the systematic literature review, but their role will be considered during the roadmap design phase.

Port call optimization: To understand the topics related to PCO, the keyword "Port call optimization" was used to get related studies and to understand what PCO meant in different researches. However, only 65 studies were related to 'vessels' out of which 46 studies were related to scope of the project. The criteria used to filter out the studies is its relation to the essential operations within the confines of PCO from the perspective of the port that deals with Just in Time (JIT) arrival of vessels, effective servicing of vessels to improve turn-around time and port operations. Other studies that focused on refueling, disruptions, port call scheduling and studies not related to sea ports were excluded.

Governance: Understanding Port governance structures is an integral part towards the scope of the project as it provides understanding on the different types of governance structures, its differences in terms of policy and operation, and their requirement and objectives. The keyword "Port governance models" is used and filtered based on 2 criteria to extract studies that relates to marine services and port performance. The studies extracted were then screened based on their abstract and unrelated topics that did not focus on seaports or did not provide insights into the different governance structures were removed. The studies were further filtered because many contained similar information across different port environments. To maintain a set of research that provided the most impactful insights, these redundant studies were removed. Moreover, a few were not accessible which had to excluded form the study as well.

tugboat, pilotage and berth: Main stakeholders for improving the vessel service and improving turn-around time includes pilots, tugboats, linesmen and terminals. It was observed that terminal operations such as berth allocation and quay crane assignment were widely studied followed by tugboat scheduling and pilotage scheduling. As detailed surveys on berth allocation quay crane assignment are available, these surveys are used to study the port side operation of the terminals. The keyword ”Tugboat scheduling” was used and filtered to extract studies that were specific to sea-side operation. studies that focused on the technology aspect of the tugboats were also removed from the study. For extracting studies pilotage scheduling, a more stringent set of constraints were required as a lot of unrelated topics are linked with this keyword. This can be found in Figure 2.3, where only 9 studies were considered finally as the rest did not fit into the scope of the project.

2.3. Phase 2: Design Phase

During the design phase, the insights gained from the discovery phase are scrutinized and leveraged to craft a framework that functions as a roadmap to systematically evaluate existing PCO tools, which may have limited functionality, and propose considerations for enhancing them into effective PCO tools adaptable to various governance structures. Subsequently, the design undergoes evaluation by a panel of industry professionals to assess its validity and practical applicability.

2.3.1. Design

The design phase consists on defining trends, requirements, solutions and building the roadmap which is explained in detail in Section 4.2. These steps provide methodological approach toward the design of a roadmap that incorporates emerging trends, requirements and validates different solution to find the best fit for the use case. The designing of the roadmap is collaborated with the set of professionals in each of its steps to ensure its relevancy to the industry.

2.3.2. Evaluation

Artifacts should be evaluated with criteria based on the requirements of the context in which the artifact is implemented [49]. Evaluation of the design artifact is crucial and there exists particular methods to evaluate a particular artifact which have been classified based on the frequency of the evaluation method used for each type of artifact [89]. Hence, this research uses expert evaluation as its evaluation method to validate its functionality, completeness, consistency, accuracy, performance, reliability, usability, fit with the organization and other relevant quality attributes.

Professionals from KOTUG Optiport and representatives from ports and academia were invited to join the evaluation committee to review the roadmap. At this stage, the OptiPort tool serves as the benchmark for evaluating the current state of the tool, with the Port of Rotterdam, a landlord port, being the reference port for its implementation. The roadmap created for this case is assessed based on the specified criteria by KOTUG OptiPort professionals, the client for whom the roadmap was developed.

2.4. Research question and methodology overview

Finally, integrating phases 1 and 2 with the overarching methodology that is the Design Science Research (DSR) along with the sub-research questions can be viewed on the process map in Figure 2.4.

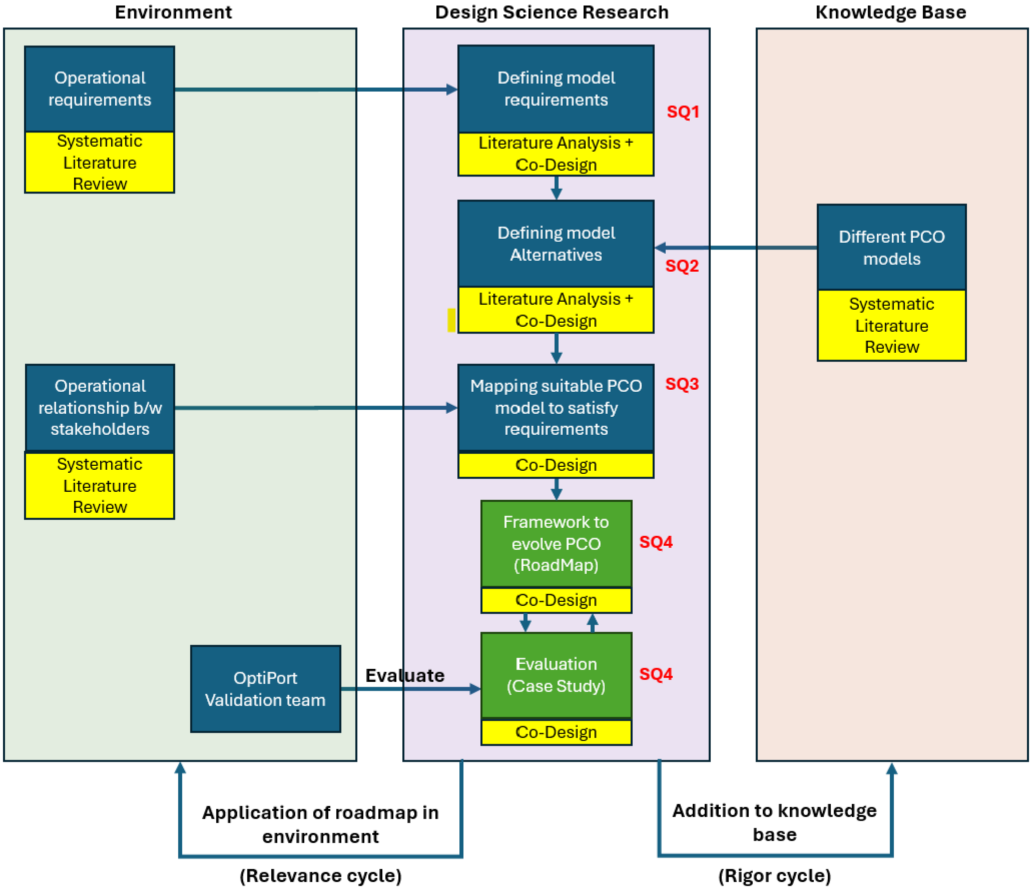

Figure 2.4: Methodology

3
Systematic Literature Review

This section provides an overview of the available literature with regard to the scope of this project. A total of 122 research papers across the five major areas as shown in Figure 2.3 were considered to have a comprehensive understanding of PCO and its associated topic with respect to different port governance structures. This section is structured starting with an general overview of the literature providing an outline of the topics covered in literature. The following sections describes the understanding of these literature which is further used to design a framework to analyze PCO models and suggest improvement considerations for various port governance structures.

Port operations play a vital role in facilitating trade and enhancing the economic prosperity of a region. Given that carriers can select which ports to call at, it is essential to optimize the port call process to ensure high-quality service for customers [18]. Inefficient port operations can result in significant costs for both the port and the vessel charterer. Specifically, delays in cargo operations, such as exceeding the allotted time for loading and unloading, can lead to demurrage costs [52]. Thus, timely cargo handling is crucial to minimizing expenses and increasing a port's appeal.

The following sections explore trends in port call optimization (PCO) to highlight the areas where ports are concentrating their efforts to improve operational efficiency and effectiveness. The next section examines governance structures in ports, offering insights into how ports are evolving to meet increasing demands. This discussion also lays the foundation for understanding stakeholder interactions, their responsibilities, and how these vary across different port governance structures.

3.1. Port Call Optimization

Port Call Optimization (PCO) is a crucial aspect of this project, requiring a thorough understanding of its importance to the research community and the breadth of studies conducted in this field. The existing literature on PCO can be classified into three main areas: shipping network design, terminal operations, and governance. Notably, research focused on optimizing services provided by tugboats, pilots, and linesmen generally does not fall within the broader scope of PCO. While some studies acknowledge delays caused by these service providers [97][64], various keywords, as illustrated in Figure 2.3, were necessary to explore their optimization strategies and models. This section aims to highlight key research contributions in PCO and its related topics, with a detailed classification of the papers provided in Table 3.1.

Significant research within PCO centers on shipping network design, covering aspects such as bunkering, vessel speed, port call scheduling, and fleet allocation. These parameters are influenced by operational costs, emission regulations, policy constraints, and environmental factors.

Fuel costs represent a major component of operational expenses. New policies mandating the use of low-sulfur fuels to reduce emissions have led shipping companies to balance different technologies and strategies to minimize operational costs while complying with environmental regulations. The International Maritime Organization (IMO) proposed speed optimization and speed reduction as part of their

Table 3.1: Literature overview on port call optimization

Main Category	Sub-Category	Papers
Shipping Network	Bunkering (4)	[11] [38] [29] [30]
	Vessel Speed (13)	[74] [99] [4] [58] [11] [56] [143] [29] [76] [33] [30] [98] [130]
	Schedule Design (15)	[133] [110] [19] [124] [91] [20] [42] [126] [56] [35] [143] [28] [33] [7] [146]
	Fleet Allocation (2)	[133] [4]
Terminal Operation	Berth Allocation (4)	[48] [15] [40] [147]
	Quay Crane (4)	[48] [15] [40] [104]
	Stowage Planning (4)	[15] [40] [145] [120]
Governance	Structure (1)	[46]
	Information Flow (3)	[53] [46] [104]
	Stakeholder Interaction (3)	[96] [59] [63]

short-term operational strategy towards reducing carbon intensity by 40% by 2030 [74]. Slow steaming has emerged as a well-researched strategy to reduce fuel consumption, emissions, and operational costs, facilitating Just-In-Time (JIT) vessel arrivals. Despite some ports adopting slow-steaming and JIT through contracts and incentives, implementation remains inconsistent due to business constraints like First-Come-First-Served (FCFS) policies, supply chain disruptions, piracy threats, and the need to maintain schedule robustness [99].

Emission restriction policies affecting port operations necessitate the adoption of advanced emission control technologies, cleaner fuels, or rerouting around regulated areas, which can sometimes increase emission levels. Sulfur fuel regulations and their associated costs require careful bunkering strategy planning [30].

Environmental factors significantly impact liner shipping networks, with weather conditions accounting for 5.3% of late arrivals [33]. Tidal windows, narrow channels, and tidal currents influence operational costs, requiring shippers to plan port arrivals within specific timeframes and adapt routes or speeds to navigate adverse weather [11].

Terminal operations are vital for port efficiency. Enhancements can be made either by building new infrastructure or by improving operational efficiency, considering all stakeholders involved in port operations [59]. Lower terminal handling costs enhance a terminal's attractiveness to shippers [133]. Research indicates that 93% of late arrivals are due to berthing and handling process delays [33], emphasizing the need for efficient scheduling of terminal operations, including pilotage, tugging, mooring, berth allocation, quay crane allocation/scheduling, and stowage planning. Significant research has focused on berth and quay crane allocation, which are central to port optimization efforts.

Effective stowage planning is essential for reducing turnaround time by facilitating quick container retrieval with minimal repositioning. Studies suggest that new technologies and operational research models can improve terminal operations planning, addressing the Berth Allocation Problem (BAP), Quay Crane Allocation Problem (QCAP), and stowage planning [40].

Finally, several studies on PCO examine the influence of port governance on the port call process and overall operational efficiency. Organizational and behavioral factors, rather than digital technology, are identified as major obstacles to PCO [46]. Research indicates that community concerns most effectively influence government actions when the responsible government is local, as local governments are more responsive to environmental issues. These studies also highlight the importance of stakeholder communication and the role of the Port Authority (PA) in providing the necessary infrastructure and technology to support port development.

3.2. Port Governance

The term "Port Governance" is characterized as a system that organizes a diversity of institutions and groups of individuals to achieve a common purpose, through rules, regulations, policies, and regulatory frameworks, with the participation of the public and private sectors [17]. The Literature study on port governance has been studied due to its relevance to the scope of this project. It is vital to understand how the organizational change within different port governance structures can impact the performance of the port. 37 papers were selected based on the criteria presented in Figure 2.3 and have been categorized into 5 main categories based on the content found in these researches, found in Table 3.2.

Table 3.2: Literature overview on port governance

Main Category	Papers
Port Organizational model (7)	[118] [117] [44] [34] [79] [75] [65]
Role of Port Authority (4)	[66] [116] [41] [109]
Port Performance (9)	[16] [118] [65] [44] [119] [26] [25] [36] [113]
Port Reform (10)	[84] [85] [24] [87] [61] [27] [3] [39] [86] [32]
Policy/Strategy (9)	[114] [136] [138] [62] [5] [103] [22] [23] [144]

The literature available sheds light on the types of governance models, ways and reasons for its transformation from one model to the other, and the functional and operational impacts of these models. However, the literature fails to create a comprehensive understanding of how this information can be used to design a port call optimization tool that serves the functionality for a port.

3.2.1. Port organizational model

Changes in the economic environment, technological advancements, globalisation of production and distribution and changes in cargo transportation forms has led to the evolution of port organizational model or the port governance structure. Port governance structure can be closely related to the port performance as a good fit between the structure, strategy and environment can lead to good port performance [118]. A poorly formed governance model can induce trade tensions, increase export restrictions, and increase economic and social costs [34]. More on port performance is discussed in section 3.2.4.

Devolution: Devolution involves transferring the responsibilities of state authorities to the private sector. This can be done through sales, concessions, or by establishing a system where responsibilities are shared [118]. More on transferring of power through various methods is discussed in section 3.2.5. The drivers for the port governance change are [65] -

1. port users: want port operations to be privatized and require favourable conditions
2. government: want PA to be self-sustaining and reduce spendings.
3. NGO: holds PA responsible for negative externalities such as congestion and environmental damage

The world bank categorized ports into four categories as shown in figure 3.1 with respect to characteristics such as provision of service (public, private or mixed), orientation (local, regional or global), ownership of infrastructure, ownership of superstructure and equipment and status of dock labour and management [94]. These models are as follows:

Service ports
In public service ports, the port authority handles all port-related services and owns all the infrastructure. Typically, these authorities are part of a government ministry, and most of their employees are civil servants [108]. The main advantage of this model is that it centralizes responsibility within a single entity, promoting cohesion. However, the absence of internal competition can lead to inefficient management, a lack of innovation, and services that are not focused on the user or market needs [117].

Tool ports
The tool port is similar to a public service port, but it differs in that cargo operations are privately handled, although the port authority still owns all or part of the terminal equipment. In many cases, a tool port serves as a transitional form between a public service port and a landlord port [108]. The strength of this model lies in avoiding duplicate investments, as the public sector provides the facilities. However, it has several weaknesses: fragmented responsibility for cargo handling can lead to conflicts between

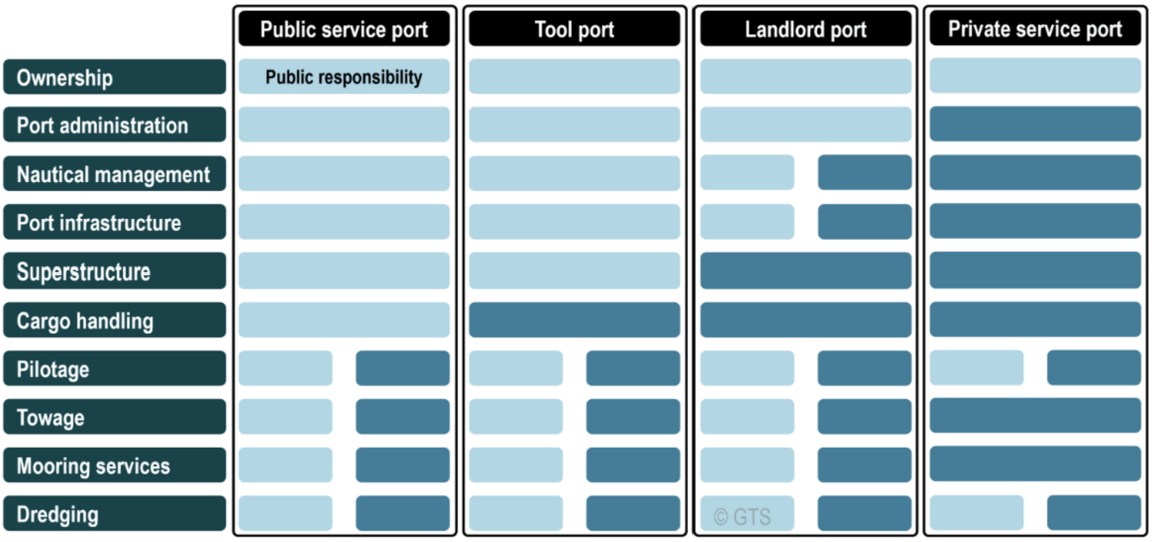

Figure 3.1: Public and Private Roles in Port Management [94]

small-scale operators or between them and port administration, there is a risk of under-capitalized investments, and it creates barriers to developing strong private operators [117].

Landlord ports
Landlord ports are the most common management model, where infrastructure, especially terminals, is leased to private operating companies, while the port authority retains control of the land. This control is either through ownership or exclusive exploitation rights granted by the relevant public authority. The typical lease arrangement is a concession agreement, where a private company is granted a long-term lease in exchange for rent, which is based on the facility's size and the investment needed for building, renovating, or expanding the terminal. Private operators in these ports provide and maintain their superstructure, including buildings like offices, sheds, warehouses, container freight stations, and workshops. They also employ dock labor and supply terminal equipment to ensure operating standards are met. This model is currently the most prevalent in larger and medium-sized ports, particularly in Europe and the Americas [108]. This model supports effective planning and adaptation to market conditions. However, if multiple private operators attempt to expand, it can lead to overcapacity. Additionally, there might be redundant efforts in promoting the port by both terminal operators and the port authority, necessitating coordinated marketing and planning efforts [117].

Private ports
This model results from the complete privatization of the port facility, ensuring that the facilities continue to serve their maritime functions. The port authority and nearly all port functions are under private control, while the public sector maintains standard regulatory oversight [108]. The primary weakness of this model is the risk of monopolistic behavior, especially if there is a lack of significant competition from other ports [117].

3.2.2. Role of Port Authority (PA)

The role of the PA is to ivest in activities besides safe and efficient managemnt of vessels, are those that have benefits for the port community. This can include investments in ICT, innovation and deversified port regions, investments in warehouses, etc [66]. The PA plays a crucial role in aligning governance models with environmental changes and port performance (as detailed in section 3.2.4). Effective governance models should improve responsiveness, ensure sustainable practices, and balance public and private interests to optimize port operations [66]. The success of these efforts largely depends on the authority and functionality of the PA.

Study identifies three hypothetical types of PA: conservators, facilitators, and entrepreneurs, each with distinct operational objectives and strategies [116].

1. **Conservators** Concentrate on preserving existing infrastructure and operations, with limited emphasis on innovation or expansion. They generally maintain a passive approach, which may lead to obsolescence.
2. **Facilitators** Bridge economic and societal interests, promoting regional collaborations and community engagement. They frequently participate in strategic partnerships beyond their immediate port vicinity.
3. **Entrepreneurs** Merge facilitation with active commercial investments, both locally and globally. They exhibit a proactive approach towards market opportunities and often face increased financial risks due to their ambitious nature.

Apart from preserving infrastructure and operations, bridging economic and societal interests, and facilitating commercial investments, the PA has been seen to provide other operations within the port. These include terminal and port operations and vessel services such as pilotage and towage, where the PA is the main stakeholder. However, such a structure is likely to seen only in smaller ports compared to larger ports [78]. The role of the PA evolves as the organizational structure of the ports change. The PA takes up more managerial role and focuses more on ensuring sustainable development of the port while giving up its operational roles to private entities when transitioning from a public to private port. The operational objectives of the PA can also differ based its governance structure [85].

1. **Municipal and Regional Port Authorities**: For municipal and regional port authorities, the focus is on the efficient utilization of public funds, improved services for residents and the local tourism industry, and support for social cohesion in island areas. These authorities prioritize the needs of the local community and economy, ensuring that ports serve as vital infrastructure for regional development and connectivity.
2. **Corporatized Port Authorities**: The primary operational objectives for corporatized port authorities are to increase competitiveness in global maritime transport, enhance sustainable and integrated port development, and improve service quality for users. These objectives are aimed at ensuring that ports operate efficiently and effectively on an international scale, aligning with global standards and market demands.

The national government's role in port operations includes overseeing regulatory compliance, ensuring fair competition, and promoting national economic interests. The government ensures that ports adhere to legal and regulatory standards, fostering a competitive environment that benefits the national economy and supports strategic economic goals.

Involving the private sector in port operations brings a set of objectives centered around enhancing operational efficiency, attracting high-yield investments, and integrating into international logistics chains. Private entities aim to optimize port operations through innovation and investment, driving economic growth and improving service delivery.

3.2.3. Relationship between stakeholders

The relationship between stakeholders, although not highlighted within the literature study of port governance, was found to be a vital component for the implementation of a PCO tool in a port. Therefore, this section aims to provide insights into the complexity of data-sharing capacity between stakeholders. Relationship among stakeholders varies among different port governance structure and their level of centralized decision-making. A study by [21] provides insight into the level of power and interest of different stakeholders which can lead to power struggles, lack of trust, resistance to change, and incompatibility of operating and strategic goals [81]. This hinders information-sharing potential among stakeholders and slows down progress. Therefore, [81] uses the partnership model to define four possible cooperative relationships between organizations.

1. Arm's Length Partnership: A transactional business relationship that lacks a sense of mutual commitment. The relationship terminates when the exchange is completed.
2. Type 1 Partnership: Organizations collaborate on tasks and project-related matters, coordinating activities and planning on specific cases. However, there is limited trust and little to no joint investments.
3. Type 2 Partnership: Organizations merge their activities and functions throughout the partnership.

4. Type 3 Partnership: The partnership encompasses both organizations' strategic and tactical operations.

3.2.4. Port performance

Port authorities worldwide are competing with each other to improve throughput and enhance performance to obtain a competitive advantage. A study on port competitiveness underscores the importance port performance on port choice [100], where user satisfaction is one of the critical factors determining port performance, as it has been studied that in its absence, ports fail to progress sustainably [16]. To effectively understand performance criteria, it can be broken to its two key metrics: effectiveness and efficiency, making key performance indicator easier to define.

Effectiveness refers to the ability of a port to meet customer service expectations and minimize delays or disruptions. On the other hand, efficiency is measured by the optimal utilization of port assets and resources to maximize productivity. There is often a trade-off between effectiveness and efficiency. By improving efficiency through higher asset utilization, ports may compromise on effectiveness as waiting times in anchorages increase for vessels. Conversely, if a terminal operator improves its asset utilization by leaving more vessels at anchor to minimize downtime, its utilization is improved, but the customer's service expectations may not have been met. In this case, efficiency has come at the expense of effectiveness. Striking the right balance between effectiveness and efficiency is crucial for ports to maintain their competitiveness and attract more business. Ports must continuously evaluate their performance metrics and implement strategies to optimize both aspects while keeping customer satisfaction as a top priority [18].

However, as all ports are different, it is difficult to find a relation between port governance and performance [27]. To ensure optimal performance, a port must address and adapt to the external environment, which encompasses various factors such as industry trends, economic conditions, technological advancements, regulatory landscapes, and socio-cultural factors. A theoretical model known as the Matching Framework (Figure 3.2) describes how an organization's success is determined by the alignment of three crucial components: the external environment, the organization's strategic decisions (including goals and strategies), and its organizational structures and processes.The organization's strategy outlines the approach it plans to take to accomplish its goals, considering the external environment. Organizational structures refer to the information and control systems, operational procedures, and hierarchical reporting relationships that dictate how the organization functions internally.

For a port to achieve optimal performance, it is essential to ensure that its strategic decisions and organizational structures are well-aligned with the external environment in which it operates [10]. By continuously monitoring and adapting to changes in the external environment, and aligning its strategy and internal structures accordingly, a port can enhance its competitiveness and achieve sustainable success.

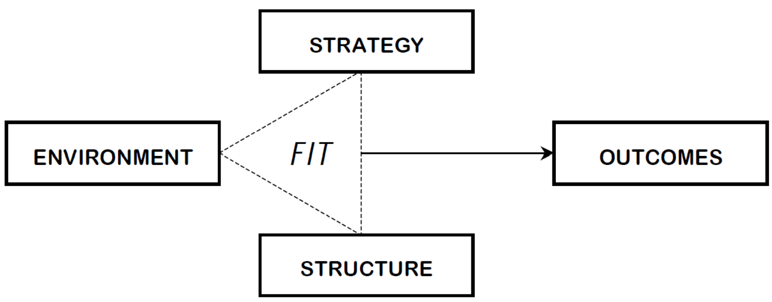

Figure 3.2: Matching framework [9]

The framework also suggests that there is no one-size-fits-all kind of model for organizational success. Instead, the optimal choices for strategy and structure depend on the specific characteristics of the organization's external environment. By doing so, ports can enhance their performance, adapt to changing conditions, and better serve the needs of their stakeholders.

Performance criteria of ports are selected at the managerial level which translates into operational objectives at the service level. These differ from port to port based on various environmental conditions and port governance structure.

3.2.5. Port reform

As reviewed in the previous section, according to the matching framework, ports adapt to the changing environment to fit better with the changing industry trends, economic conditions, technological advancements, regulatory landscapes, and socio-cultural factors to stay competitive. These factors become crucial based on the geographic location of the port and the economic significance that the location has [85]. Therefore, policy actors decides to change as per the conditions of the port as well as the environment - based on what they would like the port performance would look like [18].

It can be seen that the main reason behind ports transferring its operations to private entities are inherent delay in decision making process within the port, unavailability to release funds for development, lack of professional expertise and satisfying social and environmental concerns. The cause for delays can be generalized to bureaucracy which necessitates the need for privatization [78]. These factors can hinder the efficiency of the port in a constantly changing environment.

Ports need to decide on their goals to either fully privatize or partially privatize to retain control over port operations and services. Developing countries are reluctant to engage in full privatization as it complicates regulation and risk of achieving country's development goals. Centralization or decentralization is tied to the country's socio-economic objectives [78]. Partial privatizing involves privatizing cargo handling and other non-landlord activities. This can be done effectively using various forms of concessions where agreements are signed for the transfer of operating rights with contingencies in place to safegaurd the general interests of the port society [94].

A contemporary model of port governance must safeguard adequate and economically viable investments in the port superstructure and infrastructure whilst facilitating the efficient flow of goods and passengers through the port and protecting the port system from monopoly situations as well as serving the general interest of the public and other stakeholders [87].

Effect on vessel service operations due to privatization

This section provides insights into the changes in vessel service operations that occur due to the privatization of these services.

Monopolistic control over vessel services can lead to several negative outcomes, such as increased service rates, barriers to market entry for other companies, difficulties in adapting to disruptions, and a decline in service quality. The literature indicates that a public port model can ensure steady funding for investments in infrastructure and equipment. Nevertheless, political interference often hampers the port's responsiveness to customer requirements [44].

One way to address these issues is through public-private partnerships (PPPs), which involve collaboration between the public and commercial sectors in the ownership and operation of the port. With the help of concessions, the PA can retain control over the service providers and encourage them to use port resource efficiently. These services are monitored by the PA to ensure if the standards set are met. This approach leverages the stability and long-term financing capabilities of the public sector, while also benefiting from the expertise and efficiency focus of the private sector. However, managing such partnerships can be complex and requires careful negotiation to clearly define the roles and responsibilities of each partner [44].

In contrast, a private port model entails ownership and operation by a private company, which may be an independent firm or a subsidiary of a larger corporation. Private ownership offers greater financial flexibility and allows for quicker responses to market demands, as investment and operational decisions can be made based on profitability considerations. Despite these advantages, private ports are more susceptible to market fluctuations and may not prioritize social and environmental concerns to the same extent as publicly-owned ports [44].

As seen from the case of South Africa's ports [78], the governance model plays a fundamental role in pricing, investments, effectiveness and productivity in providing marine services. This affects the competitiveness of the port which makes the choice of port reform crucial for the development of the port. Although privatization can improve efficiency, care must be taken to preserve the socio-economic interests of the port as full privatization can impede the improvement in port performance [137].

3.2.6. Policy/Strategy

Lowering entry barriers can lead to increased competition and a reduction in rent/prices for services. Corporatized Port Authorities aim to increase competitiveness in global maritime transport, enhance sustainable and integrated port development, and improve service quality for users. Municipal and Regional Port Authorities focus on the efficient utilization of public funds, improving services for residents and the local tourism industry, and supporting social cohesion in island areas. Private sector involvement is geared towards enhancing operational efficiency, attracting high-yield investments, and integrating into international logistics chains. The national government plays a crucial role in overseeing regulatory compliance, ensuring fair competition, and promoting national economic interests [85].

[136] discusses the strategy to increase capacity in the expense of high capital investment or increase service charges to reduce service demands. Increasing rates might work if they have market power. government tends to commit to more capacity than private investors to improve regional economic benefits and port well-being while private investors tend to focus on maximizing utility and increasing prices, driving out customers .

3.3. Tugboat scheduling

This section provides the information gained after a systematic literature review on tugboat scheduling. This section shall provide an introduction to tugboat services, various operational constraints that must be taken into account, various scheduling problems and objectives considered

3.3.1. Operation

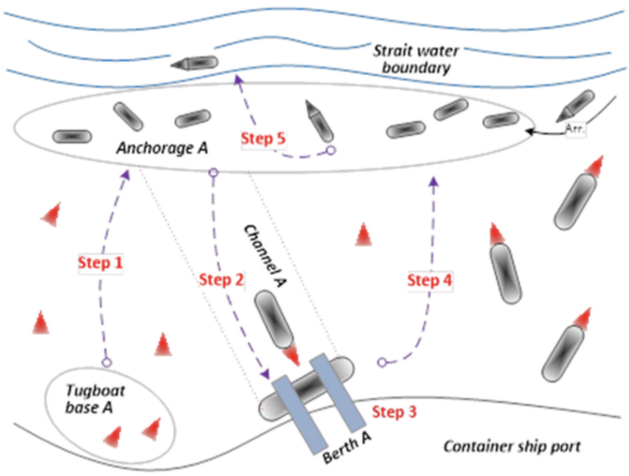

Figure 3.3: Simplified stages of tugboat service operation [142]

Figure 3.3 illustrates the various stages involved in the tugboat service when a vessel arrives at a port. The process begins at the anchorage area, where vessels wait for tugboats to assist them. Due to narrow channels and shallow waters, vessels navigate at low speeds, reducing their maneuverability [128]. Consequently, tugboat assistance becomes crucial to prevent accidents within the port. Many ports mandate the use of tugboat services to ensure the safe transit of vessels [128]. Tugboat companies face high operational costs due to substantial investments in tugboats and high fuel consumption. Therefore, they strive to optimize tugboat assignments for maximum efficiency. However, these companies may be contractually obligated to service vessels within specific time windows, as dictated by the port and customer requirements.

Vessels of varying sizes entering the port require the assistance of two tugboats [135]. When a ship approaches a berth, it needs to slow down and may require additional tugboats to assist. To optimize tugboat utilization, these tugboats provide teh extra supprt support at different waypoints along the vessel's journey to the berth [125] [127]. Additionally, tugboats have varying power capabilities, which must be considered for efficient assignments to reduce operational and environmental emissions [106].

Efficient tugboat scheduling not only helps tugboat companies utilize their resources effectively but also improves vessel turnaround times. Effective scheduling, considering estimated arrival times at berths and the availability of other stakeholders, can enhance the overall port call process [90]. When there are too many vessels to moor and unmoor in a short time, some may not be served due to limited tugboat availability. When determining work schedules for tugboats, the operator may reject service requests from certain vessels. If a vessel is rejected for service, the port operator may need to adjust the berth plan, such as changing the expected berthing or departure time, to ensure successful service [55]. This demonstrates the value of joint scheduling for port call optimization.

3.3.2. Modeling

Various literature has been found to solve the tugboat scheduling problem using multiple models and levels of complexity. [122] [123] develops a Mixed Integer Program model and an algorithm to solve the tugboat assignment problem. However, This model considers the simplest of constraints which makes it far from reality. [139] considers the berthing, shifting and unberthing operations within the scheduling model to incorporate various tugging operations in a port. [128] considers various practical constraints in its Mixed-integer linear programming (MILP) model to solve the scheduling problem. This provides a more realistic model into the operation of tugboats in a port call process. [57] Considers the uncertainty of container ship arrival and tugging process times in large container ports and solves using a proactive scheduling strategy by considering the expected degree of variability during the execution of tugboat scheduling. [55] has considered the tugboat services in a mooring operation. This has not been considered in any of the other research papers that were reviewed. [148] recognizes the need for customer satisfaction and the reduction of fuel consumption for reduced environmental emissions. The research tries to solve this bi-objective problem by using a multi-objective evolutionary algorithm. [125] considers a detailed model with waypoints, time windows of for the available working hours of the tugs and for the berthing at terminal. One challenge faced by tugboat operators when dealing with the TugSP is that requests are not completely known beforehand, but continually disclosed as the existing schedule is being performed, thus tugboat scheduling needs to be continually updated to satisfy the newly arrived requests [127].

It is clear that the complexity and the amount of research that has gone into tugboat has been increasing providing more realistic models. However, as problems become more complex with the increase in requests and available tugboats, it becomes difficult to find a solution. Therefore, heuristics are used to find a solution within a reasonable time-frame which is discussed in Section 3.3.4.

3.3.3. Constraints

Constraints used for tugboat scheduling are derived from geographic restrictions, to improve operational efficiency, and various policies enforced by the PA to ensure customer satisfaction and reduce environmental emissions.

Operational efficiency: Tugboats are operated either by a tugboat company or by the local maritime authority [55]. These companies own tugboats of various horsepower, dedicated to serve incoming vessels. Due to high investment cost, resources are used efficiently. A major strategy used in practice is incremental attachments of tugboats as they approach the berth. Also, vessel have specific requirements that has to be met by the tugs. As tugs vary in their horsepower, assignments have to made optimally to reduce overall cost of operation.

Geographic restrictions: Ports like the Abu Dhabi port are restricted by one way channels that need to be considered. Other conditions include tidal constraints that restricts the passage of vessel in a low tide situation which may cause grounding of vessels [148].

Safety restrictions: Ports require tugging operations of consecutive vessels to be spaced apart to reduce collision risks and maintain traffic flow.

Policy restrictions: Ports have strict restrictions on the maximum allowable speed of tugs during operations. Other restrictions include concessional contracts that mandates tugboat companies to provide vessel services within the assigned time interval to maintain customer satisfaction, and optimize operations to reduce environmental emissions [148].

3.3.4. Solution methodology

Tugboat assignment is a typical optimization problem. There are two types of approaches for solving assignment problems. Traditional mathematical programming methods, such as Branch and Bound are efficient for solving small-sized problems [121]. The complexity of the problem increases exponentially with the number of assignments. However, there is always a tradeoff between efficiency and accuracy in algorithm design [57]. Therefore, metaheuristic algorithms need to used to approximate solutions within a reasonable time frame for complex optimization problems containing a higher number of vessel and tugboat.

Several studies have been conducted to investigate the use of heuristic methods to solve the tugboat scheduling problem. However, a comparison study on the application study of the heuristics on the scheduling problem has been done.

3.3.5. Objectives

It is seen that the research explores various objectives to solve the scheduling problem. However, the objective of the tugboat services will depend upon the concession that it is under, other policies that it must adhere to and objectives based on the strategy of the company.

Minimizing the maximum completion time improves the port service levels as compared to minimizing total service time which may increase the service times for a few vessels [45][139]. However, this objective might not be as efficient as minimizing total service time in improving port performance. [128] focuses on the profits of the tugboat companies by minimizing the total travel cost of the tugboats. This objective can cause longer waiting periods for vessels at the anchorage. Therefore, additional costs of service delays has to be added into the objective as well. Authors in [57] [55] [135] uses weights to combine different objectives into one problem. These weights are selected based on their relative importance amongst each other. This can include reducing berthing and departure tardiness, and operating cost.

3.4. Terminal planning

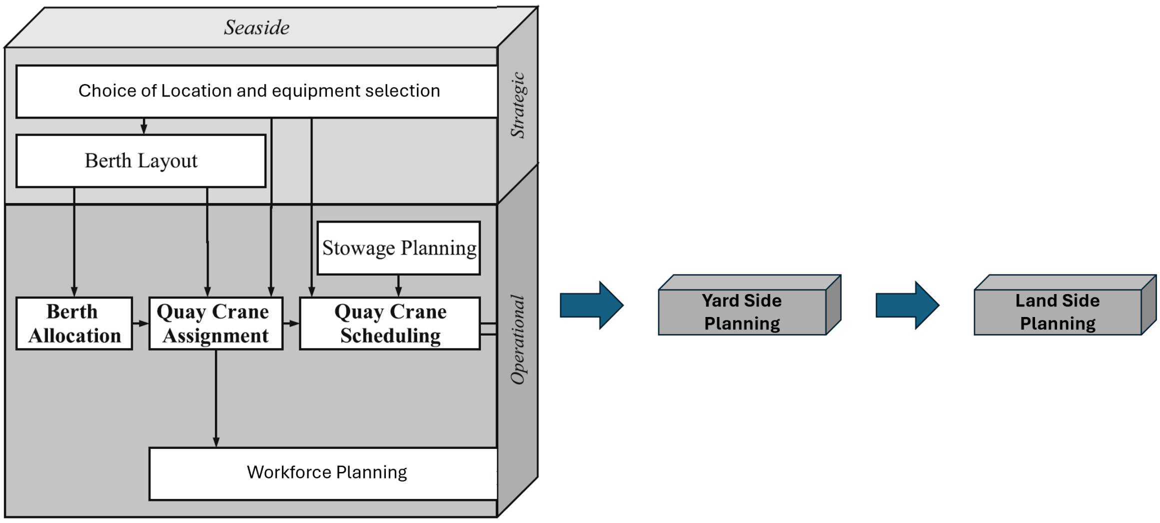

Figure 3.4: Planning problems within seaside of container terminal [14]

Port terminals are critical to global trade because they serve as the primary nodes for connecting sea and land transportation [101]. As a result, extensive research has been conducted in this area to improve port performance. The planning problem in container terminals can be classified into seaside, yardside and landside (as shown in Figure 3.4) while considering strategic and operational levels of planning [14]. However, for the scope of this project, the focus is on the seaside planning of terminals. This is because of their possible interaction with with incoming vessels. Berth allocation problem (BAP) involves assignment of quay space and service times to vessels for loading and unloading at the terminal. Berth allocation is the first level of planning in terminal operation and has an impact on all subsequent operations at port terminals. Once the vessel arrives at the quay, specialized cranes mounted on tracks are used for loading and unloading. The assignment of these quay cranes (QC) to vessels and the determination of the work plan of the cranes contribute to the quay crane assignment problem (QCAP) and quay crane scheduling problem (QCSP).

The integration of these decisions can be made sequentially, but this will result in poor-quality plans because BAP may be scheduled without knowing the actual availability of the QCs which can result in infeasible solution or unproductive use of port resources. A solution to improve decision-making is to combine the two sub-problems into a combined problem, which eliminates the need for instruction transfer. Another method is through functional integration in which a feedback loop where the top-level problem instructs the base level problem and the base-level reaction is used in the top-level to revise instructions. This loop terminates once a steady state is reached.

Integrating BAP, QCAP and QCSP can help in achieving better planning schedules that can even help in reducing fuel consumption of vessels by considering arrival time as a decision variable in BAP. The goal is to optimize an objective function by assigning a berthing position and time to each vessel [14]. Such models can be classified based on four attributes: spatial attribute, temporal attribute, handling time attribute and performance measure. These attributes have been discussed in detail by [13].

3.5. Pilot scheduling

Pilot scheduling is a pivotal aspect of maritime logistics, ensuring that vessels can navigate port waters efficiently and safely. Some ports have pilotage as a mandatory requirement to ensure safety within the port environment [134]. The pilotage service contains a set of limited pilots of high wages which need to be effectively utilized to minimize delays of vessels and reduce operational costs. This makes it a combination problem where pilots are assigned to vessels and the optimal set of task is considered for a pilot. The complexity of this problem further increases when considering various legal regulations concerning the working times of pilots. Pilots cannot be given tasks past their shift time and it could be the case that pilots earn a day of rest after a day of piloting which needs to be considered when scheduling vessel services. Moreover, Tidal constraints and channel restricts further adds on to the complexity of the problem.

Planning of the pilotage service is done by the Vessel Traffic Services (VTS) based on the berth schedules provided by the terminals. If the provided berth plan is found to be infeasible, the terminals are asked to revise their berth plan. This underscores the need for an optimization tool that considers the resource constraints of different stakeholders into the planning of port operations.

Initial research on pilot planning [71] focuses on minimizing the pilotage time using a genetic algorithm. However, it does not consider the waiting time of vessels or the costs associated with delay in tasks performed. [54] considers scheduling of the vessel traffic by assigning vessels to navigation channels along with pilot scheduling to manage congestion in ports. This study focuses on reducing the total waiting time of vessels by minimizing total berthing and departure tardiness cost, cost of unsatisfied vessel requests and total pilot dispatching cost. This objective shows the focus of the port on customer satisfaction in its planning. [134] optimizes the scheduling problem considering various operational costs. These cost components include dealt cost when a task starts later than the earliest start time, pilot dispatching cost, pilotage costs for executing tasks, and pilot transport cost. Consideration of pilot transport modes and resources adds a layer of complexity that improves overall performance by taking pilot transport availability into account.

3.6. Key Insights from the Literature Review

The systematic literature review conducted seeks to establish the essential background and comprehension of the concepts necessary for developing a PCO model of sufficient functionality, taking into account various port governance structures. This included an exploration of the general concept of PCO and related efforts. Additionally, a detailed examination of port governance, crucial for the scope of this study, was performed. Lastly, the scheduling optimization models of individual service providers was analyzed to understand operational constraints, objectives, and various methods used to solve the scheduling problem.

Port call optimization aims at maximizing the port call process through various optimization within the arrival, port visit and departure processes. Thus improving turnaround times of vessels and resource allocation. The literature found on PCO provides insights into the critical areas that has been considered for optimization. Due to high cost of fuel, its impact to overall shipping operation and its impact towards the environment, major research has been done to improve the shipping network which affects the arrival of the port call process. Slow-steaming and optimizing schedule design were identified to be prominent areas of optimization. However, These optimization methods are from the perspective of the shipping companies. Regarding port operations, the review recognizes that most inefficiencies are caused due to berthing and handling process delays. The review also emphasizes the importance of port efficiency towards enhancing terminal's attractiveness to shippers.

The review on port governance focuses on various port organizational models, the role of port authorities, port performance, port reform, and the policies and strategies influencing governance structures. It highlights the importance of selecting the appropriate organizational model to enhance port performance, ensuring it aligns with the port's environment and strategic initiatives. These models vary in their degree of centralization or decentralization and the role of the port authority. The review indicates that a port's success significantly depends on the authority and functionality of its port authority. Additionally, it reveals that a port's geographic location and its economic significance are crucial factors in facilitating port reform.

Due to limited number of research on optimizing nautical services under the pretext of PCO, an extended literature review was required to gain knowledge for the scope of this project. This review provided various operational constraints, objectives and modelling strategies. The literature reveals that service providers in ports have varying objectives influenced by economic factors, geographic location, safety concerns, and policy restrictions. Additionally, it has been observed that stakeholders often prioritize their individual benefits over collaborative efforts to enhance the overall performance of the port, such as reducing vessel waiting times. These insights are crucial for the development of a comprehensive PCO tool.

4 Conceptual Design

4.1. Introduction

The design phase of this research builds on the extensive findings from the systematic literature review to create a detailed roadmap for port call optimization (PCO). This chapter outlines the process used to develop this roadmap, providing insights into the methodology, the benefits of co-design, and the outcomes from each discussion session.

Roadmapping is defined as a process that identifies the necessary actions, steps, and resources required to achieve an organization's vision [107]. It offers a strategic, long-term approach to reaching organizational goals.

The co-design approach in roadmapping involves actively engaging with consumers and users in the design process to ensure the roadmap aligns with client needs, objectives, and future trends. This method is generally effective in creating a good fit between technology and its users. However, involving a large number of consumers and users can significantly prolong the design process. Considering the scope of this project, the OptiPort team was chosen for the co-design process. OptiPort is a leader in implementing scheduling tools for vessel service providers, such as tugboat services, and is at the forefront of developing a comprehensive PCO tool that will include a variety of other vessel service providers in the industry.

4.2. Design steps

The roadmap design follows a sequential approach as shown in figure 4.1, where the results from each step serve as inputs for the next. The process begins with a trend analysis to identify the latest developments in port call optimization (PCO). This step ensures that the proposed innovations align with future industry trends, maintaining their relevance. Various trends are evaluated to determine how well they fit within the project's focus on coordinating the schedules of vessel service providers across different governance structures. The OptiPort team collaborates in this evaluation to identify which trends will influence the subsequent steps of the roadmap.

Trends identified through discussions with clients are used to define requirements to ensure the functionality of a comprehensive PCO. These requirements serve as criteria that must be fully or partially met to align with the identified trends and the functionality of PCO. The same discussion panel then evaluates and prioritizes these requirements and objectives.

The next stage is crucial, as it involves designing solution strategies tailored to the requirements and objectives established for each stakeholder. These solutions may vary depending on the governance structure within which each stakeholder operates. Therefore, this stage also involves analyzing potential obstacles to solution adaptability and resilience. The proposed solutions are then assessed for feasibility and effectiveness by the discussion panel before being considered for inclusion in the roadmap.

In the final step, an action plan is developed for the selected solution strategies, tailored to different governance structures. This plan ensures that the strategies meet the defined requirements and objectives while adhering to the identified trends.

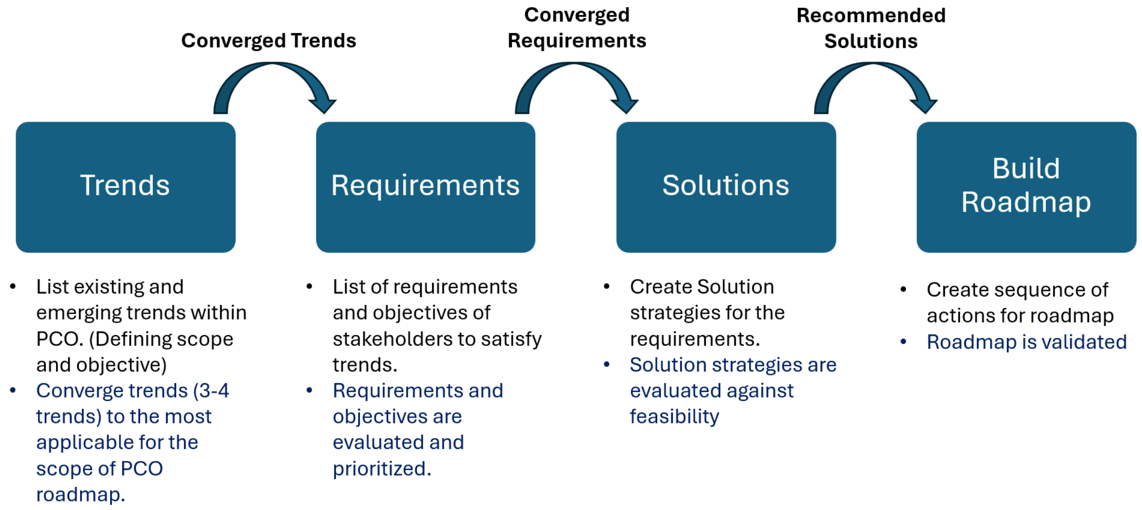

Figure 4.1: Design Steps

4.3. Trends

This section aims to identify trends in port call optimization (PCO). It starts with a review of the literature on emerging trends in port operations, followed by an exploration of organizational initiatives that support these trends, to gain insight into their practical application and future direction.

4.3.1. Trend study from literature

Literature review on emerging trends can provide provide strong scientific grounds to determine important trends in PCO. Figure 4.2 shows a study to identify emerging trends using a focus group of industry experts to to evaluate various PCO trends. According to this study, changes in ports are driven by global trends across technology and energy that result in changes to traditional business models and functions of ports. Green shipping and ports; Additive manufacturing; and Digitalization and big data are the ones identified by [104] through structured communications with a panel of experts. These trends are regarded as highly pertinent and influential for the future of ports [104]. Notably, while autonomous vessels currently have no effect on ports, they are anticipated to have a significant impact in the future. Consequently, this trend is included in this study as well.

Green shipping and ports involves decarbonization of port and logistics supply chain, use of renewable energy and efficient management of the grid, and green port operations. Decarbonizing port operations include electrifying terminal operations and port processes and use of onshore power for ships at berth are effective measures to reduce emissions. Use of renewable energy and other alternate fuels are also being explored by ports [47].

Digitalization, identified as one of the most significant trends by [104], encompasses the use of technology to monitor and trace goods, provide real-time information, and optimize the movement of goods within ports. A few sub-trends within digitalization include blockchain and smart ports. Blockchain technology, in particular, plays a crucial role in enhancing the connectivity of the supply chain. According to [140], there is a positive inclination towards utilizing this technology for customs clearance and management, digitizing and streamlining paperwork, and promoting standardization and platform development. Blockchain facilitates supply chain transparency and traceability.

Smart ports in Industry 4.0, as reviewed by [88], leverage data optimization to enable informed decision-making, reduce costs, enhance efficiency, mitigate risks, and foster growth. Implementing a smart port necessitates a comprehensive infrastructure. The main characteristics of Industry 4.0 include hyper-

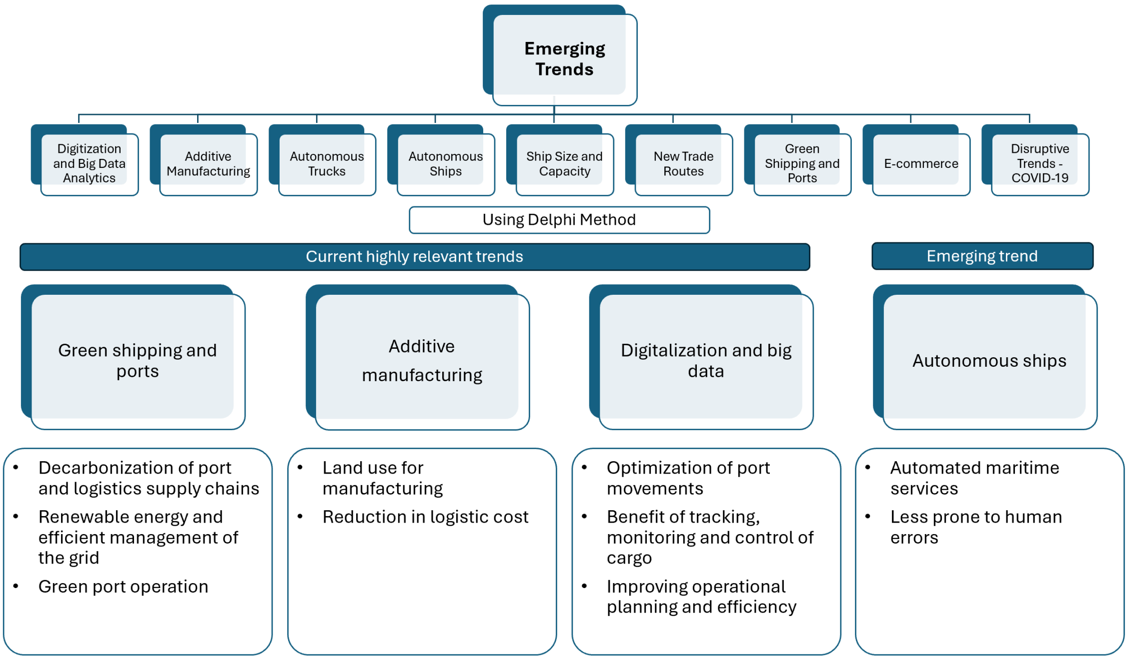

Figure 4.2: Study on emerging trends using Delphi method [104]

connectivity, intelligence, autonomy, and predictability. Ports are increasingly transitioning towards becoming smart ports by integrating advanced technologies, which align with these characteristics.

According to [104], **additive manufacturing** is an emerging trend that involves using 3D printing technology to create products. This trend may result in less transportation by sea, road, and rail as products are produced closer to consumers. However, sea transportation of raw materials would increase.

Autonomous vessels offer various advantages due to the absence of crew, such as reduced operating costs, enhanced security, decreased GHG emissions, and the creation of new shipping services. Although the technology for autonomous vessels is available, ongoing efforts aim to optimize cost-effectiveness. Additionally, maritime law must be revised before the widespread adoption of autonomous ships [104]. [68] anticipates that the first commercial vessel to navigate entirely by itself could be a harbor tug. With autonomous vessels, a large amount of human errors can be avoided which accounts for a large percentage of maritime accidents, leading to less operational disruptions.

After reviewing the available literature in the domain of PCO as shown in Table. 3.1, it is found that the majority of the research has been done with the focus of reducing greenhouse emissions. Numerous recent studies have been conducted to optimize vessel speed, ensure Just in Time (JIT) vessel arrival, and design vessel schedules. These research focus on areas such as reducing waiting times at anchorages and slow steam to reduce fuel consumption.

4.3.2. Organizations focusing on PCO

Various International organizations and associations have dealt with port call optimization by providing guidelines and roadmaps on ways to improve the port call process. As shown in Table 4.1, these efforts have been mainly towards improving communications and making sure that data/info are shared effectively between stakeholders/ports. The international taskforce port call optimization [52], has decided on a road for port call optimization. However, the taskforce focuses on standardized documents transferred and incentives for sharing data between stakeholders to streamline the port call process. The IMO and the IAPH, on the other hand, has taken up initiatives such as Just In Time (JIT) arrival of vessels to reduce port congestion and fuel consumption. They recommend that low congestion at anchorage can reduce the probability of collisions, and reduce greenhouse gases and fuel consumption of idle vessels. By using slow-steaming, vessels can reach the port just in time for vessel service providers (tugs, pilots, etc) and save fuel in doing so.

Table 4.1: Few initiatives taken up by different organizations

Organization	Initiative	Measure category
International Maritime Organization (IMO)	JIT	Reduce greenhouse emissions
Sea Traffic Management (STM)	PortCDM	Collaboration
International Association of Ports and Harbors (IAPH)	Best practices in port operations, JIT	Reduce greenhouse emissions
PortXchange Products BV	PortCDM	Collaboration
Global Port Call Optimization Task Force	Standardized processes	process improvements

4.3.3. Trend analysis

Using the co-design method, the collective experience of the OptiPort team was used to review and analyze the industry trends. Through these discussions, it was agreed that decarbonization through green measures and the adoption of digitalization are significant trends influencing the future of ports. However, the trend towards additive manufacturing was deemed less relevant for the development of the Port Call Optimization (PCO) tool. While additive manufacturing, through localized production, could alleviate some supply chain pressures, it does not significantly affect the port call process. This conclusion was reached after considering the trends that have an impact in the port call process.

During discussions, the trends of digitalization and green measures for decarbonization were identified as key enablers for developing a PCO tool. Digitalization plays a crucial role by ensuring the safe and efficient transfer of data and providing a unified platform for all stakeholders to communicate and collaborate. Technologies like blockchain, which enhance terminal operations, enable vessels to reach berths more quickly. However, this can increase pressure on vessel service providers, who may then become bottlenecks in the optimization process. Additionally, other digital innovations that promote collaboration among stakeholders are also essential for the success of PCO. These technologies facilitate better coordination and communication, highlighting why digitalization is considered a vital enabler for PCO development. Sea Traffic Management (STM) recognizes digitization as an opportunity that facilitates communication and connectivity among stakeholders [77].

Green measures have gained widespread acceptance in industries as a result of various policies in place and the economic benefits they provide to stakeholders through the efficient utilization of their resources. PoR's extensive GHG reduction measures include energy transition, which has been adopted by many other ports as well. These include wind farms, the use of hydrogen, carbon capture, biofuels, heat capture, and so on. Such green measures taken up by the port have little impact on the operations of vessel service providers. It was discussed that such green measures allow for the development of PCO by reducing waiting times and emissions through an optimized schedule.

Moreover, autonomous vessels are attracting interest from ports due to economic advantages such as lower crew costs and minimized human error. These ships could also boost efficiency by optimizing routes and shortening transit times [68]. However, the absence of established rules and regulations for autonomous ship operations could result in legal and liability challenges. Therefore, shipping companies and regulatory bodies need to collaborate to develop a framework that ensures the safe and responsible utilization of autonomous ships [68].

Within these discussions, it was suggested to consider the concept of PortCDM in the development of a full PCO tool. However, a lot of similarities were found within PortCDM and PCO. The following section clears this overlap for better understanding.

PortCDM and PCO

PortCDM builds upon both internal and external collaboration. Connecting external actors such as ships, port and hinterland operators and internal actors such as tugs, pilots, linesmen and terminals enhances situational awareness which improves the planning horizon allowing actors to better plan their services [77]. Hence, PortCDM is a concept that facilitates the dynamics of collaboration within internal and external actors through standardized data sharing platforms and connectivity between

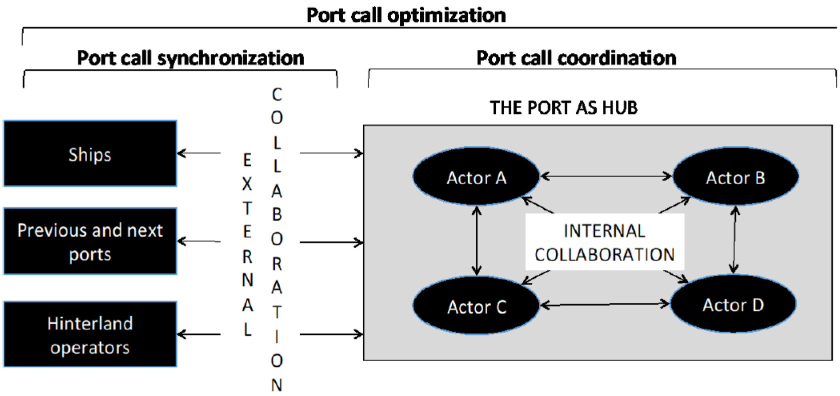

Figure 4.3: Collaboration in Port Call Optimization [70]

different [70]. This enhances the decision making process between stakeholders.

Thus, PortCDM is not designed to serve as the planning tool for port call activities. Instead, PortCDM aims to offer all participants involved in and around the port call process a shared situational awareness derived from a unified system of record [69]. This makes the concept of PortCDM an important condition that needs to be satisfied to facilitate the development and implementation of a PCO tool at a port setting.

4.4. Requirements

To address stakeholder needs effectively, it is crucial to define requirements that specify the necessary capabilities or functions of a system [8]. In this context, the solution involves creating a Port Call Optimization (PCO) tool that fully optimizes the port call process through collaboration among various stakeholders in the nautical chain and terminals. Achieving this goal requires a well-defined plan to guide the development of the optimization tool within an organization. This development strategy should consider multiple alternatives, which must be analyzed based on specific criteria. The requirements help gauge the different alternatives proposed for the development of the tool, ensuring it meets stakeholder needs effectively. This approach answers sub-research question 1, which concerns the requirements for implementing and deploying a comprehensive PCO tool.

A study on pre-conditions for collaborative PCO defines the requirements for an effective implementation of port call optimization at a port [21]. This research is backed up by expert interviews and corroborates the findings. This framework is applied to obtain the requirements for developing a full PCO tool for different governance structures. However, the framework provides the requirements for implementing a collaborative port call optimization. Therefore, these requirements act as references and are used to translate into the requirements for developing a PCO tool.

The requirements derived from the TOEI (Technological-Organizational-Environmental-Interorganizational Arrangements) framework presented in [21] are in close relation to the development stages presented within PortCDM [77]. This confirms the applicability of this framework to analyse the requirements for the development of the PCO tool as PortCDM is the driving concept that the PCO is based upon.

The TOEI framework outlines the prerequisites for adopting PortCDM, focusing on technology, organizations, the external environment, and inter-organizational arrangements. These prerequisites are then converted into constraints and objectives for developing the PCO tool. The constraints and objectives detailed below stem from brainstorming, interviews, and abstraction. Additionally, a systematic literature review offers insights into stakeholder needs, aiding in the formulation of requirements.

4.4.1. Constraints

Figure 1.2 highlights the critical role of real-time data sharing in better coordinating the arrival process, increasing predictability, and avoiding unnecessary waiting times [77]. Interviews with PCO tool developers indicate that current tools rely on predicted data from other stakeholders due to limited data transfer among them. Therefore, it is essential that information is shared among stakeholders in a consistent format and standard, enabling its use across the board and allowing stakeholders to alert others of any changes in the environment. STM supports this requirement to facilitate effective collaboration between port stakeholders [77]. It is also observed that a large amount of static and dynamic data is transferred between different stakeholders during a port call process. However, the complete set of data need not be completely standardized before implementing a PCO tool. Therefore, this study suggests an initial standardization of critical information in the port call process which is the primary reason for delayed port calls [80]. This critical information is listed in Appendix A.

To optimize port call processes, it is essential to involve various stakeholders, including port authorities, shipping companies, and nautical service providers, in decision-making. Liner shippers typically schedule their networks and port calls well in advance, but these plans can change during their voyages. Engaging multiple users in the decision-making process facilitates effective collaboration among stakeholders, leading to better decision outcomes. Involving stakeholders from both upstream and downstream of nautical services contributes to more efficient scheduling and supports the port's socio-economic goals. A study by [83]) highlights the benefits of joint scheduling for vessels and service providers, underscoring the positive impact of multi-user collaboration.

To implement a PCO tool effectively, different stakeholders need to cooperate with each other effectively. Such cooperation only works if it is beneficial to individual stakeholders. This is also recognized in level 6 of PortCDM maturity levels where the stakeholders agree to an optimal plan that raises the overall performance of the port call process [77].

Below are the constraints for the design of a PCO tool:

1. The tool must use standard formats for critical communications between stakeholders to allow direct communication and transparency.
2. The tool must allow data sharing between multiple users to ensure effective decision-making.
3. The tool must be able to find a compromise between stakeholders to facilitate collaboration.

4.4.2. Objectives

To implement PCO tool effectively, the proposed solution must be adequately prepared and suitable for operational support. This means the solution should align with and be compatible with existing port practices to ensure successful implementation. This includes considering fleet restrictions, operational constraints, and even environmental conditions such as tidal changes and wind variations.

Financial autonomy is crucial for facilitating port developments. This can vary greatly from port to port based on the governance structure of the PA and of the port. The performance of the PA is considered to be the precondition for an attractive business environment which would result in enhanced port performance [113]. Therefore, maritime attractiveness is highly influential on the port governance structure as it enables the port authority to take up entrepreneurial roles.

The literature review reveals that minimizing operational costs is a key objective for stakeholders and remains crucial in designing the PCO tool. In addition to reducing operational costs for individual stakeholders, minimizing vessel delays is also recognized as important, as it helps lower environmental emissions and enhance safety.

Finally, ports implement various policies to reduce emission rates in the port area. This leads to a change in the operation of stakeholders to adhere to the set policies.

Below are the objectives for the design of a PCO tool:

1. The tool should consider the operational and environmental constraints of all stakeholders.
2. The tool should potentially be supported by the government.
3. The tool should be able to provide minimum cost of operation to all stakeholders.
4. The tool should be able to reduce delays in vessel operations.
5. The tool should satisfy current green policies in ports.

4.4.3. Requirement analysis

The requirements were reviewed with the OptiPort team, a key stakeholder in the development of the PCO tool. During the discussion, concerns were raised about using advanced technology to gather information on vessel service and terminal operations without effective data sharing. While technology can extract unshared data to improve scheduling for individual stakeholders, it does not effectively optimize the overall port call process.

Concerning data-sharing standards, it is essential for stakeholders to share critical parameters to ensure collaboration and transparency. Transparency involves exchanging information whenever there are schedule changes due to delays or other reasons. However, transparency does not extend to sharing the mathematical models used for schedule optimization.

Concerns were raised about the benefits received by each stakeholder. Collaboration can be difficult when stakeholders are not working toward the same goal. As a result, this requirement was deemed the most important in terms of stakeholder collaboration from OptiPort's perspective.

Additionally, because ports vary significantly, the PCO model must be tailored to each port's specific constraints and operating procedures. This necessitates updating the PCO model to fit each port's unique requirements. This requires the development of multiple roadmaps for different ports as the level of technology availability, stakeholder collaboration, policies and horizontal competition vary greatly from port to port.

4.5. Alternative solutions and evaluation

The aim of this research is to propose a roadmap for the development of a full PCO tool. Implementing a PCO tool necessitates collaborative efforts among stakeholders, the availability of technology, adherence to policies and constraints, data sharing standards, and an optimization strategy for decision-making. Although it is crucial to thoroughly analyze and develop solutions for each of these aspects, this research specifically focuses on the optimization strategy for decision-making.

The systematic literature review in section 3 examines tugboat, pilot, and berth scheduling, offering a thorough analysis of existing scheduling techniques, parameters, constraints, and objectives. The literature reveals that multiple models, varying in complexity, are designed to closely replicate real-world scenarios, resulting in increased computational time. Consequently, heuristic methods have been developed to tackle the scheduling challenge. In this section, we propose optimization solutions for the port call process and evaluate them based on their effectiveness in meeting the requirements.

4.5.1. Optimization method alternatives

The models reviewed in the literature reveal several approaches to optimizing operations for single or multiple stakeholders and hierarchy levels in decision-making. These methods include single-objective optimization, multi-objective optimization using Pareto efficiency, multi-objective optimization with scalarization, simulation-based optimization, and bi-level optimization. Each of these strategies is evaluated for its suitability to different port governance structures, taking into account the unique characteristics of each structure.

1. **Single Objective:** This model solves the optimization model involving multiple stakeholder using a single objective function. Usually, these objectives are to improve the overall performance of the port. This includes minimization of turnaround time, minimization of deviation from planned schedule or minimization waiting time of vessels. Although using a single objective can bring the port performance to optimum based on the objective used, this may lead to sub-optimal performances for some stakeholders. Thus affecting collaboration between stakeholder. Therefore, such a strategy can be used for public/service ports, where all stakeholders are owned and controlled under one entity which allows for such an optimization method.

   Nikghadam [83] proposes a model for joint scheduling of vessels and service providers by minimizing the maximum deviation from the requested times. Although this approach effectively optimizes resource use and schedules vessels closer to their requested times, it assumes full collaboration among stakeholders. In reality, organizations have multiple objectives to satisfy their stakeholders, and different entities within the nautical chain often have conflicting goals, making joint scheduling challenging.

2. **Multi-Objective Optimization:** Multi-objective optimization (MOO) strategy provides a way to tackle multiple stakeholders' objectives. [43] suggests two common methods of MOO, Pareto and scalarization, that do not require complicated mathematical equations, making the problem simple.

   (a) Scalarization: This method solves the optimization model using multiple objectives which are added into the main objective function using normalized weight components for each subsequent objective. [141] proposes a heuristic approach to solve a multi-objective optimization that considers travel cost and travel time and costs associated with operational and idle times of tugboat operations. These costs are measured and validated through data available from past operational data.

   However, Selecting appropriate weights for problems with multiple stakeholders' objectives is challenging and causes a bias in finding a trade-off solution [43]. This method tries to find the solution that fits best into the objective function but does not compromise on different objectives.

   (b) Pareto: A Pareto optimal point is achieved when one objective function cannot improve without reducing the other objective function. This helps in finding the compromise solution between two or more objective functions which could not be performed with scalarization [148]. Such a method can be used when the weights of the different objective functions are not known and a compromise solution needs to be derived. This is done by identifying a set of Pareto optimal solutions considering different trade-off between the objective functions and finding the Pareto optimal point.

   However, by using Pareto optimization, the preferences of stakeholders are considered through a-posteriori evaluation [132] which fails to achieve an integrative design approach. Therefore a sub-optimal compromise solution is achieved.

3. **Multi-Objective Multi-Stakeholder Optimization:** Preferences are crucial in the design and decision theory because they are closely linked to human behavior [132]. An analysis of the preferences at a macro and micro level, and across ports was conducted by [105]. This optimization model considering multiple stakeholders requires an accurate representation of the preferences in the objective function. Therefore, Tetra software needs to be used to perform a performance aggregation such that the combined preferences accurately reflect the individual preferences of all stakeholders as closely as possible.

4. **Simulation-based optimization:** Stochastic and dynamic nature of the problem can lead to increased complexity. [50] proposes a simulation-based optimization solution for the combined planning of berth allocation, tug allocation and quay crane allocation. A simulation model replicates real-world systems that are too complex to analyze directly [37]. This optimization strategy incorporates the dynamic nature of the port environment in vessel arrivals, departures and resource availability to provide robust scheduling solutions [50]. A framework for the simulation-based optimization is shown in Figure 4.4.

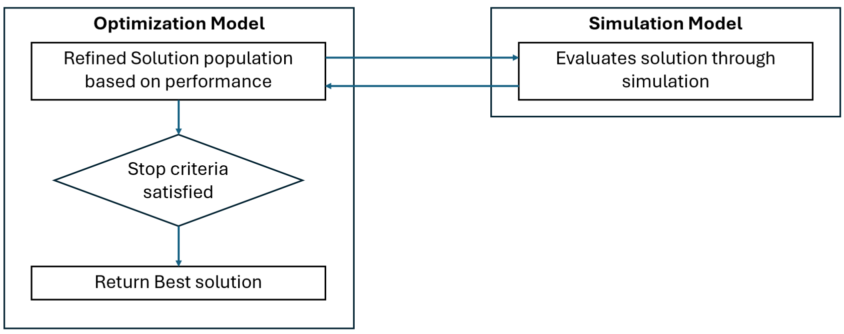

Figure 4.4: framework for simulation- based optimization [50]

5. **Bi-level optimization:** The problem of berth allocation and nautical service scheduling can be seen as a hierarchical decision-making process in ports. Terminals decide on the berth allocation with the vessel agents who then communicate with the HM to schedule the nautical services to meet the required berth timings. With bi-level optimization, the parameters required for the lower level are obtained from the upper level. The structure of the bi-level problem is shown in figure 4.5.

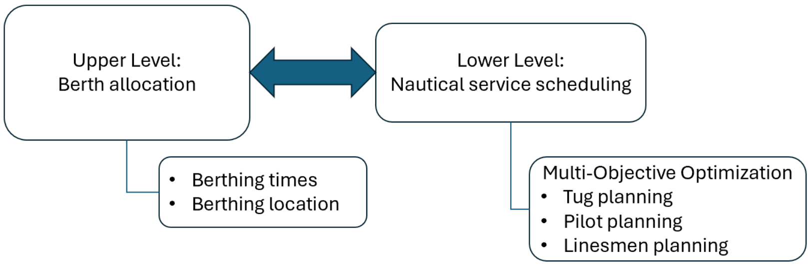

Figure 4.5: framework of bi-level optimization

4.5.2. Alternate evaluation

This section offers a thorough evaluation of various optimization strategies that are essential for the PCO software tool, as they play a critical role in supporting decision-making processes. These strategies enable the model to effectively guide decisions throughout the port call process by meeting several key requirements. The software must handle multiple objectives since most organizations operate with numerous key performance indicators (KPIs). It also needs to find compromise solutions among multiple stakeholders, considering their varying levels of influence, interests, and preferences, which is vital for fostering collaboration. As highlighted by [105], understanding stakeholder preferences is crucial. Moreover, the decision-making hierarchy within a port must be taken into account. For example, berth allocation is a central aspect of port planning, and nautical services need to be scheduled in accordance with berth availability. Therefore, the model must integrate this decision hierarchy to ensure practical applicability.

Figure 4.7 compares various optimization strategies suitable for different use cases. Although single objective optimization is widely discussed in literature, it is often impractical for most scenarios since organizations typically operate with multiple KPIs. However, it can be useful in situations where a port aims to minimize total delay or increase throughput. For more comprehensive analyses involving multiple objectives and stakeholders, multi-objective optimization can be employed, where weights determine the relative importance of each objective for different stakeholders. Determining these weights can become challenging as the number of objectives increases. In such cases, Pareto optimization can be used, assigning weights to find a compromise solution among all objectives. Multi-objective multi-stakeholder optimization effectively incorporates stakeholder preferences into the weights of the objective functions, resulting in decisions that are better accepted based on human preferences.

Figure 4.6 compares different optimization strategies for non-hierarchical decision-making in ports, focusing on the level of centralization and the number of objectives with the size of the bubble representing number of stakeholders involved in the decision-making process. In public ports, where all services are managed by a single entity, a single objective optimization strategy, often cited in research [82], can be used to minimize delays. This strategy relies on high levels of collaboration and centralized control. However, organizations typically have multiple KPIs to meet, requiring strategies that address multiple objectives. Multi-objective optimization using scalarization can meet these needs but is only effective for single stakeholders or multiple stakeholders governed by a single entity, as it does not consider individual preferences. Therefore, this strategy is suitable for public ports or situations where decisions are made by a single entity without individual stakeholder input. As the number of stakeholders in the decision-making process increases and collaboration among them decreases, more advanced strategies are needed to incorporate individual stakeholder preferences. A multi-objective optimization strategy using Pareto can find a compromise solution among different objective functions and select an optimal solution from the Pareto front based on stakeholder preferences. However, since

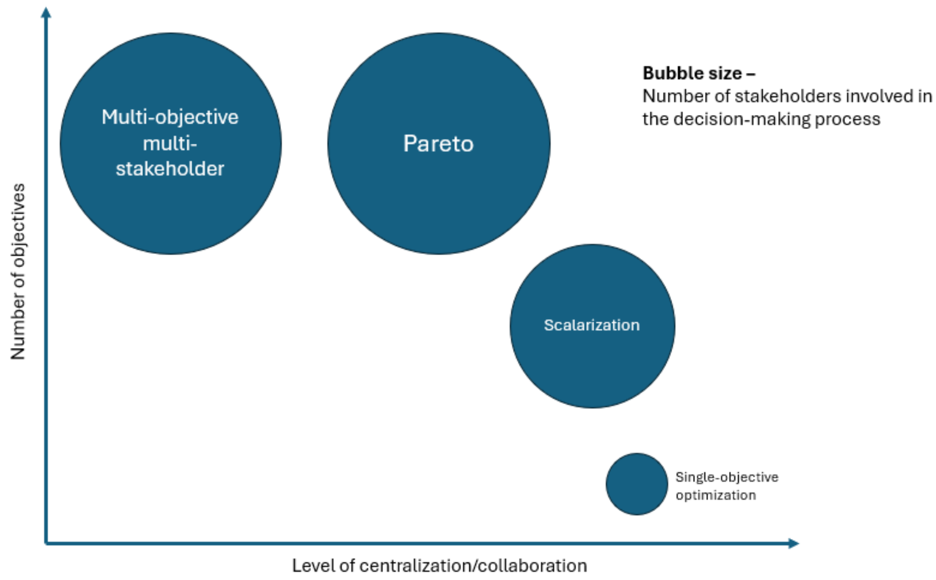

Figure 4.6: Comparison of Optimization Strategies for non-hierarchical decision making

this strategy employs an a-posteriori method, it may miss the global optimum and is most effective when there is some level of stakeholder collaboration [132]. The Odesys method, on the other hand, uses an a-priori approach that integrates stakeholder preferences into the optimization model, considering socio-technical interactions. This strategy is crucial in situations with limited stakeholder collaboration and significant differences in stakeholder preferences.

Hierarchical decisions are an important aspect to consider when the decision of one stakeholder affects the input parameter of the others. For such hierarchy based decision making process, suitable models should be in place. A simulation-based optimization which uses discrete event simulation can be used to replicate complex systems. However, implementation of such a model would require a close understanding of each stakeholder and can be computationally intensive. A bi-level optimization approach is an analytical approach which is less computationally intensive and can be used by updating current single-level multi-objective optimization models.

Current research considers the involvement of collaboration among stakeholders for the implementation of PCO. However, in highly decentralized port settings, full information availability between stakeholders may not be possible due to their sharing policies of sensitive information [73]. Therefore a federated approach is worth exploring which lets stakeholders optimize locally and share only critical information to arrive at a global optimum. This method is not explored in this study and is worth exploring.

4.6. Conceptual framework for roadmap development

Developing a roadmap for implementing a PCO necessitates a comprehensive understanding of the current port environment, strategy, and structure, as detailed in section 3.2.4. The matching framework defined in this section is crucial for identifying the optimal alignment between these three elements to enhance port performance and determine the appropriate structure and strategy in a dynamic environment. However, this study focuses on the port's static state to create a tailored roadmap for specific port settings. Therefore, the matching framework is broken down into its components to analyze the port for PCO implementation.

Analyzing the organization's external environment is essential, which includes the remote, industry, and operating environments [9]. The contents of these are shown in table 4.2. The external environment, port governance structures and port strategy which can be translated into the influence by the PA are used for evaluating the prerequisites towards implementing a PCO. Lastly, port governance structure, as discussed in section 3.2, forms the 'structure' component of the matching framework that helps to assess the hierarchical reporting relationship and regulatory framework.

Table 4.2: components of external environment

Remote environment	Industry environment	Operating environment
Political	Number of participants	Buyers
Technological	Size of organization	Suppliers
Economic	Extent of collaboration	Competitors
Socio-cultural	Policy regulation	Potential new entrants
		Substitute services

Figure 4.8 depicts the conceptual framework for evaluating ports for the implementation of the prerequisites. Since the roadmap is for a PCO tool that must meet the requirements listed in section 4.4, the prerequisites correspond to the actions needed to satisfy the core requirements listed in the previous section. These prerequisites are influenced by factors derived from the components of the matching framework, which impact the feasibility and timeline of the tool's development and implementation. Each prerequisite in this framework is detailed below to ensure a comprehensive approach to optimizing port performance within the given parameters.

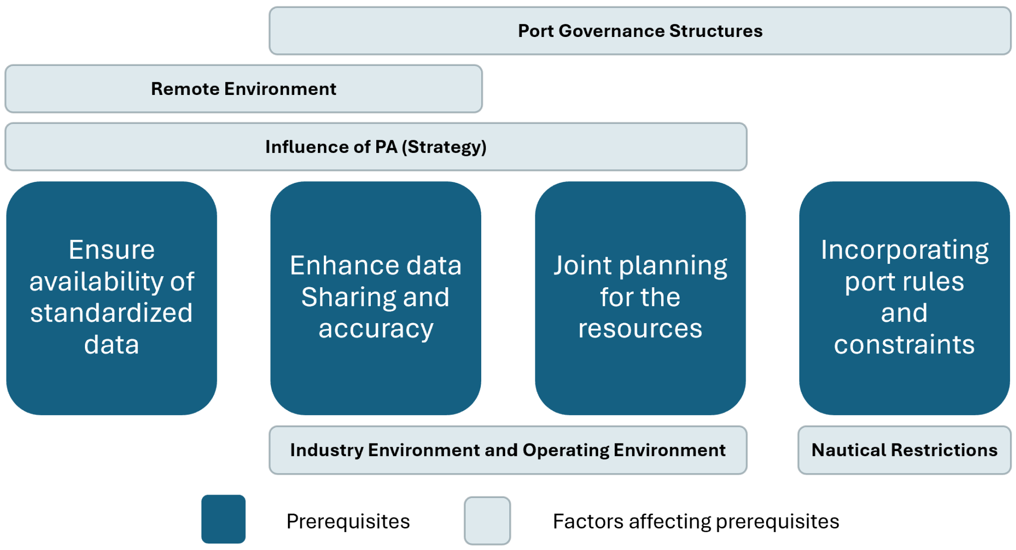

Figure 4.8: Conceptual roadmap framework

4.6.1. Ensure availability of standardized data

Standardized data is an important component for the implementation of PCO. Standardized data helps in notifying multiple stakeholder without possible misinterpretation and significantly reduces workload due to data management [52].

Communication technologies in place can also influence the use of standardized data. A port with an established PCS can help in facilitating efficient communication between stakeholders by requesting data to be entered in standardized formats. A PCS also ensures availability of data to analyze current processes and suggest future improvements.

The International PortCDM Council (IPCDMC) has developed the S-211 standard to improve how data is shared during port calls. This format allows for standardized communication about movements, services, and administrative events in a port. It ensures precise details, like arrival and departure times, are shared clearly between ships, ports, and other related parties. By focusing on essential operational data and excluding sensitive business information, S-211 helps enhance coordination and efficiency in maritime transport [12].

4.6.2. Enhance data sharing and accuracy

[80] underscores the importance importance of information and takes a systematic approach to derive the critical information sharing links to improve port performance. Once the standardized information are established, data sharing is next crucial step towards the implementation of a PCO tool. Data needs to be shared among stakeholders accurately and efficiently. The communication technology in place in a port can have a major advantage in facilitating information sharing. Such platforms provide a secure location for sharing information.

Data sharing protocols becomes crucial and easier to implement in ports susceptible to nautical restrictions such as tidal windows, locks, day-light restrictions and long narrow river. This increases the need for coordinated efforts by different stakeholders. The PA and VTS takes up higher responsibilities in sequencing vessel arrivals and ensures vessel safety in port area.

Competition within the horizontal chain has been seen to impede data sharing to remain competitive. For example, while some terminals are open to sharing its data to improve efficiency, others try to monetize on this data.

Lastly, the governance structure has a significant impact in the data sharing capabilities of the stakeholders, A centralised port would find it easier to share data between its stakeholder as everything is governed by one entity. However, a decentralised port requires a system in place to facilitate data sharing.

4.6.3. Joint planning of resources

The most critical feature of a Port Call Optimization (PCO) tool is its ability to plan resources across multiple stakeholders. However, this integrated resource planning is highly dependent on the port's governance structure. Ports with centralized governance find it easier for stakeholders in the nautical service chain to collaborate, while differing motivations and facilitators, as suggested in [82], can complicate joint planning.

When stakeholders fail to communicate their plans effectively, advanced prediction tools must be deployed to forecast vessel arrivals, resource demands, and operational constraints. Leveraging leading technologies in machine learning and AI, such predictions can achieve high accuracy, as demonstrated by OptiPort in reducing port delays and operational costs. However, these solutions are highly data-dependent and may underperform during disruptions. This underscores the importance of collaboration among stakeholders for the successful implementation of PCO. Section 4.5 explores various model alternatives that can facilitate stakeholder collaboration and develop a resource scheduling plan while considering individual preferences.

4.6.4. Port rules and constraints

The harbour control center (HCC) and the vessel traffic service (VTS) are responsible for ensuring the safety of vessels within the port area. This task requires comprehensive knowledge of the weather, tides, and water depth in the vicinity of the port. The HCC and VTS update the service providers' planning based on these factors to guarantee the safe passage of vessels. Ensuring vessel safety is a critical component of PCO, as it minimizes incidents and enhances the port call process. Including these rules in the PCO tool can significantly improve the proposed schedule and reduce the time required to achieve a suitable schedule for all stakeholders.

4.7. Roadmap development steps

The conceptual framework for roadmap development outlined in the previous section offers a theoretical understanding of the factors that influence the implementation of PCO, which must be analyzed before creating the roadmap. The framework also outlines the necessary steps for successfully implementing a PCO tool. However, varying port governance structures and regulatory frameworks impact decisions at different stages of implementation. Thus, careful consideration must be given to different optimization strategies and implementation stages to develop an effective roadmap tailored to a specific port setting. The roadmap development steps is built upon the information detailed in this chapter and can support the development of the roadmap for different port settings. The summarized view of the roadmap development steps is provided in Appendix B.

To generalize roadmap development, the following should be followed:

1. Identify port governance structure:
   Port governance model or organizational model has a strong influence on the performance of the port. This has been discussed in detail in section 3.2.1. Port governance provides insights into the level of centralization of different activities in the nautical chain which can help in proposing the strategic decisions for the implementation of PCO.
2. Identify the role of the Port Authority:
   The PA can have a major impact on the implementation of the PCO. As discussed in section 3.2.2, the PA can take different roles and differ based on its governance structure.
3. Identify collaboration levels between stakeholders:
   Although the governance structure partly sheds light on the level of collaboration between stakeholders, this can vary greatly from port to port. Section 3.2.3 describes the use of the partnership model and how it can be used to assess relationship potential between different stakeholders. The collaboration levels impact the optimization strategy and the timeline of PCO implementation. The industry and operational environment as shown in the the conceptual roadmap in figure 4.8 provides a deeper understanding of the environment which forms the foundation for assessing port stakeholders.
4. Identify the level of digital technology maturity:
   Technology includes the system used for communication and data sharing and the current state of the existing PCO tool and its implementation level. Ports such as Port Arthur have adopted tools such as OptiPort to schedule their towage services [105]. Such available technology can facilitate the implementation of PCO.
5. Identify current port call decision flow process of the port:
   Identifying the decision flow process in assigning the nautical services to vessels for a port is crucial in determining the steps for PCO integration. Assessing the decision flow can provide insights into the areas of improvement.
6. Develop the sequence of stages for implementation:
   The development of the sequence of action for the implementation of the PCO tool is highly dependent of the governance structure, role of PA, collaboration among stakeholders, level of digital technology maturity and current decision flow of the port call process. Therefore, these steps have to be carefully undertaken to determine the stages for PCO implementation ensuring. These stages include integrating stakeholders, selection of optimization strategy as discussed in section 4.5, determining timeline, external influences required to facilitate the implementation of PCO.

Optimization Strategy	Multiple objective	Multiple stakeholder	Stakeholder preferences	Decision hierarchy	Remarks
Single objective optimization	☐	☐	☐	☐	1. Easy to implement 2. Does not consider multiple KPIs of an organization 3. Trade-off between stakeholders are not considered 4. Non-compromise solution
Multi-Objective optimization					
Scalarization	☑	☑	☐	☐	1. Difficult to find weights for all parameters in the objective function 2. Trade-offs between stakeholders depends on weights assigned 3. True compromise not found 4. Preferences of stakeholders not considered
Pareto	☑	☑	☑	☐	1. Provides a compromise solution 2. Preferences of stakeholders are considered through a posteriori evaluation 3. Optimal solution may be ignored for large number of design alternatives
Multi-objective multi-stakeholder (Odesys design methodology)	☑	☑	☑	☐	1. Provides compromise solution 2. Considers preferences of stakeholders 3. a-priori group design/decision making process 4. Full integration between subject desirability and object capability
Simulation based optimization	☑	☑	☑	☑	1. Can easily incorporate stochastic and uncertain nature of ports 2. Provides planning support at a tactical level 3. Can replicate complex real-world systems
Bi-level optimization	☑	☑	☑	☑	1. Combines required optimization strategy with hierarchical relationships.

Figure 4.7: Solution evaluation

5

Roadmap development Case Study: Port of Rotterdam

In this section, the Port of Rotterdam (PoR) is considered for study for the application of the framework, development of the roadmap and validation. The roadmap is designed considering the current state of OptiPort, which is a tugboat scheduling model and needs to be transformed into desired level of functionality to serve PoR. The development steps detailed in section 4.7 is used to design the roadmap for PoR. Finally, the roadmap is validated with the OptiPort team.

5.1. Identifying port governance structure and role of PA

Port of Rotterdam is classified as a Landlord port with its characteristics described below.

Port authority

The PoR port authority belongs to the category of 'Corporatized port authority' as mentioned in Section 3.2.2 with the municipality of Rotterdam and the Dutch state as the two shareholders with 70% and 30% stake in the independent company.

The port authority is committed to promoting sustainability in ports and actively collaborates on the digitalization of the port and logistics chain. Core tasks of the port authority includes managing, operating and developing the Rotterdam port and industrial area, and is responsible for maintaining the safe and smooth handling of shipping.

Harbour master

The harbor master is responsible for enhancing the competitive position of the Port of Rotterdam (PoR) by ensuring vessels are managed as efficiently as possible. The Rotterdam Harbor Master (DHMR) has numerous duties and operates 24/7 to guarantee the safe, efficient, and sustainable management of shipping activities within the port. This role requires close collaboration with pilots, tug services, linesmen, terminals, shipping companies, and other port partners.

At PoR, the harbor master continually strives for improved and more intelligent supervision. The role integrates trends like digitalization and energy transitions aimed at reducing greenhouse gas emissions into its core operations. The main tasks of the harbor master's division include managing the harbor coordination center, overseeing vessel traffic service operators, deploying harbor patrol boats, conducting inspections, and handling port health and security.

Nautical service providers

PoR has outsourced its nautical services to private organizations to relieve its responsibility in these operations and focus more on sustainable development, management and operation of the port, maintenance of the smooth and safe handling of shipping and supporting the future-resilience of the port of Rotterdam [93].

The pilotage services and mooring services are performed by the Rotterdam-Rijnmond Pilots and KRVE respectively. These are private companies working under port rules. The linesmen at the PoR has formed an association which made it easier for mutual coordination and avoid competition. The towage services are performed by three private companies in PoR. These include Fairplay, Baluda Towage and Svitzer. These towage companies compete against each other to perform services for vessels [93]. Towage companies can have contracts with shipping companies which allows them to be the sole service provider for their vessels.

5.2. Collaboration between stakeholders

Nikghadam's study [82] explores the intricate dynamics between the various stakeholders in the Port of Rotterdam's nautical services. The research reveals a significant communication gap, particularly highlighting that terminals are reluctant to share their information with the Harbor Master. This lack of transparency hampers the collaborative planning efforts necessary for the efficient coordination of vessel services. Despite this, terminals maintain communication with boatmen, providing updates on delays and estimated completion times, which are subsequently shared with the pilot organization.

The core reason for this selective information sharing is the competitive nature of the privatized terminals, where disclosing sensitive data could potentially undermine their profitability. This intense competition among terminals fosters a protective stance over their operational information. Additionally, terminals have discovered a revenue-generating opportunity by creating subscription-based platforms that allow customers to track their shipments. This monetization strategy further incentivizes terminals to withhold information from broader, cooperative channels and instead leverage it for direct financial gain.

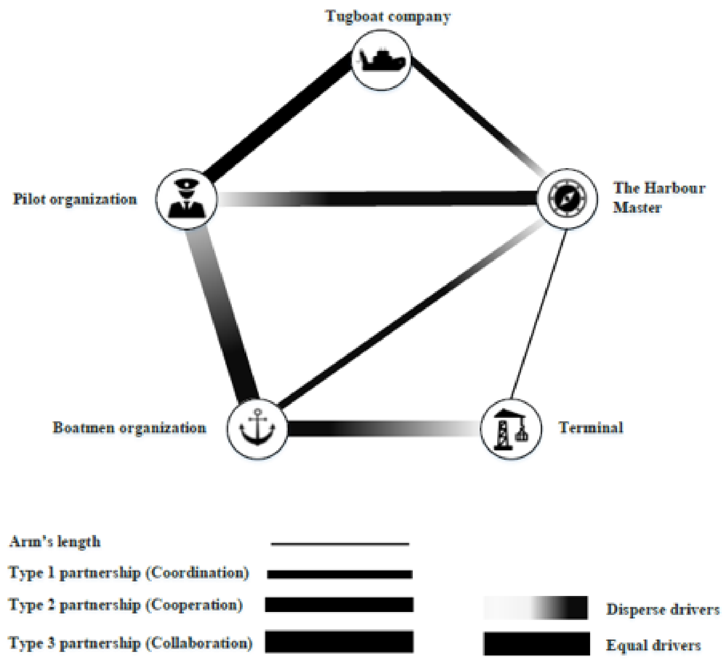

Figure 5.1: Relationship potential in the Port of Rotterdam [82]

The boatmen organization maintains a strong relationship with the pilots, serving as a critical link between terminals and pilots by sharing data related to berthing delays or loading/unloading operations. Tugboats and pilots also exhibit a high level of functional interdependence, which enhances their communication during operations. However, this effective communication is primarily limited to the operational phase after the pilot has boarded the vessel, rather than during the planning stage.

5.3. Digital maturity

PoR has a port community The pilots have a communication platform on which pilots and boatmen schedule their resources together.

1. VHF: Very High Frequency (VHF) radio is employed for communication and coordination among stakeholders in the nautical chain after a vessel arrives at the port. Different sectors of the port area have designated specific VHF frequencies. Vessels use these VHF channels to communicate with two traffic centers in the Port of Rotterdam (PoR) [93]. Additionally, VHF communication is utilized by pilots and other stakeholders to maintain ongoing discussions about vessel intentions and port traffic [82].
2. AIS: The Automatic Identification System (AIS) is a digital system used by VTS and OptiPort for tracking vessels and sharing vessel information. AIS can transmit both static and dynamic data about vessels. Static data includes unique vessel codes and dimensions, while dynamic data comprises automatically updated information such as the vessel's position and speed. Manually updated information, like voyage details, tends to have low dependency in practice. Accurate prediction models are therefore essential to estimate future positions based on the vessel's speed and direction.
3. PCS (PortBase): The Port Community Service system, offered by Portbase, serves as a unified platform for all ports in the Netherlands. Portbase, acting on behalf of the port authorities of Rotterdam and Amsterdam, facilitates digital connectivity within the port community. The objective is to optimize the efficiency, sustainability, and security of goods and data flow through Dutch ports and their associated supply chains [95]. According to the international Port Community System Association, a PCS system is trusted third party, providing neutral and secure exchange of information between public and private stakeholders to improve the competitive position of searport communities [131]. The PCS consists on 3 main parts:
   - A digital infrastructure that facilitates secure and efficient data sharing.
   - Ensures a clear and consistent collaboration method among various parties in the chain.
   - Allows data to be shared with other parties for different applications, ensuring proper permissions are in place.

   An interview with Portbase reveals that they have been proactive in PCO through its platform known as the Portbase Marketplace. This platform allows third-party APIs to be deployed using data stored and authorized by Portbase. It serves customers in freight forwarding and nautical services by providing vital information such as vessel arrival times, berth availability, and estimated loading/unloading schedules. Additionally, it offers various analytics to give a comprehensive overview of port operations, aiding in effective decision-making. However, the technology still lacks from collecting the data from stakeholders to achieve this level of sharing and collaboration. Moreover, private stakeholder data requires authorization before they can be shared which increases the complexity for collaboration.

   This initiative highlights the advanced level of technology currently available for future developments. The well-developed data-sharing platform indicates significant potential for further innovations in port operations and management. However, the quality of data remains a concern as vessel agents and other stakeholders often fail to update their information when changes occur. This inconsistency hinders the reliability and applicability of the stored data, necessitating additional effort to accurately analyze the current situation.

5.4. Current port call process

Arriving vessels communicate their estimated time of arrival at the berth (ETA Berth) to the terminals through their vessel agent. The terminals then plan for the available berths and provide the vessels with a requested time of arrival at the berth (RTA Berth). The vessel either confirms the RTA Berth or proposes a new arrival time. The agreed-upon arrival time at the berth between the terminal and the vessel is known as the planned time of arrival at the berth (PTA Berth). This berthing information is then shared with the Harbour Master (HM), who plans the vessel services to align with the PTA Berth.

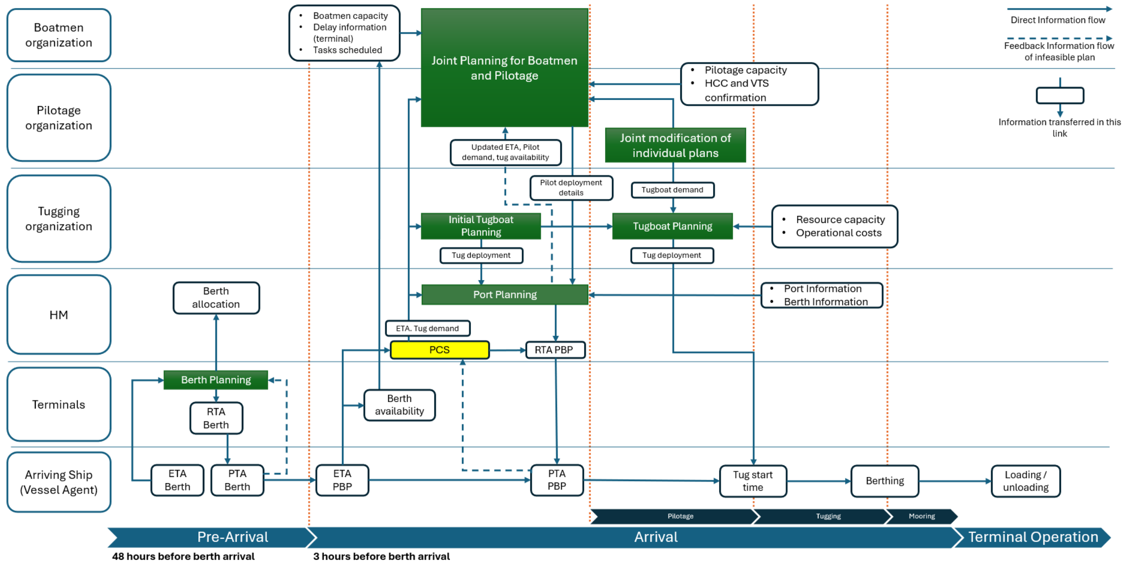

Figure 5.2: current port call information flow of PoR

The planning for vessel services begins 2-3 hours before berthing due to the unreliability of vessels as they approach the port. The process starts with the vessel sharing its estimated time of arrival at the pilot boarding place (ETA PBP). The vessel agent ensures this information is uploaded into the Port Community System (PCS). With this data, the pilot organization and boatmen plan their resources and create a deployment plan to receive the vessel at the pilot boarding place, which is then sent to the Harbour Master (HM). Similarly, the tugboat planning team uses the information from the PCS to plan their resources and develop a deployment plan, which is also shared with the HM. The HM ensures all nautical services are available before the vessel arrives. If not, the HM updates the requested time of arrival at the pilot boarding place (RTA PBP) and provides feedback to the pilot and tug planners for adjustments [6]. Additionally, the HM is responsible for managing safe vessel traffic within the port, which is considered while planning the RTA PBP.

Once the vessel arrives at the PBP, the pilots board the vessel and begin communication with the tugboat organization. The pilots request the number of tugs needed for the vessel's safe passage to the berth. This is a two-way communication process between the tugboat and pilot organizations [82]. The number of tugs requested by the pilots may differ from what the vessel agent initially requested and is entirely at the pilot's discretion. The tugboat planners then reallocate their resources to accommodate the incoming vessels while adhering to the new tug demands provided by the pilots. If there are delays or resource shortages, the tugboat organization directly communicates with the pilot organization to request an updated time [82].

Updates on berth availability and delays at the terminal are communicated to the pilots by the boatmen, Vessel Traffic Service (VTS), or other pilots. If a delay is confirmed, the pilots relay this information to the tugboats. However, if the delay in scheduled berthing exceeds 0.5 hours, the vessel agent is informed, and this update is then entered into the Port Community System (PCS).

5.5. Key insights of PoR

After understanding the governance structure of PoR, the relationship dynamics among key stakeholders in the nautical chain, the technologies currently facilitating the port call process, and the existing port call process, the following insights were derived. These insights are used to create a suitable roadmap for PoR in the following section and serve as a reference for analyzing other ports for the implementation of a full Port Call Optimization (PCO).

1. The Port of Rotterdam (PoR) operates as a landlord port with an entrepreneurial Port Authority (PA) that facilitates companies' transition towards a sustainable future. This is achieved through initiatives like CO_2 capture, renewable energy, hydrogen production and transport, shore-based

power, digitalization, circularity, and utilizing residual heat. Current trends in PoR reflect the PA's supportive role, demonstrating its high power and interest in implementing a full Port Call Optimization and influencing the timeline for its achievement [93].

2. The privatized nature of port services, including terminal operations and nautical services, significantly impacts port operations. Competition among terminal operators drives them to invest in technology to enhance operational efficiency and reduce costs. Lower operational costs result in higher profits and further investments, thereby increasing the port's overall competitiveness [85].
3. Planning of services occur 3 hours prior to the estimated time of arrival at the berth. This is mainly due to the inaccuracy of the ETAs provided by the vessel.
4. Terminals at PoR have poor communication with the HM. They communicate with the vessel agent who updates the information in the PCS which is viewed by the HM and the nautical service providers. Terminal operators are seen as organizations with high power compared to pilot and tugboat organizations. However, their interests in optimizing the port call process is lower than these organizations. Terminals are only concerned with their operations and efficient allocation of berths [105].

   This lack of collaboration between the terminal and the vessel service providers is seen to cause delays in operations and inefficient planning of resources.
5. The pilotage services in the PoR are monopolized by a private organization. This creates a power struggle within the port, particularly during joint planning with other stakeholders in the nautical service chain. It was noted that pilots request tug services only after boarding the vessel, giving tugboat planners a limited time to allocate their resources.
6. The PCS system is not used efficiently

5.6. Roadmap for OptiPort: Case of PoR

Using the framework presented in section 4.6 a roadmap is built for OptiPort for the case of PoR. This begins with understanding the current capabilities of the OptiPort software and providing future development milestones for the implementation of full PCO tool.

5.6.1. Current state of OptiPort

OptiPort is a tugboat scheduling software designed to optimize tug dispatching plans during the inbound, outbound, and shifting phases of the port call process. It is utilized in various ports worldwide to provide cost-effective scheduling for tug operators.

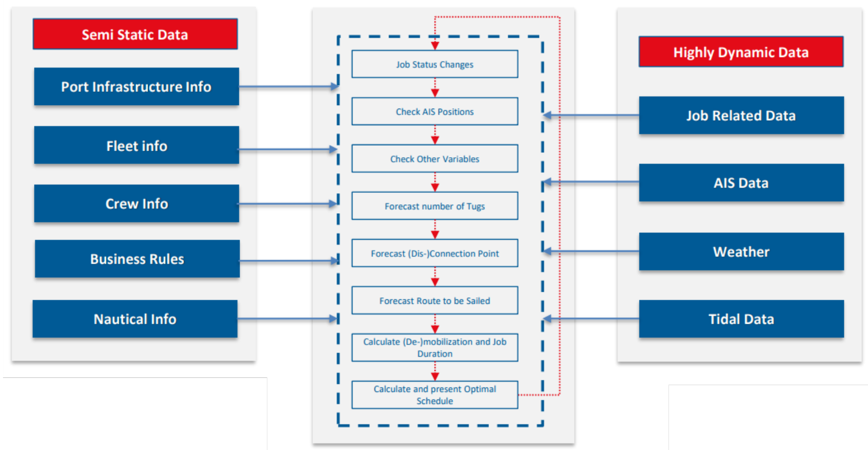

Figure 5.3: Optimization process flow of OptiPort

The optimization flow process within OptiPort, illustrated in figure 5.3, includes semi-static data, highly dynamic data, and the process flows used for calculating the optimal schedule. Static data encompasses port infrastructure details such as channel length, berthing and anchorage locations, and tug stations. This data helps calculate time and fuel costs between locations. Fleet information includes the number of available tugs, their capacities, and the costs associated with dispatching them. Crew information provides details on crew availability, shift timings including working and rest hours, and policies regarding crew assignments. Business rules account for contractual obligations with certain freight forwarders to prioritize their vessels, as well as specific rules on the type of tug required for certain vessels.

Due to limited communication between tug operators and other stakeholders regarding arrival times, service start/end times, resource requirements, and other uncertainties in the port, OptiPort utilizes a range of dynamic data to predict the number of tugs needed for a job, service start/end times and locations, costs, and operation feasibility. These predictions are made using AIS data, weather data, and tidal data. AIS data assists in predicting the arrival times of incoming vessels and tracking current tug operations. As pilots adjust the number of requested tugs based on weather conditions such as wind, OptiPort predicts these changes using weather data. Tidal currents and heights, which can impact tug operations and costs, are also integrated into OptiPort to achieve an optimal schedule given the dynamic nature of nautical service planning in a port.

Model structure of OptiPort
This research aims to contribute to a roadmap for OptiPort and provide a suitable time frame to achieve its transformation into a full PCO tool. This requires understanding the current model structure of OptiPort to factor in the required time needed to implement modifications to the model.

OptiPort Initializes by receiving all the necessary information regarding the port, tug company, and costs associated with fuel, operation, and delay. A network model is created with the possible pick-up/drop-off, anchorage and berth locations which is then used to create a cost matrix from each point in the map to the other. The model then obtains dynamic data such as AIS, weather, tug availability to create predictions on possible pick-up and drop-off locations. These data are used as the input parameter to determine tug assignment, and estimated time for service start/stop times.

5.6.2. Proposed roadmap

The road map shown in Figure 5.4 provides clear development steps, requirements and other influences that impact the implementation of a full PCO specific to the case of Port of Rotterdam. The timeline indicates the year at which the stage is ready for implementation. This depends on the readiness level of the technology, current information flows, level of standardisation, role of PA, policies in place and level of collaboration between stakeholders.

Considering a landlord port governance structure of PoR, where the individual service providers are privatized, the relationship potential between these stakeholders affects the level of collaboration. The privatization of services has been considered to be an important step towards improving the efficiency of the ports as they bring in advanced technologies and efficient operations. Competition within the horizontal chain can support reducing service rates which improves port satisfaction. Therefore, maintaining such competition is necessary and needs to be safeguarded.

Current state

The current state of OptiPort as discussed in the previous section is a tugboat scheduling software that uses prediction models to anticipate the job information from the pilots. This helps with efficient tug resource planning and allows for minimum deviation from the original plan. This makes it highly dependent on past data of pilot operations and fails to incorporate the experience level of pilots and other uncertainties in predicting (dis)-connection locations and the number of tugs required.

The optimization model uses a scalarized multi-objective function which converts different decision variables into costs and assigns weights based on the requirement of the client, which is the tugboat company in this case. This objective function reflects the objectives of the tugboat company which is mainly to reduce operation costs, fuel costs and delays. However, there is no collaboration between stakeholders and optimization of the port call process does not extend to other stakeholders.

In this stage, pilots, tugs and boatmen plan their resources separately and try to align with the berth planning. The HCC along with the VTS performs the port planning with the given berth timings, availability of the nautical services and port safety to determine the ETA. However, actual service start times

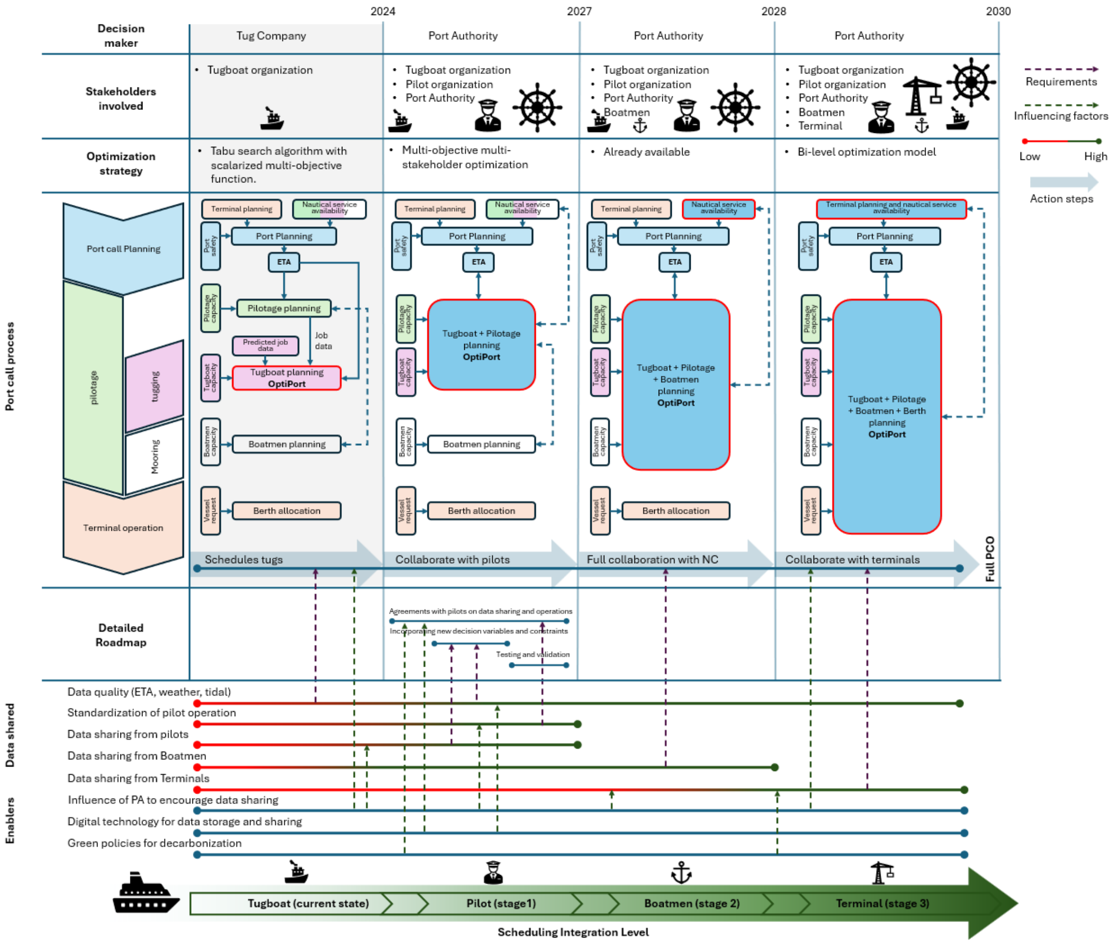

Figure 5.4: OptiPort roadmap towards full PCO in the Port of Rotterdam

are dependent on the actual time of pilot boarding, the request of tugboat service made by the pilot and the availability of berth and linesmen. As no communication is made between the stakeholders regarding their resource availability and service start times, delays are often inherent in this stage. The effective sharing of standardized data between different stakeholders can improve this.

Stage 1 - Collaborate with Pilots

The development of OptiPort to facilitate joint planning between pilots and tugboats is a significant advancement towards PCO. Tugboats are frequently seen as the bottleneck in the port call process because they struggle to plan resources in advance. This integration is crucial in addressing that issue.

Reaching a consensus on the decision-making process is crucial to enhance consistency and effectiveness. This involves setting clear agreements on the roles of parties involved, decision-making procedures, and conflict management [31]. To ensure impartiality, an independent third party should oversee the process as a manager. In this context, the PA is well-suited for this role, given its objective to improve port efficiency without vested interests in the service providers. Additionally, the decision support tool for PCO discussed in this research helps maintain stakeholder agreements by incorporating their objectives and preferences. While tugboat scheduling decisions are independently managed by the tugboat company, collaborative resource allocation with other stakeholders necessitates a decision tool overseen by a public entity to ensure neutrality. Thus, the PA should manage this tool to build and maintain trust among all stakeholders involved.

The relationship between pilots and the tugboat company is crucial to ensure support between the actors. As discussed in the previous section, Pilots and tugs hold a functional and strong relationship with each other which holds an interdependency between each other [31]. Stakeholder involvement

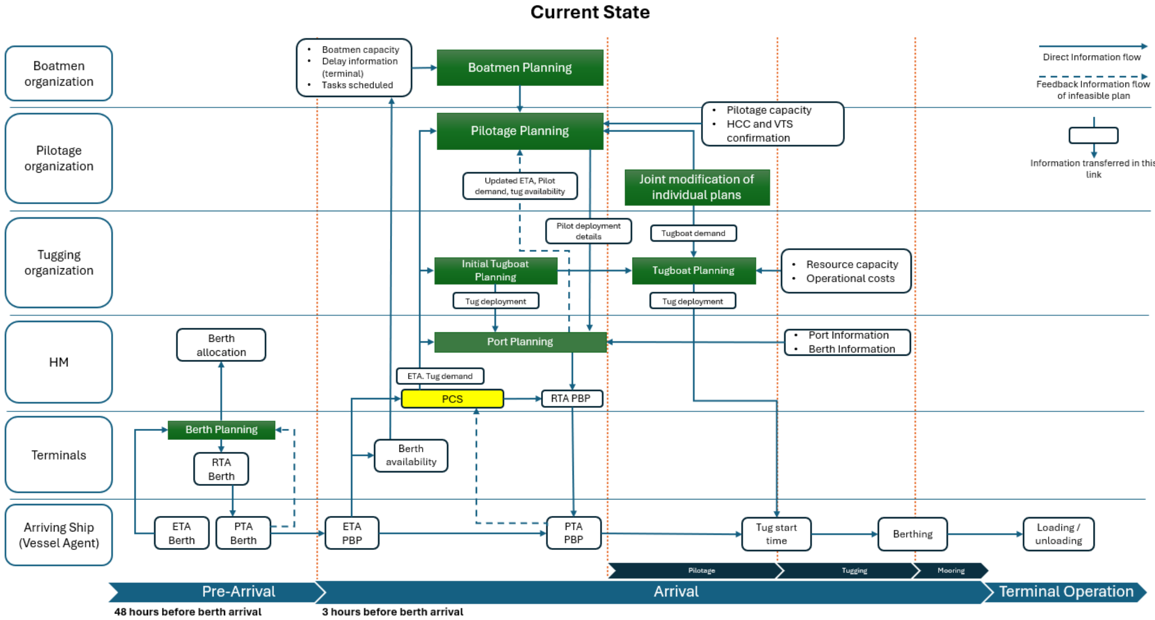

Figure 5.5: Port call information flow of PoR - Current state

depends on their willingness to collaborate and share data. In the PoR, pilots and tugboats communicate well, but this two-way communication typically starts only after the pilot boards the vessel. The PA can enhance collaboration between these stakeholders. PoR has policies that empower the PA to manage the deployment of pilots and tugboats, especially during peak traffic times and times of emergencies, reflecting its commitment to joint resource allocation to improve vessel throughput. Recent policies regarding the Pilot Exemption Certificate (PEC) highlight the port's initiative to lessen reliance on pilots [93]. Standardizing pilot operations with a focus on vessel safety can significantly reduce reliance on predicted tugboat demand. While these practices positively impact the port call process, the pilotage organization in PoR and many other ports has leverage in the Nautical Chain (NC) that can disadvantage tugboat companies. Hence, the PA's influence is crucial.

Another essential criterion for facilitating data sharing is the availability of a common digital platform. The PoR utilizes a robust PCS system by Portbase, which provides the necessary digital infrastructure for this purpose. The maturity of this technology as discussed in the previous section greatly accelerates the timeline for achieving such integration.

To effectively implement a joint planning solution, the optimization model used by OptiPort requires an update. Currently, it employs a scalarized multi-objective function that necessitates setting weights for each parameter. However, to integrate pilots and consider their preferences, it is crucial to incorporate stakeholder preferences into the scalarized function. This ensures the decision is minimally resisted by all stakeholders. A study by [105] examines the preferences of various stakeholders in relation to their own objectives and those of others. The study of stakeholder preferences, along with the use of Tetra software, provides a foundation for identifying the appropriate weights to be included in the expanded linear objective function, aiming to achieve a compromise solution.

Figure 5.6 illustrates the updated information flow process in the Port of Rotterdam (PoR) after including pilots in the decision-making process. This integration demonstrates that achieving consensus between pilots and tugboats can streamline the exchange of planning information, leading to optimized planning with the flexibility to update during emergencies.

Stage 2 - Incorporate Boatmen planning

The integration with the boatmen can be achieved swiftly due to the existing effective communication and coordination with pilots, as well as the technology from previous stages. Figure 5.1 demonstrates the strong potential for a cooperative relationship between pilots and boatmen in the Port of Rotterdam. This high functional dependency greatly facilitates joint resource planning.

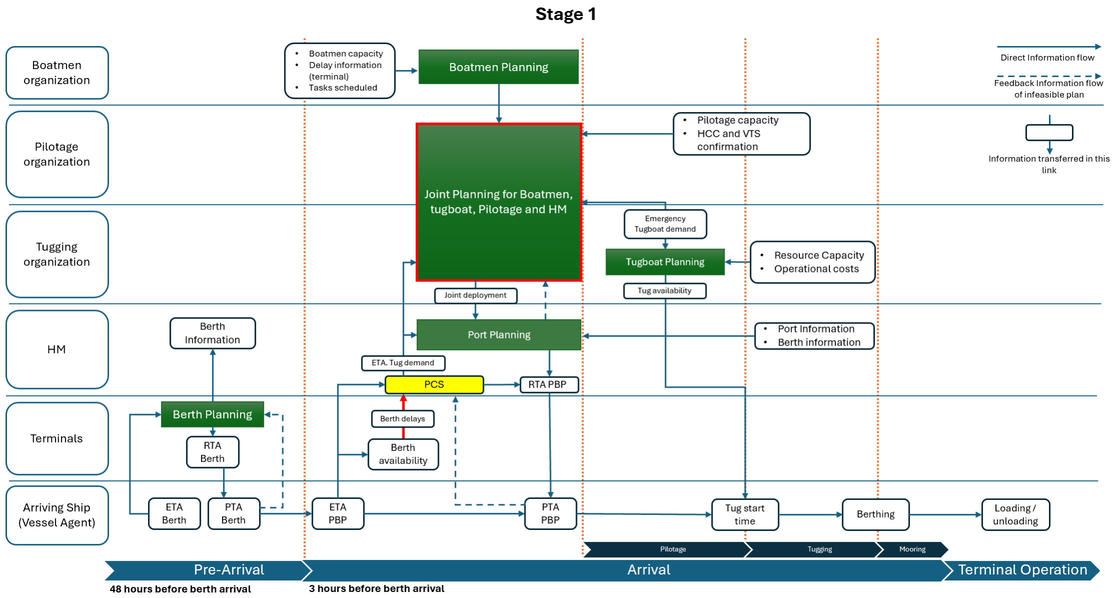

Figure 5.6: Port call information flow of PoR - Stage 1

Incorporating the boatmen into the joint planning process unifies the entire nautical chain. The model requirements for this stage are already satisfied from previous stages, simplifying implementation. Additionally, the boatmen organization shares a common planning platform with the pilots, further supporting the integration process.

Figure 5.7 illustrates how joint planning by nautical services shares their deployment plans with the Harbour Master (HM) for port planning. This ensures coordinated resource deployment, reducing vessel delays in the port.

Stage 3 - Incorporate Berth planning

The final stage involves integrating the berth planning with the joint planning of the nautical services. As terminals are considered with much higher in power within Medelow's stakeholder power grid [21], collaboration with terminals is envisioned to happen in a longer time frame. Some terminals in PoR monetize on their operational insights, preventing them from collaborating with other stakeholders and restricting transparency with the nautical services. However, developments within the PoR have led to the integration of the terminal planning with the port planning. This proves the port's ambition to monitor berth availability to advance towards PCO. However, this initiative does not consider berth re-allocation and tries to align the nautical services to arrive at the allocated berth in time. This increases the stress within the nautical service resources.

This research proposes a PCO vision in which the berth planning is done considering the availability of the nautical services which allows terminals to re-allocate their berth location based on the availability of the nautical services which would reduce delays in ports and improve throughput. This requires an influence of the Dutch PA to recognize the benefits of joint scheduling to bring the terminals to coordinate with the vessel service providers. The technology required for such a leap is already available or developed from previous stages.

Lastly, it is evident that the decision-making process involving berth allocation and nautical service scheduling follows a hierarchical structure, necessitating a bi-optimization model. This is due to the fact that the results from the berth allocation problem serve as the input for nautical service planning, as NC planning cannot proceed without knowledge of the destination berth. This necessitates incorporating the berth allocation problem as the upper level in a bi-level optimization framework, where the allocated berth is then communicated to the lower level. The primary objective at the upper level is to minimize overall delays, while considering constraints from the lower level. To enhance efficiency and reduce computation time, appropriate heuristics should be applied.

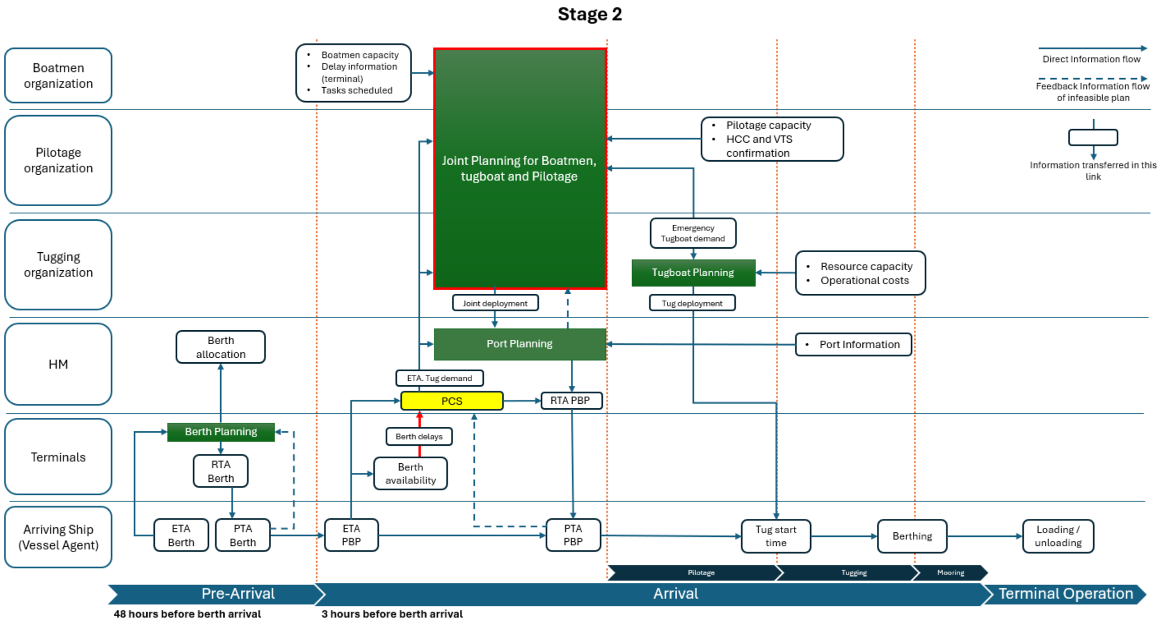

Figure 5.7: Port call information flow of PoR - Stage 2

5.6.3. Validation of roadmap

The validation of the roadmap has been conducted with the OptiPort team and through interviews with both the Port of Rotterdam (PoR) and Portbase. Communication with PoR was carried out via an interview and a series of email exchanges. These interactions essentially confirmed the current port call information flow for decision-making, as depicted in Figure 5.5 for PoR. Additionally, the information flow was updated based on inputs provided by the OptiPort team.

Regarding the technologies required for data sharing, the Port Authority (PA) has confirmed the availability of the necessary technology. This was also revealed through an interview with Portbase where various APIs are being made to provide information to various stakeholders by analysing the data shared through Portbase. However, the challenge lies in getting stakeholders to cooperate. The PA is actively educating customers and advising stakeholders on the impact of port call optimization. This is being done through conferences involving various customers to promote Port Call Optimization (PCO). Furthermore, the PA has agreements with certain customers for standardized documents, which are aimed at improving the turnaround time of vessels.

The PA of PoR is focusing on integrating berth planning with overall port planning to ensure that the right information is shared with all stakeholders, thereby enhancing Just-In-Time (JIT) arrival of vessels at the berths. This integration is seen as a major bottleneck in the port call process at PoR and is currently a primary focus. The integration of the nautical services into the port planning is also something that the PA has planned in the future. Hence 3 years from 2024 seems to be reasonable time-frame to implement a decision support tool for joint planning with the pilot organization and get the stakeholders agree to the new terms.

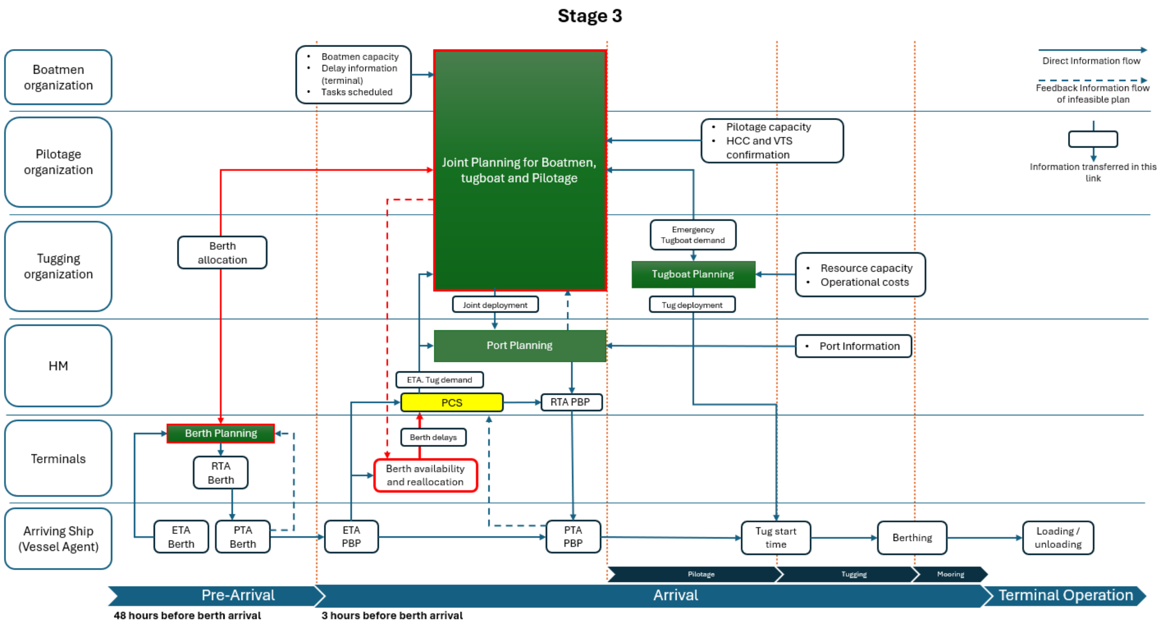

Figure 5.8: Port call information flow of PoR - Stage 3

6 Impact of governance structures on PCO roadmap

Ports adapt to changing environments by crafting strategies that respond to external conditions, leveraging their unique resources and capabilities, and establishing an appropriate organizational structure to implement these strategies [9]. This can be understood clearly using the matching framework as shown in Figure 3.2. The roadmap developed for the Port of Rotterdam in Section 5 uses the conceptual roadmap framework shown in Figure 4.8 to determine the factors affecting the implementation of PCO.

Despite the significant differences among ports, the same conceptual roadmap framework can be applied to identify the factors influencing PCO implementation, allowing for necessary adjustments in technology and policy to support PCO adoption.

As outlined in Section 3.2.1, ports are categorized by their degree of centralization/decentralization and the extent of governmental influence on port infrastructure and operations. The literature identifies four types of ports: public or service, tool, landlord, and private ports. Figure 3.1 illustrates the level of public involvement in ownership and operations. However, it does not provide specific details about the port's remote, industry, and operating environments, as shown in Table 4.2, nor the influence of the Port Authority (PA) or the decision making flow of the nautical chain for port calls. These details are crucial for assessing a port's readiness for PCO tool implementation. For instance, a fully centralized public port might lack a digital platform and have a PA not focused on development, whereas a decentralized private port could have an efficient port community system with data sharing and an entrepreneurial PA engaged in various initiatives to enhance stakeholder collaboration.

Essential port functions include port landowner, port utility, and port regulatory functions. These are the main functions that change during port reforms from public to private ports [115]. This section examines the inherent factors linked to various port governance structures. In this research, tool ports are considered similar to public ports due to their only difference being in their privatized cargo handling. To distinctly differentiate between port governance structures, the study focuses on public, landlord, and private ports to understand how each type affects PCO tool implementation.

6.1. Public port models

Public ports are usually controlled and operated by the ministry of transport [94]. This includes owning port infrastructure and being responsible for its developments and handling port operations. The organization has complete control over all its operations including the nautical services such as pilotage, towage and mooring. The operational standards are set at the organizational level which determine port policies and objectives. The port authority of such ports is seen to have the complete control over the port operations which makes communications among different stakeholders within the nautical services highly efficient.

In such a governance model, marine services are controlled by a public entities making it difficult for private companies to enter the market because of high investment, low market, and union. This makes the prices for marine services low, provides high flexibility of services but low operational efficiency [78]. In this case, although collaboration among stakeholders may be high as they controlled by a single entity and do not compete with each other, the efficiency may be low due to limited resources and under performing technologies and experiences that can be obtained through privatizations.

A publicly owned and operated port often faces delays in decision-making due to inherent bureaucracy and political agendas, which can hinder the port's ability to adapt its strategy to implement PCO effectively. This primarily falls on the role of the PA that governs the port. As discussed in Section 3.2.2, PA can take roles of conservators, facilitators or entrepreneurs which determines the involvement of the PA in not only infrastructure and operations, but also in bridging societal and economic interests and facilitating commercial investments.

Public ports can receive funds from the government for investments in infrastructure and equipment. This is seen as a initiative to improve the economic state of the region. However, The release of these funds can be hindered due to political interference which can have different agendas to promote their personal objective. This hampers the response rate of serving the needs of the customers and other stakeholders of the port [44].

Once these criteria are met, the tool can be implemented with relative ease that integrates all the stakeholders involved. Within this port governance structure, stakeholders can be integrated in a single stage as opposed to step by step integration. Optimization strategy options include single objective optimization and multi-objective optimization with scalarization. These optimization strategies can be used since stakeholder preferences are not considered and a single entity controls the activities within the nautical chain.

6.2. Landlord port models

he case study conducted for the Port of Rotterdam (PoR) offers valuable insights into implementing a PCO tool in a landlord port. However, the process is influenced by numerous factors that cannot be generalized based solely on port governance structure. In landlord ports, terminal handling operations and nautical services are managed by private organizations through concessions, leading stakeholders to pursue their own interests and objectives. These concessions are often performance-based, creating incentives for agents to align with the principal's goals [84], which can improve efficiency through more autonomous management and increased investment opportunities [65][115]. Nonetheless, opening services to private actors introduces multiple private companies competing for the same service, which, while potentially beneficial in providing efficient services, lower rates, and high customer satisfaction, can also hinder communication and collaboration among actors across the horizontal and vertical chains.

Reduced governmental influence in a landlord port simplifies the investment process by minimizing bureaucratic delays that could otherwise slow decision-making. Privatized nautical services allow private companies to manage operations, leading to enhanced efficiency and improved customer satisfaction. However, the success of this privatization is heavily dependent on factors such as the number of participants, the size of organizations, the level of competition, and the potential for new market entrants. These elements influence companies' incentives to optimize operations and collaborate with stakeholders.

Compared to public ports, where the port authority manages operations, landlord ports rely on private entities for nautical services and cargo handling. This situation leads stakeholders to prioritize individual objectives, making it essential to consider these preferences alongside stakeholder collaboration levels to determine optimization strategies and integration steps with a timeline. Optimization strategies can be multi-objective using Pareto or multi-objective multi-stakeholder approaches for non-hierarchical decision processes. Alternatively, simulation-based optimization or a bi-level strategy may be necessary when there is a clear decision-making hierarchy. The choice of stakeholder for integration depends on the ease of integration based on collaborative levels and the impact on the port call decision-making flow.

Moreover, the governance role of the PA, which is influenced by government oversight, can affect the implementation of the PCO. Additionally, the digital technology maturity level at the port can significantly influence the effectiveness of implementing the PCO tool.

6.3. Private port models

Private port models differ from public and landlord models in terms of land ownership and port operations. In private port models, private entities own and operate the ports. These private entities are distinct from one another. However, if a single private entity has complete control over the port, it would be classified as a public port model.

In a private port model, the PA, terminals and nautical services are provided by private companies. This makes the port highly decentralised and requires a high level of communication between stakeholders to complete a port call process. By using the conceptual roadmap framework for Port Arthur, which is a private port, we can determine key elements that would affect the implementation of PCO in such port structures.

Studying the remote environment, private ports do not have any influence from the government. This provides greater financial flexibility to improve operational efficiency and technology and allow more response to market demands. However, social and environmental concerns may not be prioritized [44]. Therefore, trends such as the reduction of greenhouse emissions may have a lesser impact on developments in these ports.

Understanding the industry environment is essential for assessing the power and interests of different stakeholders in a private port model. For example, a single pilot organization manages the entire Sabine water channel, serving Port Arthur and Beaumont. This centralization grants the organization significant power, including the role of harbor master. Despite being privatized, this pilot organization prioritizes port safety over serving specific customers.

However, the plans set by the pilots must be aligned with the needs of other stakeholders in the navigational channel (NC). This monopoly within a private port facilitates coordination but often overlooks the resource capacities of tugs and linesmen. Consequently, political obstacles are minimized, making it easier to implement an optimization model that uses standardized data sharing with vessel agents.

By centralizing pilot operations, the system benefits from streamlined decision-making and enhanced safety protocols. Yet, the lack of consideration for tug and linesmen resources can lead to inefficiencies. Optimizing this model with shared data could further improve port operations, balancing safety with operational efficiency.

7 Discussion and Limitations

This research highlights that while port governance structure provides valuable insights into the level of collaboration between stakeholders and the controlling entity of port services, there are additional factors that must be considered when developing a roadmap for implementing a Port Collaborative Optimization (PCO) tool. The study demonstrates that Port Collaborative Decision Making (PortCDM) is a fundamental component of PCO, as standardized data and data sharing are crucial for collaborative decision-making. Consequently, the requirements for a PCO tool can be traced back to those of PortCDM and those identified through literature review, brainstorming sessions, interviews, and abstraction.

7.1. Developing roadmap for PCO development

The aim is to advance PCO from merely facilitating collaborative decision-making to enabling joint planning of resources within the port call process. The developed roadmap must be capable of producing a solution that meets the defined key constraints. These constraints can then be translated into actionable steps for implementing a PCO tool in any port environment. However, since port environments vary significantly, each must be studied in detail to propose appropriate technological advancements, policies, and data-sharing standards that foster collaboration among stakeholders and agreements on joint resource planning.

Notably, various aspects of the environment can impact the timeline for PCO implementation in any port. The external environment is analyzed by breaking it down into its components to examine any given port. In the remote environment, political influences can shift the port's strategy to align with the governing party's agendas, potentially diverting focus from port-specific developments. Additionally, the availability of sufficiently mature digital technology can positively affect the adoption of data-sharing standards, providing a common platform for communication and planning, thus facilitating PCO implementation. Ports in economically advantageous locations, experiencing a surge in trade, tend to advance more rapidly in terms of technology and strategy toward PCO to meet increasing demand.

7.2. Factors affecting PCO implementation

Moving on a level deeper into the industry environment which consists of the number of participants, size of the organization, the extent of collaboration and policy regulations can impact the optimization model used to find a suitable compromise solution between the stakeholders as this can impact the preference levels of each stakeholder against their objectives and that of the others. These factors also impact the level of competition among stakeholders which accelerates port development. However, it affects communication and coordination among different participants and reduces trust. As size of the organization increases, the level of power and influence in port operations also increases. However, this is dependent on the operating environment of that organization as well.

To further develop a roadmap, it is necessary to understand the decision-making flow process in a port. The business process detailed by the ITPCO [52] is based on contracts and IMO resolutions. In this business process flow, the port planning process is done based on nautical service planning. However, no information is provided on how the nautical service is performed. This is crucial for understanding current systems, procedures and cultures currently in place for nautical service planning such that an appropriate sequence of improvements can be made to establish a joint planning environment for all stakeholders in the nautical chain.

This research stands to benefit the development process of the PCO tool for a specific port setting and help ports with target areas of improvement to facilitate the implementation of PCO. This study shall help policymakers to make appropriate changes in the strategy to set favorable conditions to facilitate collaboration.

Limitations

While this research proposes a framework that is instrumental in assessing ports for the implementation of a PCO tool, several limitations should be acknowledged.

The formulation of the requirements was solely based on interviews with the OptiPort team, a literature review that studied pre-requisites of collaborative decision-making, brainstorming and abstraction. However, widening the scope of interviews with other stakeholders who are also involved in the decision-making process would prove a conclusive set of requirements.

The roadmap designed was based on qualitative reasoning of the external environment, strategy and structure of the port. A quantitative approach that measures the readiness of each factor can provide a precise estimation time and resources required to achieve set milestones.

Lastly, The Design Science Research (DSR) approach requires an iterative process where each step in the co-design process is performed again based on the feedback received on the designed artifact. The iterative process ensures design quality and fit for a specific port [49].

8 Conclusion

Port Call Optimization (PCO) aims to make the port call process as efficient as possible for all stakeholders in the sea transport chain. Efforts towards PCO at the industry level primarily focus on standardizing shared data and creating platforms for data sharing to enhance coordination among stakeholders. Research in this area often emphasizes improving the shipping network, terminal operations, and governance.

However, both practical operations and existing literature indicate that optimizing the operations of stakeholders within the Nautical Chain (NC) has not yet been given significant attention as a critical area for PCO. This study highlights that port governance structures play a crucial role in influencing port performance and are a key factor in the successful implementation of PCO. Additionally, this study also aims to highlight steps and recommendations for developing PCO solutions that incorporate the NC.

Therefore, the following research question was proposed:

How can partial Port Call Optimization (PCO) models be transformed into desired levels of functionality to address full PCO questions, within the context of a certain port governance structure?

To aid in addressing the main research question, several sub-research questions were developed. A detailed summary of the findings from these supporting questions is provided below:

- What are the requirements for effective implementation and deployment of the PCO solution?

The requirements defined were classified into constraints that the solution must satisfy and objectives that the solution should adhere to as closely as possible to provide an acceptable solution. Interestingly, PortCDM, which is a concept of sharing standardized data through a common platform forms the base of PCO. Therefore, the TOEI framework developed in [21] was used along with interviews with the OptiPort team, brainstorming sessions and abstraction. These requirements can be used to evaluate the final PCO tool such that its implementation proves to be well within the satisfaction levels of its stakeholders. The constraints defined form the prerequisites for which the PCO tool needs to be designed.

- What are the various model alternatives that can be used to serve PCO requirements?

A systematic literature review revealed a diverse array of optimization models tailored to individual and multiple stakeholders. These models exhibited significant variation in complexity, optimization strategies and objectives. These models are highly dependent on the specific port under study and the need for realistic modelling. Examining the different optimization strategies was insightful, as the solutions provided are influenced by these factors and the port's governance structure. Evaluating the alternatives showed that stakeholder preferences are crucial in multi-stakeholder optimization scenarios. Consequently, a suitable optimization strategy that accounts for these preferences was selected.

It was also observed that some ports exhibited a hierarchical distribution of power that influenced port operations. This power structure indicated that stakeholders collaborated at arm's length, necessitating an optimization model tailored to this level of collaboration.

- How can model alternatives be evaluated to ensure that they perform effectively as a PCO solution for a given port?

Ports vary greatly in terms of organizational structure, objectives, stakeholder relations and port environment. Model alternatives are evaluated based on their ability to tackle multiple objectives, capability to involve multiple stakeholders and their preferences towards each other's objectives.

- What is the logical development roadmap for PCO tools from limited to high complexity, in different port governance contexts?

The development of the roadmap begins with evaluating the factors that influence the implementation of PCO in a port. The literature demonstrates that the matching framework can be used to understand how ports evolve in strategy and structure to adapt to changing environments and enhance performance. Since this study focuses on the static state of ports, it uses components of the matching framework for assessment. The study also found that implementing a PCO solution requires significant support from the port authority and collaboration among stakeholders. Additionally, it was observed that the dynamics of collaboration change with the varying size and power of different organizations within the port. The technological maturity of available data-sharing platforms can accelerate collaboration through secure lines of communication and data storage. Finally, the proposed roadmap needs to be validated with the views of the port to match priorities and emphasise the need for joint resource planning in bringing down the delays in the port call process.

The step-by-step roadmap development process detailed in section 4.7 provides a generalized format for assessing port for the implementation of a PCO tool.

Recommendations for future research

Future research may focus on exploring stakeholder satisfaction with the implementation of PCO. This is essential for refining the design process within the DSR methodology, which can lead to improvements in the design of the PCO tool. Moreover, widening the research scope to understand the requirements from the client's perspective can further improve the PCO tool.

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A

Critical Information

For evaluating different solutions, a literature review was done to obtain benchmarks on best practices for collaborative port call optimization and compared against available alternatives.

Important information to be shared

1. **Sharing vessel information**
   - Vessel agents need to update ETA, ETD, vessel information, and required nautical services.
2. **Sharing joint planning information**
   - Request for delay by pilot planning to HCC
   - Request for delay by tugboat planning to HCC
   - Request for delay by tugboat planning to pilot planning
3. **Sharing deployment information**
   - Estimated completion time of pilots
   - Deployment information of tugboat
   - Estimated completion time of tugboats, update on delayed arrival
   - Update on estimated completion time of pilots
4. **Sharing assignment information**
   - Updated ETA by VTS to pilots
   - Updated ETA and number of tugboats by pilots to tugboat planning
   - Update on ongoing assignment from pilot to tugboat captain
   - Updates on ongoing assignments by pilots to VTS
   - Updated ETA and ETD by VTS to pilot
5. **Peer-to-peer information sharing between the pilots**
   - update on sailing information between pilots
6. **Sharing information of shared resources**
   - Update on completion time of terminal operation by boatmen to pilot

B

Roadmap development steps

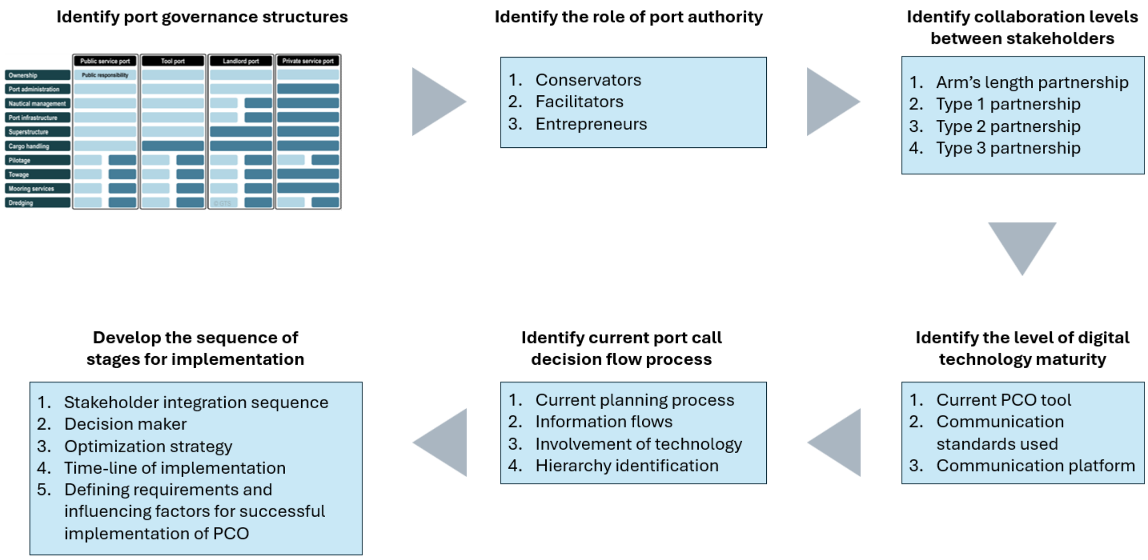

Figure B.1: Roadmap development steps

C

Scientific Paper

A framework for PCO models in different port governance structures

A roadmap for PCO tool implementation

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ABSTRACT

Seaports are critical to the global supply chain, and as maritime trade grows with globalization, inefficiencies in port call processes and ship waiting times are increasing. This research develops a framework for Port Call Optimization (PCO) models to support collaboration and decision-making between stakeholders within the Nautical Chain (NC) and terminals. The Design Science Research (DSR) approach provides a systematic way to design a PCO tool for a port that is backed by a strong knowledge base. Integrating this approach with the co-design process involving user input ensures that the tool aligns with client needs and trends. This study uncovers a framework to assess the prerequisites for PCO tool implementation and develops steps to build a roadmap for PCO tools that incorporate the intricacies of different port governance structures. The findings from this research lays the groundwork for future research regarding the implementation of a PCO tool by bridging the gap between the fragmented research in this domain.

Keywords: Port Call Optimization, Roadmap, Design Science Research, Port governance, Scheduling, Nautical services

1. INTRODUCTION

Seaports serve as vital nodes in the global supply chain, facilitating the movement of approximately 80% of global trade [12]. Projections suggest that maritime trade is expected to grow by 2.4% in 2023 and by over 2% annually from 2024 to 2028 [25]. Therefore, optimizing port performance is essential for maintaining competitiveness. As maritime trade continues to grow, this directly impacts the capacity of port services [25]. The resulting longer wait times for vessels lead to higher fuel consumption, increased $CO2$ emissions, and a greater risk of collisions [18], highlighting the need for improvements in port operations [25].

Port call optimization (PCO) refers to the systematic process aimed at maximizing the efficiency of port call processes in accordance with the requirements of stakeholders within the maritime transport value chain, thereby contributing to the optimization of the broader transportation system [15].

Vessels entering or departing seaports rely on pilotage services for safe navigation through designated waterways, ensuring safety, smooth operations, and environmental protection. Towage services, often provided by private firms, are crucial for navigating narrow passages. Mooring services secure vessels for cargo operations, requiring specialized skills, especially in complex maritime environments. This forms the nautical chain which is often overlooked in PCO discussions.

Port operations face several uncertainties, including delays in vessel readiness, fluctuations in arrival and departure times, varying service durations, and specific requirements [18]. One possible solution to address these challenges is to increase resource capacity, but this option is limited by the substantial capital investment needed. Tugboats require significant upfront investment and ongoing maintenance, while pilots, who are generally highly experienced, demand high salaries [1]. As a result, improving the existing performance of the port is considered a more practical approach.

The effectiveness of a PCO tool extends beyond efficient service scheduling; it must also comprehend the underlying objectives and dynamics of stakeholder interactions. This entails mirroring real-life relationships and preferences among stakeholders across various objectives. Moreover, the PCO tool must account for the evolving relationships dictated by specific governance structures within ports, adapting to the changing dynamics as ports evolve to meet societal and economic needs.

In essence, this study aims to facilitate the evolution of partial Port Call Optimization (PCO) tools towards achieving an optimal functionality level that is tailored to specific port contexts. This will be achieved through the development of a comprehensive roadmap outlining the requirements of multiple stakeholders and the dynamics of their relationships. Such a roadmap will serve as a valuable analytical tool, enabling the assessment of existing PCO models and the identification of necessary considerations for implementation within a particular port setting.

3. METHODOLOGY

The process of developing a roadmap for PCO tool involves understanding various port settings, stakeholder relationships, interactions, and operational dynamics. Multiple models must be analysed to build a comprehensive knowledge base applicable to different port environments. Based on this understanding, a design artifact will be created to outline the requirements and considerations needed to accommodate the unique characteristics of various governance structures within port settings. This design will then be evaluated to determine its feasibility. Given the project's scope and the iterative nature of the design process, a Design Science Research (DSR) approach is employed. The design process will be guided by a design cycle that is guided by the relevance cycle and the rigor cycle [10] as illustrated in Figure B.1.

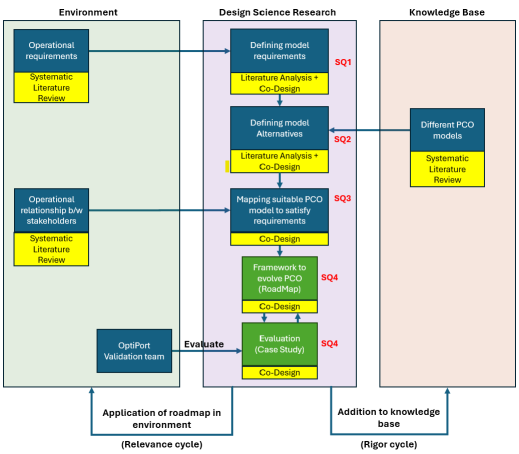

Figure B.1: Methodology

By adopting Design Science Research as the overarching methodology, the approach to execute it can be done in two phases, the discovery phase and the design phase.

3.1 Discovery Phase

The systematic literature review serves to define both the environment and the knowledge base essential for the subsequent design phase. Within the environment, details regarding diverse organizational structures, their requirements, objectives, and their correlations with port size and location are elucidated. To encompass the broad scope of understanding various components of port call optimization, the literature review was categorized into five main parts based on their relevance to PCO. These categories are Port call optimization, governance, tugboat scheduling, pilotage scheduling, and berth allocation. Papers were sourced from the Scopus database spanning from April 3rd to April 24th, 2024. Illustrated in Figure B.2, a PRISMA flow diagram delineates the keywords, decision criteria, and the number of reports selected for inclusion in this study.

3.2 Design Phase

During the design phase, the insights gained from the discovery phase are scrutinized and leveraged to craft a framework that functions as a roadmap to systematically evaluate existing PCO tools, which may have limited functionality, and propose considerations for enhancing them into effective PCO tools adaptable to various governance structures.

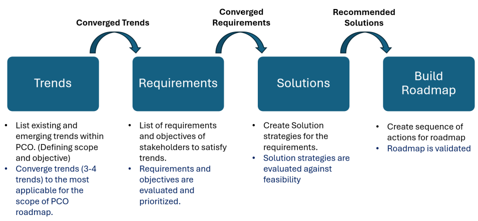

Figure B.3: Design Steps

The co-design approach as shown in figure B.3 in roadmapping involves actively engaging with consumers and users in the design process to ensure the roadmap aligns with client needs, objectives, and future trends. This method is generally effective in creating a good fit between technology and its users.

Literature review and client discussion help identify trends that define the requirements for a comprehensive Port Call Optimization (PCO) system. These requirements serve as criteria to align with trends and ensure PCO functionality. The same panel evaluates and prioritizes these requirements. Next, solution strategies are de-

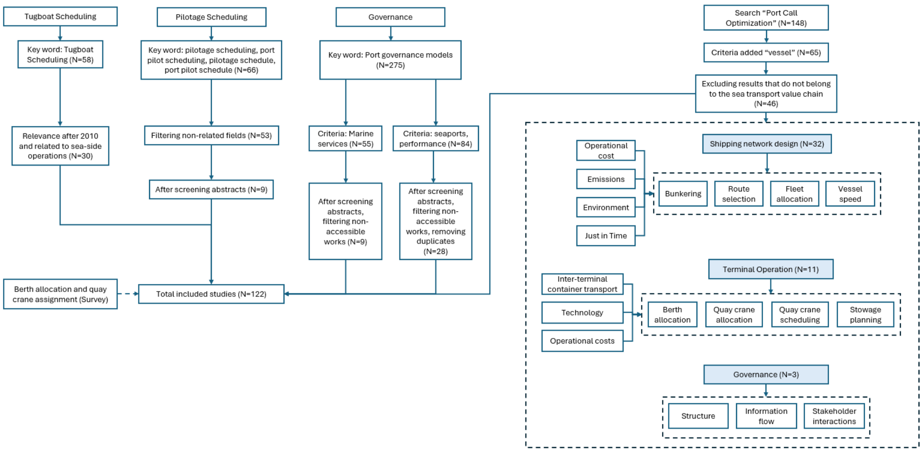

Figure B.2: Flow diagram for systematic review

signed based on these requirements which are assessed by a panel for feasibility and effectiveness before including them in the roadmap. Finally, an action plan is developed for the selected strategies, ensuring they meet the requirements and align with trends across different governance structures.

3. LITERATURE REVIEW

Port call optimization aims at maximizing the port call process through various optimization within the arrival, port visit and departure processes. Thus improving turnaround times of vessels and resource allocation. The literature found on PCO provides insights into the critical areas that has been considered for optimization. Due to high cost of fuel, its impact to overall shipping operation and its impact towards the environment, major research has been done to improve the shipping network which affects the arrival of the port call process. Slow-steaming and optimizing schedule design were identified to be prominent areas of optimization. However, These optimization methods are from the perspective of the shipping companies. Regarding port operations, the review recognizes that most inefficiencies are caused due to berthing and handling process delays. The review also emphasizes the importance of port efficiency towards enhancing terminal's attractiveness to shippers.

3.1 Port Governance

The review on port governance focuses on various port organizational models, the role of port authorities, port performance, port reform, and the policies and strategies influencing governance structures. It highlights the importance of selecting the appropriate organizational model to enhance port performance, ensuring it aligns with the port's environment and strategic initiatives. These models vary in their degree of centralization or decentralization as shown in Figure B.4 and the role of the port authority. The review indicates that a port's success significantly depends on the authority and functionality of its port authority. Hence, classifying PA as conservators, facilitators and entrepreneurs [26]. Additionally, it reveals that a port's geographic location and its economic significance are crucial factors in facilitating port reform [20].

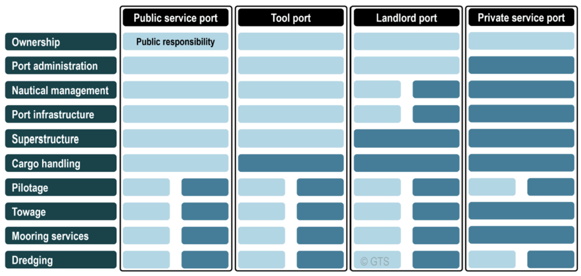

Figure B.4: Public and Private Roles in Port Management [22]

A study by [6] provides insight into the level of power and interest of different stakeholders which can lead to power struggles, lack of trust, resistance to change, and incompatibility of operating and strategic goals [17]. This hinders information-sharing potential among stakeholders and slows down progress. Therefore, [17] uses the partnership model to define four possible cooperative relationships between organizations.

1. Arm's Length Partnership: A transactional business relationship that lacks a sense of mutual commitment. The relationship termi-

nates when the exchange is completed.

2. Type 1 Partnership: Organizations collaborate on tasks and project-related matters, coordinating activities and planning on specific cases. However, there is limited trust and little to no joint investments.
3. Type 2 Partnership: Organizations merge their activities and functions throughout the partnership.
4. Type 3 Partnership: The partnership encompasses both organizations' strategic and tactical operations.

A theoretical model known as the Matching Framework (Figure B.5) describes how an organization's success is determined by the alignment of three crucial components: the external environment, the organization's strategic decisions (including goals and strategies), and its organizational structures and processes.The organization's strategy outlines the approach it plans to take to accomplish its goals, considering the external environment. Organizational structures refer to the information and control systems, operational procedures, and hierarchical reporting relationships that dictate how the organization functions internally.

For a port to achieve optimal performance, it is essential to ensure that its strategic decisions and organizational structures are well-aligned with the external environment in which it operates [4]. By continuously monitoring and adapting to changes in the external environment, and aligning its strategy and internal structures accordingly, a port can enhance its competitiveness and achieve sustainable success.

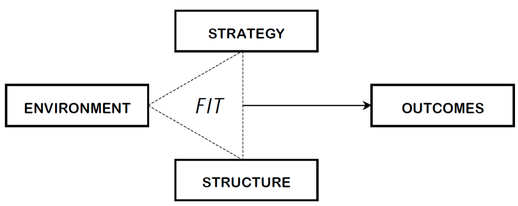

Figure B.5: Matching framework [3]

Monopolistic control over vessel services can lead to several negative outcomes, such as increased service rates, barriers to market entry for other companies, difficulties in adapting to disruptions, and a decline in service quality. The literature indicates that a public port model can ensure steady funding for investments in infrastructure and equipment. Nevertheless, political interference often hampers the port's responsiveness to customer requirements [9]. In contrast, a private port model entails ownership and operation by a private company, which may be an independent firm or a subsidiary of a larger corporation. Private ownership offers greater financial flexibility and allows for quicker responses to market demands, as investment and operational decisions can be made based on profitability considerations. Despite these advantages, private ports are more susceptible to market fluctuations and may not prioritize social and environmental concerns to the same extent as publicly-owned ports [9].

3.2 Nautical chain

Due to limited number of research on optimizing nautical services under the pretext of PCO, an extended literature review was required to gain knowledge for the scope of this project. This review provided various operational constraints, objectives and modelling strategies. The literature reveals that service providers in ports have varying objectives influenced by economic factors, geographic location, safety concerns, and policy restrictions. Additionally, it has been observed that stakeholders often prioritize their individual benefits over collaborative efforts to enhance the overall performance of the port, such as reducing vessel waiting times. These insights are crucial for the development of a comprehensive PCO tool.

Tugboat assistance are crucial to prevent accidents within the port. Many ports mandate the use of tugboat services to ensure the safe transit of vessels [27]. Tugboat companies face high operational costs due to substantial investments in tugboats and high fuel consumption. Therefore, they strive to optimize tugboat assignments for maximum efficiency. Extensive research has been conducted in the area terminal operation optimization to improve port performance [5].

The pilotage service contains a set of limited pilots of high wages which need to be effectively utilized to minimize delays of vessels and reduce operational costs. This makes it a combination problem where pilots are assigned to vessels and the optimal set of task is considered for a pilot. The complexity of this problem further increases when considering various legal regulations concerning the working times of pilots.

4. CONCEPTUAL DESIGN

4.1 Trends

Figure B.6 shows a study that has identified emerging trends using a focus group of industry experts to to evaluate various PCO trends. Green shipping and ports; Additive manufacturing; and Digitalization and big data are the ones identified by [23] through structured communications with a panel of experts. These trends are regarded as highly pertinent and influential for the future of ports [23]. Notably, while autonomous vessels currently have no effect on ports, they are anticipated to have a significant impact in the future. Consequently, this trend is included in this study as well.

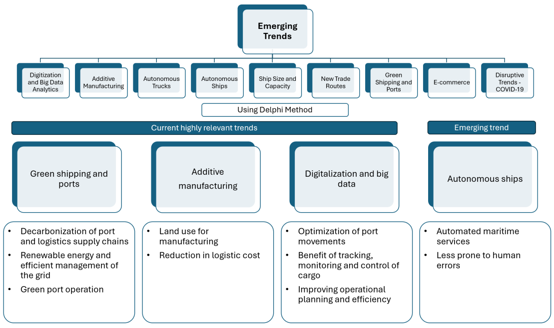

Figure B.6: Study on emerging trends using Delphi method [23]

Various International organizations and associations have dealt with port call optimization by providing guidelines and roadmaps on ways to improve the port call process. As shown in Table B.1, these efforts have been mainly towards improving communications and making sure that data/info are shared effectively between stakeholders/ports. The international taskforce port call optimization [13], has decided on a road for port call optimization. However, the taskforce focuses on standardized documents transferred and incentives for sharing data between stakeholders to streamline the port call process. The IMO and the IAPH, on the other hand, has taken up initiatives such as Just In Time (JIT) arrival of vessels to reduce port congestion and fuel consumption. They recommend that low congestion at anchorage can reduce the probability of collisions, and reduce greenhouse gases and fuel consumption of idle vessels. By using slow-steaming, vessels can reach the port just in time for vessel service provider (tugs, pilots, etc) and save fuel in doing so.

Using the co-design method, the collective experience of the OptiPort team was used to review and analyze the industry trends. Through these discussions, it was agreed that decarbonization through green measures and the adoption of digitalization are significant trends influencing the future of ports. Moreover, autonomous vessels are attracting interest from ports due to economic advantages such as lower crew costs and minimized human error. These ships could also boost efficiency by optimizing routes and shortening transit times [14]. However, the absence of established rules and regulations for autonomous ship operations could result in legal and liability challenges. Therefore, shipping companies and regulatory bodies need to collaborate to develop a framework that ensures the safe and responsible utilization of autonomous ships [14].

Upon discussion as part of the co-design process, PortCDM was found to be a concept that is leading towards PCO. PortCDM is a concept that facilitates the dynamics of collaboration between internal and external actors through standardized data-sharing platforms and connectivity between different [15]. This enhances the decision-making process between stakeholders.

4.2 Requirements

To address stakeholder needs effectively, it is crucial to define requirements that specify the necessary capabilities or functions of a system [2]. The requirements help gauge the different alternatives proposed for the development of the tool, ensuring it meets stakeholder needs effectively. The requirements derived from the TOEI framework presented in [6] are in close relation to the development stages presented within PortCDM [16]. This confirms the applicability of this framework to analyse the requirements for the development of the PCO tool as PortCDM is the driving concept that the PCO is based upon. The constraints and objectives detailed below stem from brainstorming, interviews, and abstraction. Additionally, a systematic literature review offers insights into stakeholder needs, aiding in the formulation of requirements.

Constraints

1. The tool must use standard formats for critical communications between stakeholders to allow direct communication and transparency.
2. The tool must allow data sharing between multiple users to ensure effective decision-making.
3. The tool must be able to find a compromise between stakeholders to facilitate collaboration.

Objectives

1. The tool should consider the operational and environmental constraints of all stakeholders.

Table B.1: Few initiatives taken up by different organizations

Organization	Initiative	Measure category
International Maritime Organization (IMO)	JIT	Reduce greenhouse emissions
Sea Traffic Management (STM)	PortCDM	Collaboration
International Association of Ports and Harbors (IAPH)	Best practices in port operations, JIT	Reduce greenhouse emissions
PortXchange Products BV	PortCDM	Collaboration
Global Port Call Optimization Task Force	Standardized processes	process improvements

2. The tool should potentially be supported by the government.
3. The tool should be able to provide minimum cost of operation to all stakeholders.
4. The tool should be able to reduce delays in vessel operations.
5. The tool should satisfy current green policies in ports.

4.3 Alternate solutions

The systematic literature review in section 3 examines tugboat, pilot, and berth scheduling, offering a thorough analysis of existing scheduling techniques, parameters, constraints, and objectives. The literature reveals that multiple models, varying in complexity, are designed to closely replicate real-world scenarios, resulting in increased computational time. These methods include single-objective optimization, multi-objective optimization using Pareto efficiency, multi-objective optimization with scalarization, simulation-based optimization, and bi-level optimization.

Single objective: This model solves the optimization model involving multiple stakeholders using a single objective function. Usually, these objectives are to improve the overall performance of the port. Nikghadam [19] proposes a model for joint scheduling of vessels and service providers by minimizing the maximum deviation from the requested times. Although this approach effectively optimizes resource use and schedules vessels closer to their requested times, it assumes full collaboration among stakeholders. In reality, organizations have multiple objectives to satisfy their stakeholders, and different entities within the nautical chain often have conflicting goals, making joint scheduling challenging.

Multi-Objective Optimization: Multi-objective optimization (MOO) strategy provides a way to tackle multiple stakeholders' objectives. [8] suggests two common methods of MOO, Pareto and scalarization, that do not require complicated mathematical equations, making the problem simple.

1. Scalarization: This method solves the optimization model using multiple objectives which are added into the main objective function using normalized weight components for each subsequent objective. These weights are measured and validated through data available from past operational data.
2. Pareto: This helps in finding the compromise solution between two or more objective functions which could not be performed with scalarization [29]. However, by using Pareto optimization, the preferences of stakeholders are considered through a-posteriori evaluation [28] which fails to achieve an integrative design approach. Therefore a sub-optimal compromise solution is achieved.

Multi-Objective Multi-Stakeholder Optimization: Preferences are crucial in the design and decision theory because they are closely linked to human behavior [28]. An analysis of the preferences at a macro and micro level, and across ports was conducted by [24]. This optimization model considering multiple stakeholders requires an accurate representation of the preferences in the objective function. Therefore, Tetra software needs to be used to perform a performance aggregation such that the combined preferences accurately reflect the individual preferences of all stakeholders as closely as possible.

Simulation-based optimization: Stochastic and dynamic nature of the problem can lead to increased complexity. [11] proposes a simulation-based optimization solution for the combined planning of berth allocation, tug allocation and quay crane allocation. A simulation model replicates real-world systems that are too complex to analyze directly [7]. This optimization strategy incorporates the dynamic nature of the port environment in vessel arrivals, departures and resource availability to provide robust scheduling solutions [11]. A framework for the simulation-based optimization is shown in Figure B.7.

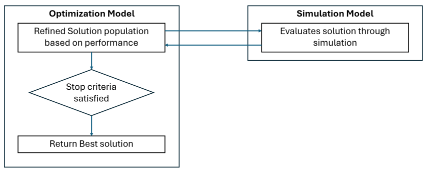

Figure B.7: framework for simulation- based optimization [11]

Bi-level optimization: The problem of berth allocation and nautical service scheduling can be seen as a hierarchical decision-making process in ports. Terminals decide on the berth allocation with the vessel agents who then communicate with the HM to schedule the nautical services to meet the required berth timings. With bi-level optimization, the parameters required for the lower level are obtained from the upper level. The structure of the bi-level problem is shown in figure B.8.

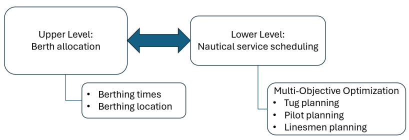

Figure B.8: framework of bi-level optimization

Figure B.9 compares optimization strategies for different use cases. While single-objective optimization can be useful for minimizing delays or increasing throughput, it often falls short in scenarios with multiple KPIs. Multi-objective optimization, which considers multiple objectives and stakeholders, uses weights to determine the importance of each objective, though this can become complex with many objectives. Pareto optimization helps find compromise solutions by assigning weights to balance objectives. Multi-objective, multi-stakeholder optimization incorporates stakeholder preferences, resulting in decisions that align with human preferences. Hierarchical decision-making models are crucial when one stakeholder's decision impacts others. Simulation-based optimization can model complex systems but requires detailed stakeholder understanding and is computationally intensive. A bi-level optimization approach is less intensive and can enhance current multi-objective models.

Figure B.10 shows optimization strategies for non-hierarchical port decision-making, with bubble size indicating stakeholder involvement. In public ports, single-objective optimization minimizes delays with centralized control, but multi-objective optimization with scalarization is needed for multiple KPIs, suitable for single-entity governance. As stakeholder numbers grow and collaboration decreases, strategies must include individual preferences. Multi-objective optimization using Pareto offers compromise solutions but may miss the global optimum and require some collaboration. The Odesys method, with its a-priori approach, integrates preferences and socio-technical interactions, crucial when collaboration is limited.

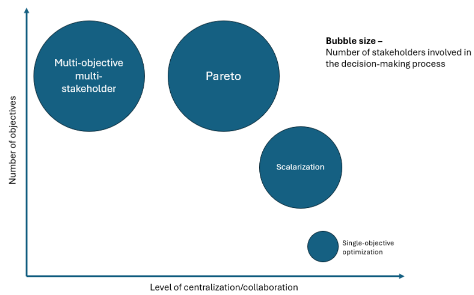

Figure B.10: Comparison of Optimization Strategies for non-hierarchical decision making

4.4 Conceptual framework for roadmap development

Figure B.11 depicts the conceptual framework for evaluating ports for the implementation of the prerequisites. Since the roadmap is for a PCO tool that must meet the requirements listed in section 4.2, the prerequisites correspond to the actions needed to satisfy the core requirements listed in the previous section. These prerequisites are influenced by factors derived from the components of the matching framework, which impact the feasibility and timeline of the tool's development and implementation. Each prerequisite in this framework is detailed below to ensure a comprehensive approach to optimizing port performance within the given parameters.

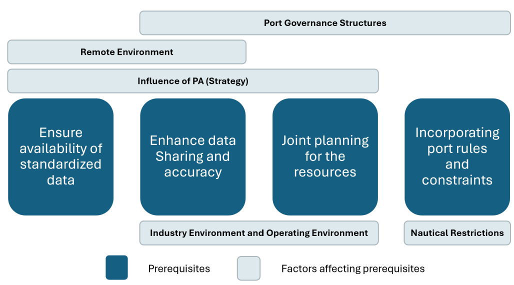

Figure B.11: Conceptual roadmap framework

Analyzing the organization's external environment

Optimization Strategy	Multiple objective	Multiple stakeholder	Stakeholder preferences	Decision hierarchy	Remarks
Single objective optimization	☐	☐	☐	☐	1. Easy to implement 2. Does not consider multiple KPIs of an organization 3. Trade-off between stakeholders are not considered 4. Non-compromise solution
Multi-Objective optimization					
Scalarization	☑	☑	☐	☐	1. Difficult to find weights for all parameters in the objective function 2. Trade-offs between stakeholders depends on weights assigned 3. True compromise not found 4. Preferences of stakeholders not considered
Pareto	☑	☑	☑	☐	1. Provides a compromise solution 2. Preferences of stakeholders are considered through a posteriori evaluation 3. Optimal solution may be ignored for large number of design alternatives
Multi-objective multi-stakeholder (Odesys design methodology)	☑	☑	☑	☐	1. Provides compromise solution 2. Considers preferences of stakeholders 3. a-priori group design/decision making process 4. Full integration between subject desirability and object capability
Simulation based optimization	☑	☑	☑	☑	1. Can easily incorporate stochastic and uncertain nature of ports 2. Provides planning support at a tactical level 3. Can replicate complex real-world systems
Bi-level optimization	☑	☑	☑	☑	1. Combines required optimization strategy with hierarchical relationships.

Figure B.9: Solution evaluation

is essential, which includes the remote, industry, and operating environments [3]. The contents of these are shown in table B.2. The external environment, port governance structures and port strategy which can be translated into the influence by the PA are used for evaluating the prerequisites towards implementing a PCO. Lastly, port governance structure, as discussed in section , forms the 'structure' component of the matching framework that helps to assess the hierarchical reporting relationship and regulatory framework.

4.5 Roadmap development steps

The roadmap development steps is built upon the information detailed in this chapter and can support the development of the roadmap for different port settings.

1. Identify port governance structure:
   The port's governance model significantly influences its performance by affecting the centralization of nautical chain activities. Understanding this structure is crucial for strategic PCO implementation decisions.
2. Identify the role of the Port Authority:
   The Port Authority's (PA) role as discussed in section 3.1 varies with governance structures, impacting PCO implementation. It can influence the process through its varying responsibilities and powers.
3. Identify collaboration levels between stakeholders:
   Collaboration levels, which can differ widely among ports, affect the optimization strategy and PCO implementation timeline. The partnership model assesses relationship potential and helps understand the operational environment's influence on stakeholder interactions.
4. Identify the level of digital technology maturity:
   Technology includes the system used for communication and data sharing and the current state of the existing PCO tool and its implementation level. Ports such as Port Arthur have adopted tools such as OptiPort to schedule their towage services [24]. Such available technology can facilitate the implementation of PCO.
5. Identify current port call decision flow process of the port:
   Identifying the decision flow process in assigning the nautical services to vessels for a port is crucial in determining the steps for PCO integration. Assessing the decision flow can provide insights into the areas of improvement.
6. Develop the sequence of stages for implementation:
   The implementation sequence depends on governance structure, PA role, stakeholder collaboration, technology maturity, and decision flow. This involves stakeholder integration, optimization strategy selection, timeline determination, and considering external influences.

5. CASE STUDY

The port of Rotterdam (PoR) is chosen for designing the roadmap for PCO tool implementation with OptiPort as the base software. The development steps listed in the previous section are used to assess the port for the development of the tool. The insights gained from this case study are used to create a suitable roadmap for PoR in the following section and serve as a reference for analyzing other ports for the implementation of a full Port Call

Table B.2: components of external environment

Remote environment	Industry environment	Operating environment
Political	Number of participants	Buyers
Technological	Size of organization	Suppliers
Economic	Extent of collaboration	Competitors
Socio-cultural	Policy regulation	Potential new entrants
		Substitute services

Optimization (PCO).

5.1 Key insights of PoR

The Port of Rotterdam (PoR) operates as a landlord port with an entrepreneurial Port Authority (PA) that facilitates companies' transition towards a sustainable future. This is achieved through initiatives like CO_2 capture, renewable energy, hydrogen production and transport, shore-based power, digitalization, circularity, and utilizing residual heat. Current trends in PoR reflect the PA's supportive role, demonstrating its high power and interest in implementing a full Port Call Optimization and influencing the timeline for its achievement [21].

The privatized nature of port services, including terminal operations and nautical services, significantly impacts port operations. Competition among terminal operators drives them to invest in technology to enhance operational efficiency and reduce costs. Lower operational costs result in higher profits and further investments, thereby increasing the port's overall competitiveness [20].

Terminals at PoR have poor communication with the HM. They communicate with the vessel agent who updates the information in the PCS which is viewed by the HM and the nautical service providers. Terminal operators are seen as organizations with high power compared to pilot and tugboat organizations. However, their interests in optimizing the port call process is lower than these organizations. Terminals are only concerned with their operations and efficient allocation of berths [24]. This lack of collaboration between the terminal and the vessel service providers is seen to cause delays in operations and inefficient planning of resources.

The pilotage services in the PoR are monopolized by a private organization. This creates a power struggle within the port, particularly during joint planning with other stakeholders in the nautical service chain. It was noted that pilots request tug services only after boarding the vessel, giving tugboat planners a limited time to allocate their resources.

5.2 Proposed roadmap

The roadmap as shown in figure B.12 for implementing Port Call Optimization (PCO) at the Port of Rotterdam (PoR) outlines development steps, timelines, and factors affecting PCO integration, such as technology readiness, governance structure, and stakeholder collaboration. As a landlord port with privatized services, PoR benefits from improved efficiency through advanced technologies and competition, particularly in tugboat scheduling via OptiPort. However, the current system's limitations highlight the need for enhanced collaboration, particularly between pilots and tugboats, and a shift towards a joint planning model facilitated by the Port Authority (PA). The roadmap advocates for standardized data sharing and integration of decision-making processes among stakeholders, leveraging PoR's Port Community System (PCS) for digital infrastructure. By updating optimization models to reflect stakeholder preferences and adopting a bi-level optimization framework, PoR can improve berth allocation and nautical service scheduling, reducing delays and increasing throughput. Collaboration with terminals remains challenging due to operational transparency issues, but the roadmap suggests leveraging the PA's influence to foster cooperation and align berth planning with nautical service availability, ultimately advancing PoR towards a fully integrated PCO system.

5.3 Roadmap validation

Regarding the technologies required for data sharing, the Port Authority (PA) has confirmed the availability of the necessary technology. This was also revealed through an interview with Portbase where various APIs are being made to provide information to various stakeholders by analysing the data shared through Portbase. However, the challenge lies in getting stakeholders to cooperate. The PA is actively educating customers and advising stakeholders on the impact of port call optimization. This is being done through conferences involving various customers to promote Port Call Optimization (PCO). Furthermore, the PA has agreements with certain customers for standardized documents, which are aimed at improving the

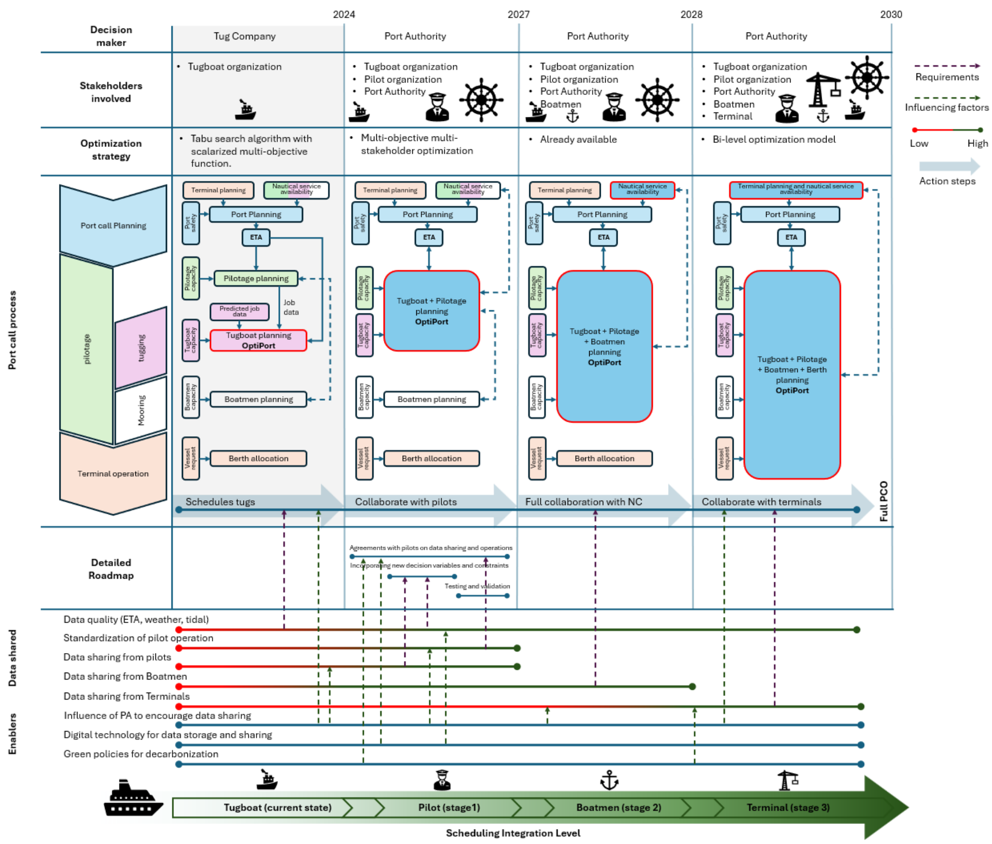

Figure B.12: OptiPort roadmap towards full PCO in the Port of Rotterdam

turnaround time of vessels.

The PA of PoR is focusing on integrating berth planning with overall port planning to ensure that the right information is shared with all stakeholders, thereby enhancing Just-In-Time (JIT) arrival of vessels at the berths. This integration is seen as a major bottleneck in the port call process at PoR and is currently a primary focus. The integration of the nautical services into the port planning is also something that the PA has planned in the future. Hence 3 years from 2024 seems to be reasonable time-frame to implement a decision support tool for joint planning with the pilot organization and get the stakeholders agree to the new terms.

6. IMPACT OF GOVERNANCE STRUCTURES

Ports adapt to changing environments by developing strategies tailored to their unique resources, capabilities, and organizational structures, as highlighted in the matching framework. This framework provides a method to align port strategies with external conditions. Despite the significant differences among ports, the same conceptual roadmap framework can be used to identify factors influencing Port Call Optimization (PCO) implementation, facilitating necessary adjustments in technology and policy. Ports can be classified into three main governance structures: public, landlord, and private, each affecting PCO implementation in different ways.

Public Ports

Public ports are typically controlled and operated by government entities, such as ministries of transport. They have centralized control over port infrastructure and operations, including services like pilotage, towage, and mooring. This centralized control can facilitate efficient communication among stakeholders but may also lead to delays due to bureaucracy and political agendas. Public ports often receive government funding for infrastructure improvements, but political interference can slow decision-making and resource allocation. The port authority (PA) plays a significant role in these ports, and their involvement can range from conservator roles focused on infrastructure to more entrepreneurial roles that facilitate stakeholder collaboration and investment.

Landlord Ports

Landlord ports, such as the Port of Rotterdam, involve private companies managing terminal handling operations and nautical services through concessions. These private entities operate autonomously, driven by performance-based incentives that align with the port's objectives, leading to increased efficiency and investment opportunities. The reduced governmental influence simplifies the investment process, minimizing bureaucratic delays. However, privatization introduces competition among multiple service providers, which can hinder communication and collaboration. In landlord ports, stakeholder collaboration and optimization strategies need to consider multi-objective approaches that account for diverse interests and decision-making processes. The role of the PA, along with the level of digital technology maturity, significantly influences the success of PCO implementation.

Private Ports

In private port models, all port functions are owned and operated by private entities, making them highly decentralized. This structure allows for greater financial flexibility and responsiveness to market demands, but may lead to less emphasis on social and environmental concerns. Private ports require high levels of communication between stakeholders to complete port call processes efficiently. The absence of government influence reduces political obstacles, facilitating the implementation of optimization models that promote standardized data sharing among stakeholders. For example, a centralized pilot organization might streamline operations and enhance safety protocols, but it may not adequately consider the resource capacities of other entities, like tugboats and linesmen. By incorporating data sharing and collaboration into these models, private ports can improve operational efficiency while maintaining safety standards.

7. Discussion

This research underscores that while port governance structures provide key insights into stakeholder collaboration and control of port services, additional factors must be considered when developing a roadmap for implementing a Port Collaborative Optimization (PCO) tool. The study emphasizes that Port Collaborative Decision Making (PortCDM) is a critical element of PCO, as standardized data sharing is essential for collaborative decision-making. The research aims to advance PCO beyond facilitating collaboration to enabling joint resource planning within the port call process.

The roadmap for PCO implementation must address specific constraints, translating them into actionable steps that consider the unique characteristics of each port environment. These environments vary significantly, necessitating a detailed analysis to propose suitable technological advancements, policies, and data-sharing standards that foster collaboration and joint planning among stakeholders.

Factors such as political influences, digital technology maturity, and economic conditions can impact the timeline for PCO implementation. The industry environment, including the number of participants, organizational size, collaboration levels, and policy regulations, also plays a crucial role in optimizing stakeholder collaboration and competition. Understanding the decision-making flow within ports, particularly in nautical service planning, is essential for developing a PCO roadmap that integrates all stakeholders.

Ultimately, this research aims to guide the development of a PCO tool tailored to specific port settings, aiding ports in identifying areas for improvement and assisting policymakers in creating favorable conditions for stakeholder collaboration and PCO implementation.

8. Limitations

While this research proposes a framework that is instrumental in assessing ports for the implementation of a PCO tool, several limitations should be acknowledged.

The formulation of the requirements were solely based on interviews with the OptiPort team, literature review that studied pre-requisites of collaborative decision making, brainstorming and abstraction. However, widening the scope of interviews with other stakeholders who are also involved in the decision-making process would prove a conclusive set of requirements.

The roadmap designed was based on qualitative reasoning of the external environment, strategy and structure of the port. A quantitative approach that measure the readiness of each factor can provide precise estimation time and resources required to achieve set milestones.

Lastly, The Design Science Research (DSR) approach requires an iterative process where each step in the co-design process is performed again based on the feedback received on the designed artefact. The iterative process ensures design quality and fit for a specific port [10].

9. Conclusion

In conclusion, this study aims to bridge the gap between the fragmented research in PCO within the scope of the nautical chain and terminals to develop a framework that assesses different port governance structures for the implementation of a PCO tool. The proposed framework for roadmap development is a culmination of the systematic literature review on different port governance structures and PCO models, and the co-design process that defined the trends, requirements, and solutions. The study underscores the importance of the influence of the PA and the maturity of digital technology required to facilitate the implementation of the PCO tool. Finally, a step by step deign process for roadmap development was proposed which highlights the complexities in different port governance structures and provides a structured analysis for ports.

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