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Digital twins for resource optimization in multi-purpose ports: A design approach for data-driven decision making

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Abstract. Multi-purpose ports' efficient and sustainable operation relies on seamless coordination and decision-making among multiple organizations. This paper underscores the critical importance of forecasting resource and infrastructure utilization for informed operational, tactical, and strategic decision-making. The proposed approach draws on digital twin technology to enable collaborative decision-making by modeling complex port environments to enable shared situational awareness among stakeholders. Illustrated through a collaborative project involving the RISE Research Institutes of Sweden, National University of Singapore, Grieg Connect, Umeå University, Kvarken Ports Umeå, and INAB, we propose a digital twin design to empower the port as a decision-maker in multi-organizational settings to proactively plan and optimize its utilization of present and future resources.

1. Introduction

World trade is now global, at a scale that has led to increased transport distances of goods and a surge in pollution. Transportation significantly contributes to global carbon dioxide (CO2) emissions, accounting for 21% of the worldwide CO2 emissions in 2018 [1]. Maritime transport plays a crucial role in several industries and society, enabling efficient and more environmentally friendly transportation of goods [2, 3]. Maritime transport, which accounts for 90% of the world's freight transport [4–7], contributes to 10.6% of the transport emissions [1]. Increased efficiency in maritime transport is thus essential from an economic and sustainability point of view.

Ports represent complex system-of-systems environments operating within larger system-of-systems environments. Consequently, ports are highly influenced by external events—and long-term insights into the future need for infrastructure, and resources are crucial to managing a port efficiently. Many ports function as multi-organizational entities, necessitating coordination among the involved actors to operate efficiently and sustainably. Each involved organization needs to ensure the availability of resources and infrastructure to meet the demands of services during port visits. Each actor's performance is also critical to avoid bottlenecks in the activity chain.

A lack of access to information and plans from involved actors in decision-making processes and port operational planning increases energy consumption, environmental impact, and costs, decreasing the port's robustness to disturbances. By using digital technology, there is potential to shorten the time of the port calls, which will reduce greenhouse gas (GHG) emissions. By providing the involved actors in the port with digital tools for situational awareness and decision support, the potential for more just-in-time (JIT) arrivals and departures of ships is created.

Maritime transport can be conceptualized as a self-organized ecosystem (SOE) [8] comprising various independent rational actors that optimize their operations independently [9]. The vital actors of the maritime industry are ports, port authorities, shipping companies, terminal operators, commodity producers, cargo owners, ship agents, pilots, towage companies, and freight brokers [10]. They are independently managed but connect daily. A challenge for ports and the maritime transport sector is the lack of knowledge, resources, initiatives, and strategies to leverage the value emerging from digital technologies [11]. A supply system operating within a SOE is both complex and vulnerable. For each actor involved to be able to make informed decisions, preferably as late as possible but with the opportunity to prepare for different action alternatives, a systemwide and shared situational awareness of planned and ongoing transport is required.

With one of Europe's longest coasts and 52 ports, Sweden depends on a well-functioning shipping industry, and ports play a crucial role in the Swedish logistics chain [12]. In 2021, the Swedish ports handled 56,782 ship visits and loaded or unloaded 134,180,000 tons of cargo [9]. However, maritime transport is vital not only for industrial production and, thus, the economy but also for the environment. A significant portion of GHG emissions from maritime transportation comes from ships visiting ports. Decreasing these emissions and increasing port efficiency through better decision-making would thus have substantial economic and environmental impacts. This article explores the challenge of deriving solid decision bases in ports through digital twin technologies.

2. Maritime ports

Ports serve as crucial interfaces where maritime and hinterland transports converge, facilitating intermodal shifts and engaging various stakeholders, including cargo owners and transport buyers seeking value-added services within the transport chain [13, 14]. Traditionally viewed as SOEs, maritime transport operations experience inefficiencies due to individual optimization efforts [8, 15]. However, digitalization provides an opportunity to challenge this predominant logic of the chain of maritime operations by enhancing connectivity, enabling data sharing, and leveraging coordination among diverse actors [6]. Multipurpose ports handle various types of cargo and require diverse physical infrastructure and resources (such as multiple wharf lines and berths, handling equipment, transport vehicles, yard areas, and warehouses) depending on the purpose of the call. This infrastructure supports stevedores with various skill sets to manage different types of cargo. Due to allocating these scarce resources across different cargo types, multiple interdependencies result in varied processing rates and priorities.

Therefore, operational decisions based on situational awareness are critical for multipurpose ports. A multi-purpose port must handle various types of cargo arriving and departing via ships, trains, or trucks, acting as a key node to ensure transport movements occur with high predictability in a seamless and continuous flow without interference. This role underscores ports' importance in increasing transport efficiency by providing digital infrastructures for data and information exchange. Digital infrastructure is "the basic information technologies and organizational structures, along with the related services and facilities necessary for an enterprise or industry to function" [16].

Despite the increasing availability of digital data streams, port call operations remain sub-optimized, with actors relying on fragmented information sources and communication channels [17]. This fragmented approach hinders collaboration, leads to low information quality, and impedes resource utilization [18]. In response to globalized and logistics-restructured environments, ports must prioritize collaboration, coordination, and standardization to adapt swiftly and capitalize on emerging opportunities [14, 19]. Recognizing their role as critical enablers in transportation systems, ports must focus on their value proposition and hinterland transport integration to meet evolving market demands [20, 21]. This necessitates a shift towards data-driven decision-making and sustainable practices [22, 23].

Building resilience and managing disruptions is about decision-making, the central activity of all organizations. One rigorous approach to decision-making is to build a digital twin of the environment and simulate the impact of possible actions or events. "A digital twin is a dynamic digital representation of an object or a system, describing its characteristics and properties as a set of equations" [24]. The emergence of disruptive technologies, such as digital twin technology and artificial intelligence, presents new opportunities for ports to streamline processes, improve efficiency, and enhance transparency. By harnessing these technologies, ports can optimize supply chain management, reduce administrative burdens, and improve overall competitiveness in the global marketplace.

This paper describes how we seek to build a digital twin for the multi-purpose ports of Kvarken Ports in Umeå. The following subchapter describes the use cases we identified as suitable for testing digital twin technology. We also describe the use case we are working on in the development and simulation phase.

2.1 Use case

The design phase of our project commenced with a two-day joint workshop. On the first day, representatives from the Swedish project team worked collaboratively to identify various use cases. The second day was dedicated to presenting these use cases to the Singaporean team, who showcased the existing digital twin model that would be adapted and utilized for the selected use cases. Following this, the Swedish project team prioritized four use cases, which were then elaborated upon and forwarded to the Singaporean project team. The first use case, 'Port Call Optimization' (PCO), primarily focuses on short-term decisions and resource utilization. The second use case, 'Decision Support for Strategic Investments' (DSSI), is geared towards long-term decisions and resource availability. The third use case, 'Past and Present Utilization of Resources and Bottleneck Identification' (P2URID), emphasizes resource utilization and is designed for mid-term operational decisions. This use case is closely linked to the fourth use case, 'Decision for Predictive Maintenance and Infrastructure Conditions' (DPMIC), which is also a mid-term operations decision but with a greater focus on resource availability.

Upon reviewing the use cases, the Singaporean team provided feedback on the feasibility of implementing them with the digital twin model and suggested a sequence for their execution. As a collective decision within the project, we agreed to commence testing with use case 1, the details of which will be presented in the subsequent subchapter. Following the adaptation and testing of use case 1 within the digital twin model, we plan to proceed with use case 3. If time permits within the project timeline, we will continue with use cases 2 and 4.

In use case 1, the coordinating body, the Port Authority (PA), oversees critical operations, is responsible for maintaining port infrastructure, and wants to predict and proactively address potential disruptions that could impact the operations. The PA can enhance decision-making capabilities by staying informed about anticipated and actual disruptions and synchronizing ships' arrivals and departures with resource and infrastructure capacity. Equipped with accurate information, the PA can strengthen their resilience and effectively manage challenges that arise.

This use case defines the PA's desire to predict and proactively address potential disruptions to enhance its decision-making capabilities, strengthen its resilience, and effectively manage challenges that arise. In use case 1, the unit of analysis and time scope is short-term predictions and decisions. E.g., let's pretend that today is the first of March, and the port gets information that a ship is bound for the port with an ETA of the third of March at noon. The port starts planning all the operations based on that information. With a digital twin, the aim is to have the information used to plan other outcomes as well. For example, what would the outcome be if the ship arrived on the fourth at 04.00 hrs instead and be ready to start operations at 06.00 hrs that day? Would it be possible to sail at the same time as coming on the third at noon? Or should the ship speed up instead and try to come earlier on the third? Having multiple planning options will help the port make better-informed decisions based on different parameters. These parameters could include time savings, environmental factors, optimal use of resources, or financial factors.

3. Methodology

3.1 Project setup

In this article, we illustrate an approach for adopting digital twins for empowered decision-making in multi-organizational settings for multi-purpose ports, emerging from the Memorandum of Understanding (MoU) inked in 2022 between RISE and Singapore Maritime Institute. The MoU surfaced four areas of collaboration being of concern for the maritime and supply chain industry:

- Supply chain innovation and efficiency
- Maritime Informatics (digitalization for maritime related activity)
- Safety and Security
- Decarbonization and sustainability

Projects emerging within this MoU build on the foundation that projects should only be possible to realize with the engagement from parties on both the Singaporean and the Swedish side. In this case, the digital twinning project engages RISE and the National University of Singapore (NUS), complemented with additional parties on the Swedish side, such as Kvarken Ports Umeå, Grieg connect, and INAB, and on the Singaporean side, the Centre of Excellence in Modelling and Simulation for Next Generation Ports (C4NGP). The project takes the generic model of a digital twin of a port, developed by the Singaporean team, and adapts the model to the circumstances in Kvarken Ports as a multipurpose port. By this, Swedish participants cut corners by building on existing knowledge, and Singapore gets validation results by adopting the digital twinning model in a particular setting. The long-term ambition is that the knowledge generated from this project become of interest for many of the ports in the world, who desire to enhance their decision-making by using digital twinning methodologies.

The approach taken to the use of digital twins is unique as most approaches to digital twinning are focused on a single entity (like an engine or a ship) a single organization or in environments with highly standardized processes containing repetitive activities [25–27] . In this case, the aim is to empower involved actors within a multi-organizational setting, such as the multi-purpose port Kvarken Ports Umeå, with capabilities of shared situational awareness as the basis for short- and long-term decisions on the utilization engagement of and investment in infrastructure and resources. The multi-organizational digital twin allows each involved actor to contribute with their insights on the expected resources and infrastructure needs, forming the basis for simulating diverse scenarios. The outcome of the simulations of the identified scenarios then aligns the actors in collaborative decision-making processes on resource and infrastructure prioritizations and investments.

3.2 Digital twin

The maritime industry is experiencing a profound transformation propelled by advancements in digital technology. One of the most revolutionary innovations in this realm is the digital twin concept, especially pertinent to multipurpose ports. A digital twin is a virtual replica of a physical entity that, in this context, includes the entire port infrastructure, encompassing ships, sensors, and other sources, facilitating comprehensive monitoring, analysis, and optimization of port operations. Multipurpose ports, which manage a wide variety of cargo types and vessel sizes, present distinct challenges and opportunities for implementing digital twins. These ports must efficiently handle diverse logistics, ensure safety, and optimize the use of infrastructure and resources. By incorporating digital twin technology, multi-purpose ports can gain improved operational visibility, anticipate and address potential issues, and make informed decisions based on data to enhance efficiency and reduce costs.

The constant demand for increasing quality and capacity while reducing costs and lead times is a pressing challenge for multipurpose ports. Achieving these improvements is complex and apparent. Multipurpose ports must maintain flexibility to fulfill their functions, making optimization through specialization unfeasible. Therefore, optimization must be achieved through resource planning, where digital twins can be revolutionary. Currently, operational planning and situational monitoring often rely on spreadsheets, windows, emails, surveillance cameras, and phone calls. While digital solutions for port operations monitoring are emerging, they typically do not estimate when a resource will be occupied or highlight current or future conflicts. To achieve this, these digital solutions would need access to a digital twin of the port. The components of a digital twin, as outlined by Lind et al. in "Digital Twins for the Maritime Sector" [25] in Figure 1, include physical entities, digital models, data management systems, simulation and analysis tools, communication infrastructure, user interfaces, and integration platforms. These elements work together to enhance situational awareness, decision-making, and resource optimization in the maritime industry. Beyond estimating resource usage and predicting conflicts, digital twins can identify, plan, and test future investments that could enhance port effectiveness and reduce environmental impact.

Complex processes involving multiple actors create challenging decision-making environments best modeled digitally before action. A digital twin includes the hardware to gather and process data and the software to represent and manipulate these data [6] . This approach empowers multi-organizational settings like multipurpose ports to make informed decisions. By enabling shared situational awareness and facilitating collaborative decision-making, multi-organizational digital twins provide a framework for prioritizing resource allocation and infrastructure investments. Leveraging digital twin technology can enhance the

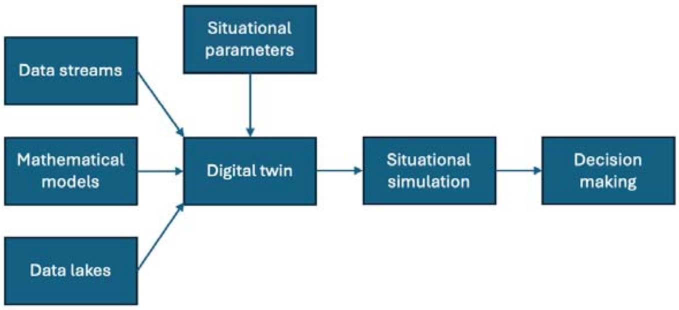

Figure 1. The components of a digital twin, based on the article "Digital twins for the maritime sector " [24]

resilience and efficiency of ports, ensuring they remain key enablers in global transportation networks.

The digital twin will be a discrete event simulation coupled with machine-learning models of specific port operations or processes (e.g., unloading general cargo from a ship or transporting non-containerized cargo within the port). The digital twin will be the core of the decision-making solution. The solution will consist of a set of decision support and monitoring tools based on the digital twin. Each of these tools will address one of the following "use cases" for the decision-making solution:

Port Call Optimization - The digital twin solution will enable the optimization of port calls by providing estimations of the time and resources needed to load and unload cargo. The predictions will facilitate the identification and selection of optimal courses of action, such as: 1) suggest a time of arrival to a given ship to minimize its idle time at a berth and save fuel on its journey to the port. 2) Suggest a time of arrival to a given ship to minimize the likelihood of delays in port operations.

Enhanced Port call monitoring – The digital twin solution will enable the enhanced monitoring of port calls by continuously providing estimates of the expected time a given resource will be occupied and highlighting possible conflicts in resource allocation due to delays. The estimations and conflict highlighting will facilitate the prevention and handling of delays through measures such as: 1) Allocating more resources to load/unload the cargo. 2) Planning of alternative resources for upcoming port calls.

3.3 Model description

Figure 2 presents the event graph as one component of the mathematical model in accordance with Figure 1, depicting the typical operation workflow at the multi-purpose port. Four key events are captured: "Waiting," "Attempting to Start Operation," "Start Operation," and "Finish Operation." The "Waiting" event simulates how the port calls have been generated and joins the waiting queue. We use V to denote the set of port calls and v to denote a specific port call. A port call v is created when a vessel arrives at the port and contains crucial details about the associated vessel, as well as information on the cargo carry profile and available resource profiles. The cargo carry profile for each port call v contains information on the quantities that need to be processed for each type of cargo. Resource profiles refer to the different combinations of resources that can be used to process a port call.

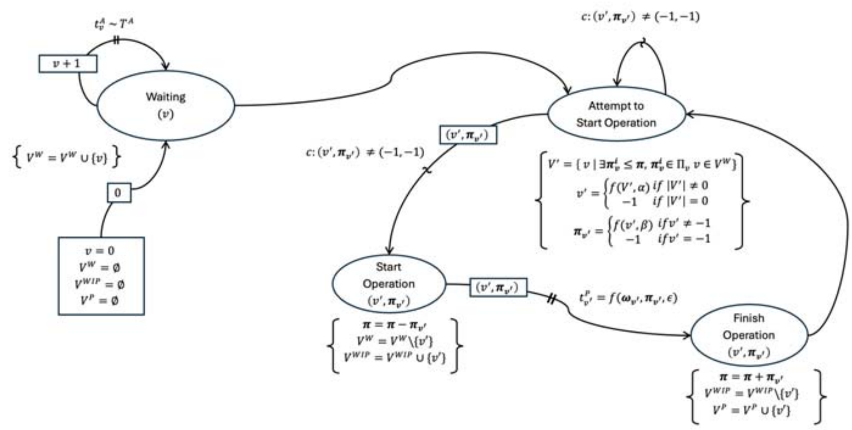

Figure 2. Event graph for the typical operations in a multipurpose port.

- **Cargo Carry Profile**: For a given port call v, we use $\boldsymbol{\omega_v}$ to denote its cargo carry profile. It is encoded as a vector with the size of $|H|$ whose h-th element represents the quantity of cargo that needs to be processed belonging to the cargo type h, i.e., $\boldsymbol{\omega_v} = \left[\omega_v^1, \dots, \omega_v^h, \dots \omega_v^{|H|}\right]$. Here, H is the set for cargo types and h represents a specific cargo type, i.e., $h \in H$.
- **Resource Profile**: For a given port call v, we use n_v to represent the number of resource profiles available, and define Π_v as the collection of all available resource profiles, denoted as $\Pi_v = \{\boldsymbol{\pi_v^i} \mid i = 1, \dots, n_v\}$, where π_v^i is the i-th resource profile. Each resource profile π_v^i is encoded as a vector with the size of $|R|$, with the r-th element representing the required quantity for the resource type r, i.e., $\boldsymbol{\pi_v^i} = \left[\pi_v^{i,1}, \dots, \pi_v^{i,r}, \dots \pi_v^{i,|R|}\right]$. Here, R is the set of resource types and r represents a specific resource type, i.e., $r \in R$. Additionally, we use $\boldsymbol{\pi} = \left[\pi^1, \dots, \pi^r, \dots, \pi^{|R|}\right]$ to denote the resource availability, where π^r represents the quantity that is currently available for the resource type r.

Once a port call v is generated, it promptly joins the queue of the port call waiting list V^W, i.e., $V^W = V^W \cup \{v\}$, and the subsequent port call $v+1$ is scheduled according to the provided interarrival time t_v^A.

The "Attempt to Start Operation" event examines each port call in the waiting list and selects one to trigger the next "Start Operation" event. For a given port call v and one of its resource profiles $\boldsymbol{\pi_v^i}$, the profile is deemed feasible if and only if the requested quantity for each resource type is less than or equal to the currently available quantity, i.e., $\pi_v^{i,r} \leq \pi^r$ for all $r \in R$. We abuse the notation $\leq$ and use it to compare between either scalars or vectors. Therefore, we can simply describe such a relationship as $\boldsymbol{\pi_v^i} \leq \boldsymbol{\pi}$. The collection of feasible resource profiles of a given port call v is denoted as Π'_v, i.e., $\Pi'_v = \{\boldsymbol{\pi_v^i} | \boldsymbol{\pi_v^i} \leq \boldsymbol{\pi}, \boldsymbol{\pi_v^i} \in \Pi_v\}$. A port call v is considered feasible for operation if there exists at least one resource profile π_v^i that can be fulfilled by current resource availability, i.e., $\Pi'_v \neq \emptyset$.

We denote all feasible port calls as V', where $V' = \{ v \mid \Pi'_v \neq \emptyset,\ v \in V^W \} = \{ v \mid \exists \boldsymbol{\pi_v^i} \leq \boldsymbol{\pi},\ \boldsymbol{\pi_v^i} \in \Pi_v,\ v \in V^W\}$. If V' is not empty, a port call $v' \in V'$ and an associated resource profile

Table 1. The notations for the multi-purpose port simulation model

Inputs	Parameters
V	The port calls set.
v	A port call, i.e., $v,\ v' \in V$.
R	The resource types set.
r	A resource type, i.e., $r \in R$.
H	The cargo types set.
h	A cargo type, i.e., $h \in H$.
Π_v	The set of available resource profiles for port call v, $\Pi_v = \{\boldsymbol{\pi}_v^i \mid i = 1, \ \dots, n_v\}$, where π_v^i is the i-th resource profile and n_v is the cardinality of the collection Π_v.
$\boldsymbol{\pi}_v^i$	(Vector) The i-th resource profile for port call v, $\boldsymbol{\pi}_v^i = \left[\pi_v^{i,1}, \ \dots, \ \pi_v^{i,r}, \ \dots \pi_v^{i,\lvert R\rvert}\right]$
$\pi_v^{i,r}$	The r-th element of $\boldsymbol{\pi}_v^i$, representing the number of quantities required by the resource r for the i-th resource profile of the port call v
$\boldsymbol{\omega}_v$	(Vector) The cargo carry profile for the port call v, $\boldsymbol{\omega}_v = \left[\omega_v^1, \ \dots, \ \omega_v^h, \ \dots \omega_v^{\lvert H\rvert}\right]$
ω_v^h	The h-th element of $\boldsymbol{\omega}_v$, representing the quantity of cargo that needs to be processed at the port for the cargo type h
t_v^A	The time delay between port calls v and $v+1$ arrivals
α	The strategy used to prioritize which port call should be operated next.
β	The strategy used to prioritize which resource profile should be used for a specific port call.
ϵ	The noise for the operation time.

$\boldsymbol{\pi}_{v'} \in \Pi_{v'}$ can be selected according to the selection strategies α and β, respectively, which can be modified based on actual operations requirements. After that, the selected pair of $(v', \boldsymbol{\pi}_{v'})$, if it exists, is sent to the "Start Operation" event. The "Attempt to Start Operation" event will continue to trigger itself until it can no longer find a valid pair $(v', \boldsymbol{\pi}_{v'})$, minimizing the possible idle time of resources.

In the "Start Operation" event, resources are allocated to the port call according to the selection of $(v', \boldsymbol{\pi}_{v'})$, and resource availability is updated as $\boldsymbol{\pi} = \boldsymbol{\pi} - \boldsymbol{\pi}_{v'}$. Then, the port call v' is removed from the port call waiting list V^W and added to the port call processing list V^{WIP}, i.e., $V^W = V^W \backslash \{v'\}$ and $V^{WIP} = V^{WIP} \cup \{v'\}$. The processing time for the selected port call v', denoted as $t_{v'}^p$, is a function of the cargo carry profile for the port call v' $(\boldsymbol{\omega}_{v'})$, the selected resource profile $(\boldsymbol{\pi}_{v'})$, and the noise (ϵ), i.e., $t_{v'}^P = f(\boldsymbol{\omega}_{v'}, \ \boldsymbol{\pi}_{v'}, \ \epsilon)$.
The "Finish Operation" event is scheduled to occur after the timespan $t_{v'}^p$. The "Finish Operation" event signifies the completion of the port call operation. Once triggered, the port call processing list V^{WIP} and processed list V^P are updated as $V^{WIP} = V^{WIP} \backslash \{v'\}$ and $V^P = V^P \cup \{v'\}$ accordingly. The allocated resources are then released and updated, i.e., $\boldsymbol{\pi} = \boldsymbol{\pi} + \boldsymbol{\pi}_{v'}$.

Consequently, it is necessary to re-examine for any feasible pending port calls awaiting operation and trigger the "Attempt to Start Operation" event if any.

Table 2. Definition of state variables.

Variables	States variables
$\boldsymbol{\pi}$	(Vector) The number of resources available, $\boldsymbol{\pi} = [\pi^1, \ldots, \pi^r, \ldots, \pi^{\|R\|}]$
π^r	The r-th element of $\boldsymbol{\pi}$, representing the number of resources available for the resource type r
V^W	The set of port calls waiting for operation.
V^{WIP}	The set of port calls is currently being operated.
V^P	The set of port calls has been processed.
V'	The set of port calls feasible for being operated $V' = \{ v \mid \exists \boldsymbol{\pi}_v^i \leq \boldsymbol{\pi},\ \boldsymbol{\pi}_v^i \in \Pi_v,\ v \in V^W \}$.
v'	The port call is selected according to the selection strategy α and sent for operation if V' is not empty; otherwise, $v' = -1$, i.e., $v' = \begin{cases} f(V', \alpha) & if\ \|V'\| \neq 0 \\ -1 & if\ \|V'\| = 0 \end{cases}$
$\boldsymbol{\pi}_{v'}$	The resource profile is selected according to the selection strategy β for the selected port call v' if $v' \neq -1$ is not empty; otherwise, $\pi' = -1$, i.e., $\boldsymbol{\pi}_{v'} = \begin{cases} f(v', \beta) & if v' \neq -1 \\ -1 & if v' = -1 \end{cases}$
$t_{v'}^P$	The operating time for the selected port call v', where $t_{v'}^P = f(\boldsymbol{\omega}_{v'}, \boldsymbol{\pi}_{v'}, \epsilon)$.

4. Initial results

So far, the project has focused on generating the foundations for the digital twin. This process entails gathering and examining a variety of data sets. Some data were easily accessible, while certain assumptions were necessary for other data sets. The experiences accumulated thus far pertaining to the different facets of a digital twin are summarized in Table 3 and depicted in Figure 1.

Table 3. The quest to derive enough basis for running the model. In the table below we derive some experiences related to the categories associated to a digital twin depicted in figure 1

Category	Experience and concerns
Data lakes	Some historical data sets, such as data on arrivals and departures of ships and the type of ship, have been easy to acquire, while assumptions have been necessary for other historical data sets, such as the type and quantity of goods connected to a specific port call and resource profiles, e.g., output from different resources, the type of different operations resources can execute, and the rate they can operate at.
Mathematical models	Development of the mathematical model described in section 3.3 is the result of an iterative process of representing the objects, and their relations, and attributes of concern to direct attention towards the problem focused.
Data streams	Experiences from this task has not yet been gained, but the mathematical model and experiences from deriving data from existing data lakes guides us on the necessary requirements for data sets to continuously feed the digital twin.
Situational parameters	Situational parameters capture the specifics of operations constituting the practice of Kvarken Ports Umeå. During the collaborative meetings between NUS, RISE, and Kvarken Ports Umeå, a series of questions was raised to understand the necessary adoptions and variations to be reflected in the emerging mathematical model and the requirements for data. Examples of such questions are: What operations are directly managed by the port? Can you outline the port's operational model and workflow? What data or metrics do Kvarken Ports use for planning?

5. Conclusion and further work

The implementation of digital twin technology in multi-purpose ports shows significant potential and opens a world of possibilities for enhancing operational efficiency, decision-making, and resource optimization. Digital twins can be modeled in complex port settings and used to provide shared situational awareness among stakeholders. This means all port actors can make more informed decisions and optimize operations based on the overall system status. This approach enables ports to act as decision-makers in multi-organizational settings, facilitating proactive planning and optimizing current and future resources.

Initial learnings on how to coordinate and collaborate in a digital twin project includes the importance of generating a shared cognitive framework through iterations between actors with deep model competence and contextual understanding. This includes both gaining insights into the functionality of the model and the specific operational conditions in the port. In this project, important activities to facilitate generation of such a shared cognitive framework included the identification of use cases, evaluation of the feasibility and potential value from the associated design, regular follow up meetings to discuss obstacles during development, and data harmonization.

Our future work will be marked by a clear focus on several key areas. We aim to build on the initial success of this project by expanding the use cases of digital twin technology in ports and delving into more advanced applications. This will include predictive maintenance, infrastructure investment decisions, and long-term strategic planning. The project will continue to develop and test additional use cases beyond the initial port call optimization, covering other aspects such as predictive maintenance, infrastructure investment decisions, and long-term strategic planning. The project will explore integrating digital twin technology with data sources from the port, such as a resource and planning module planned to be implemented in the port. The project will continue to explore and integrate with other emerging technologies, such as artificial intelligence and the Internet of Things, to enhance data accuracy, security, and real-time decision-making capabilities. Furthermore, the project will investigate the digital twin model's scalability to other ports with different operational characteristics and requirements. This includes adapting the model to handle larger data sets and more complex scenarios.

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Appendix A: Model Input format

The simulation model has been developed employing the Object-Oriented Discrete Event Simulation (O2DES) framework, implemented using Python. Li et al. (2016) introduced the O2DES simulation framework, which offers a structured environment conducive to the efficient development of discrete event simulation models. A sample of the model input is presented in Table 4:

Table 4. The input data sample for the simulation model

Port Call S/N	Interarrival Time (in days)	Cargo Profile (Type)	Cargo Profile (Qty)	Resource Profiles (Type)	Resource Profiles (Qty)
(A)	(B)	(C)	(D)	(E)	(F)
1	0	[7, 8]	[200, 300]	[[1, 2, 3], [4, 5]]	[[10, 20, 30], [40, 50]]
2	2	[2, 5, 9]	[100, 100, 100]	[[3, 6], [7], [8]]	[[15, 15], [20], [30]]
……					

Column is the series number of the port calls, while Column (B) denotes the timespan (in days) between two successive port calls. It's noteworthy that the time unit can vary, including options such as minutes, hours, weeks, and so forth. Columns (C) and (D) present the cargo carry profile for each port call. Specifically, Column (C) delineates the cargo type, while Column (D) specifies the corresponding cargo quantity required to be processed. Columns (E) and (F) detail the available resource profiles. In Column (E), the resource types needed to process the port call are provided, while Column (F) specifies the quantity of each resource type required at the port. Here, we use the Example 1 to illustrate this format. The first port call is created at the beginning of the model as the interarrival time for the first port call has a value of zero. The second port call is generated 2 days later as the interarrival time for the second port call has a value of two. The first port call contains two types of cargo: Cargo Type 7 and 8, with the quantity of 200 and 300 units, respectively. To process this port call, there are two available resource profiles: (1). Resource Types 1, 2, and 3 with quantities 10, 20, and 30, respectively, or (2) Resource Types 4 and 5 with quantities 40 and 50, respectively. The reason we are using this input data format is to enhance computational efficiency and reduce memory consumption within our model.