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Using Digital twins for the future development of the port of Vaasa

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ABSTRACT:

Digitalization and sustainability in ports have become more significant recently because of increasing operational complexity, environmental considerations, and energy transition. Terms such as smart ports, digital twins, renewable energy use, and sector coupling play an increasingly significant part in enhancing the efficiency and sustainability of operations and decisions in port infrastructures. This thesis is concerned with the potential application of digital twin technology in developing future smart ports. Specifically, the possibilities of including energy functions and sector coupling ideas into the digital twin environment are considered.

The thesis study includes a literature review and the actual development of a digital twin prototype for the Port of Vaasa. In the theoretical background, topics related to smart ports, digital twins, renewable energy sources, Power-to-X solutions, and sector coupling were examined. Based on the theoretical background, a web-based digital twin prototype was designed using CesiumJS and a variety of other tools.

The developed prototype includes functionalities such as 3D visualization, land use layers, context information, port statistics, weather integration using external APIs, and scenario creation for energy usage. This prototype illustrates how digital twins can help visualize the port situation, increase situational awareness, and even make decisions, while keeping flexibility and accessibility through the utilization of open-source tools.

Based on the findings, it can be concluded that digital twins have a lot of potential to be used for the future development of smart ports. This is related to data integration and the increased understanding of operations and energy planning within the ports. Moreover, by integrating sector coupling ideas into port digital twins, the future of ports becomes clear, as ports will serve as more than logistical centers, but also as parts of energy systems in the future.

KEYWORDS: Digital twins, Sustainable development, Smart ports, Energy, Sector Coupling, Data

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1 Introduction

Ports are undergoing a major transformation due to digitalization, automation, sustainability objectives, and the shift towards renewable energies. Historically, ports were considered logistics and cargo-handling facilities. However, operational difficulties, increased regulation regarding environmental protection, and the integration of renewable energy facilities have started to change the roles of ports to make them become more interconnected, intelligent, and energy-related systems. Smart ports, digital twins, and sector coupling are among the concepts that play a crucial role in achieving this goal.

Over the past decade, digitalization has changed ports from isolated cargo terminals to connected digital environments. Contemporary ports are an integration of devices, systems, and stakeholders, which enables decision-making in real time. This process improves the efficiency of port operations, minimizes environmental effects, and increases economic performance. At the same time, the growing dependence of ports on digitalization creates new challenges, especially in the field of cybersecurity. The development of smart ports has incorporated this aspect as one of its core elements (World Bank, 2025).

The Digital Twin (DT) technology is a key enabling technologies in such a transformation. In the port environment, digital twins have the potential to increase situational awareness, optimize operation planning, improve predictive maintenance, and increase energy efficiency. Simultaneously, with increasing electrification of ports, new energy supply models based on renewables also pose a challenge requiring flexible management solutions.

This thesis examines the connection between smart ports, digital twin technology, and sector coupling, with the focus on developing a versatile digital twin prototype for the Port of Vaasa. It aims to understand how digital twins can assist in the future development of smart ports, especially when it comes to energy usage and scenario planning.

The primary aim of this thesis is the creation and presentation of an adaptable digital twin prototype, which would be able to combine contextual, operational, and energy-related data in a web-based setting. Furthermore, the research intends to analyze how digital twin technology, as well as sector coupling, may contribute to future smart ports.

The research will be carried out based on the following research questions:

- How can digital twin technologies support the development of future smart ports?
- How can sector coupling concepts be integrated into port-related digital twin environments?
- What capabilities can a flexible digital twin prototype provide for the Port of Vaasa?

This thesis deals with the theoretical and practical aspects related to the concept and development of a digital twin. Limited access to real-time data and integration into the physical infrastructure mean that the prototype is merely an illustration of visualization, data integration, and analysis functionalities to be developed in future smart port projects. Nevertheless, it creates a valuable basis for further development, showing how the technology of digital twins can help create better-connected and greener port ecosystems. The first part of the thesis is dedicated to theoretical foundations such as smart ports, digital twins, renewable energy, power-to-X, and sector coupling. Then, the methodology used in the research and prototype development is discussed, and finally, the results and conclusions of the project are provided, together with the roadmap for further development at Port of Vaasa.

Note: Generative AI tools (ChatGPT) were used during the process to support language refinement, text structuring, and editing. The author reviewed and validated all final content.

2 Literature Review and Theoretical Background

This section is dedicated to the presentation of the theoretical framework of this thesis. The main concepts are threefold: smart ports, digital twins, and sector coupling, which are the main pillars of this research. This section aims to gain a comprehensive understanding of each concept separately and to understand the link between each concept, as related to this particular project. These main concepts are meant to help clearly define the problem, as well as lay a strong groundwork for further research and solution development.

2.1 Smart ports

2.1.1 Definitions and Evolution of Smart Ports

Ports are essential infrastructure components of the global economy, as they process approximately 80% of international shipments. Historically, ports have been primarily engaged in handling shipments and providing sea transport services. However, they are currently undergoing a radical metamorphosis due to the influence of digital technology. This is creating a new wave of change in the interfaces of maritime, ground, and air transport, which are becoming less reliant on human interaction, faster, and more environmentally friendly. This is not only a means of improving efficiency but also a form of digital transformation (Paraskevas et al., 2024).

Moreover, ports can differ in their dimensions and roles, ranging from simple piers serving one ship to large and multifunctional port complexes that combine terminals, industries, and logistics services. Similarly, the literature indicates that ports can be considered as waterfronts, interfaces for multiple modes of transport, logistics centers, gateways, industrial centers, or trading centers. However, it is worth noting that ports can be considered not only as seaports but also as nodes that can assist in the flow of goods (Bichou & Gray, 2005). From the public policy viewpoint, it is clear that ports can be considered as economic growth centers.

The process of digital transformation in ports has been incremental. The initial stages of digitalization involved the internal efficiency of the port, including email communication, booking systems, and invoicing systems (level one). Subsequently, as the need for integration arose, internal systems were linked to provide support for internal port operations (level two). The launch of Enterprise Resource Planning (ERP) systems in the 1980s, with the pioneering role of SAP, contributed to the development of Terminal Operating Systems (TOS), integrating data systems in the operation of the terminals (Heilig et al., 2017). The incremental process has therefore laid the groundwork for the higher stages of port automation.

The concept of the "smart port," which was first introduced in 2011, is an expansion of this digital evolution, using advanced technology to improve efficiency, transparency, and interactivity in port services (Paraskevas et al., 2024; Bichou & Gray, 2005). In keeping with the ideals of Industry 4.0, smart ports do not simply aim to automate individual processes but to optimize the entire chain of logistics, including terminal operators, shipping companies, railways, trucking firms, etc. Automation is the starting point, but the ultimate goal is to develop flexible, reliable, and predictable transportation centers to deal with increasing complexity in the chain of logistics.

Nevertheless, the meaning of the term smart port is still debatable. According to Triska et al. (2022), the term "smart" is sometimes used to mean technologies, sometimes to mean aspirations for the future, and sometimes to mean defining attributes. Such ambiguity in the meaning of the term smart port is due to the dynamic development of both digital technologies and ports in general. Generally speaking, the smart port is defined as "a technologically advanced port that utilizes the powers of automation and digital technologies to improve the port’s performance, sustainability, and robustness" (Kosek et al., 2025).

More specifically, port smartization can be defined as the integration of various technologies such as the Internet of Things (IoT), cloud computing, big data analytics, and intelligent sensing systems to enhance efficiency and sustainability (Zhang et al., 2024). Such technologies enable real-time data accessibility, process optimization, energy efficiency enhancement, and reduced emissions. Examples of such applications include automated guided vehicles (AGVs), smart vessel traffic management, and smart container terminal automation.

However, technology alone is not sufficient to make a port smart; smart ports also have to be governed, collaborated, and integrated in terms of ecosystems. To achieve this, shipping companies, terminal operators, logistics providers, local communities, organizational change, personnel, and strategic planning are also required for effective change (Fundación Valenciaport, 2020). In this context, the smart port is not simply a technological upgrade but a complete change of the entire value chain of the port.

Fundación Valenciaport (2020) describes this evolution as the move through four stages of digital maturity, from the digitalization of each company to the integration between key players at the port level, to the port community systems that facilitate the sharing of data between the logistics system as a whole, to the hyperconnected port. Here, the advanced technologies such as IoT, AI, blockchain, and digital twin are used to integrate the entire ecosystem. Although this is where the major gains in terms of efficiency and sustainability are achieved, it is also where the most complicated coordination, as well as the highest level of investment, is required (see Figure 1 and Table 1).

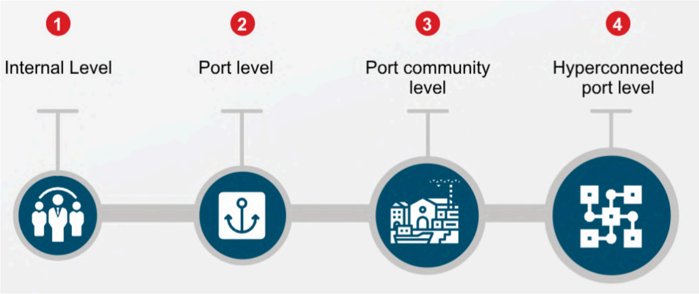


Figure 1. Levels of Digital Transformation into a Smart Port (Fundación Valenciaport, 2020, p.9).

Table 1. Levels of Port Digitalization and Integration (Fundación Valenciaport, 2020).

Digitalization Level	**Scope & Focus**	**Key Features / Technologies**	**Challenges / Notes**
Internal Level	Individual port organizations	Investments in information systems, standardized procedures, and digital tools to improve efficiency and reduce costs	Manual and paper-based interactions with external stakeholders may persist
Port Level	key port actors	Electronic systems, single-window platforms, digital documentation, scheduling, and regulatory streamlining	Requires coordination across multiple organizations
Port Community Level	Entire logistics ecosystem	Port Community Systems (PCS), shared data platforms, reduced silos, coordinated operations	Integration depends on stakeholder engagement and data sharing
Hyperconnected Port Level	Full ecosystem integration	IoT, big data, AI, blockchain, digital twins; integration of people, infrastructure, and systems	Implementation complexity requires advanced technology adoption and global supply chain alignment.

2.1.2 Technologies and Digital Transformation in Ports

Ports carry out a variety of activities related to each other, which can be broadly classified into two main areas: ships and cargo. Ship-related activities include maritime activities such as dredging, pilotage, mooring, berth allocation, maintenance, and bunkering. On the other hand, cargo-related activities occur at the ship-shore interface, such as loading, unloading, stowing, and landside activities such as storage, consolidation, and distribution in container freight stations. Additionally, cross-cutting activities such as customs inspection and health inspection act as links between ships and cargoes, while inland logistics sometimes go beyond the confines of the ports to dry ports/depositories (Bichou & Gray, 2005).

The role of port authorities and terminal operators in the digital transformation is different but complementary. Port authorities are generally the orchestrators of digital ecosystems in ports through the development of platforms such as the Port Community System (PCS), the deployment of IoT-based infrastructures, and the facilitation of data exchange between different stakeholders. Terminal operators, on the other hand, are concerned with operational technologies in ports through the development of automation systems such as automated stacking cranes (ASC), automated guided vehicles (AGV), as well as remote-controlled quay cranes. IoT sensors are also used in cranes, trucks, and gates for tracking and maintenance (Li et al., 2025).

This is a strategic decision in the sense that the selection of smart technologies has a direct bearing on the quality of service, efficiency, and the overall financial performance of the port. The smart technologies involved in the port range from relatively simple systems like RFID tracking systems to more sophisticated systems like AI-based traffic management systems. Though the relatively simple systems offer cost benefits as well as easier implementation, the more advanced systems offer higher productivity benefits but demand huge capital costs in the process (Li et al., 2025).

In terms of digital technology, Port Community Systems (PCS) are considered to be the foundation of digitalization within ports. A Port Community System (PCS) refers to "a digital infrastructure allowing for seamless information exchange between shippers, carriers, terminals, freight forwarders, customs, and other regulatory bodies." The advantages of a Port Community System are considered to be the reduction of costs by eliminating redundant data input, improved efficiency through better planning and reduced idle time, better compliance by improving traceability, improved operations by enhancing cargo tracking and clearance procedures, trade facilitation by incorporating single windows, and promoting innovations and sustainability (Ollivier et al., 2024).

The exchange of information is vital because the process of cargo movement is characterized by interrelated processes, including hinterland transport, terminal handling, and maritime navigation, as presented in Figure 2. This facilitates the real-time exchange of data, which improves the identification of bottlenecks. An example of the application of the exchange of information is the optimization of the call process at the ports, which aims to improve coordination, facilitate just-in-time operations, and reduce time spent at the terminals. Global initiatives aimed at promoting standardized digital platforms are enhancing the exchange of information among the global port community, as presented in Ollivier et al. (2024).

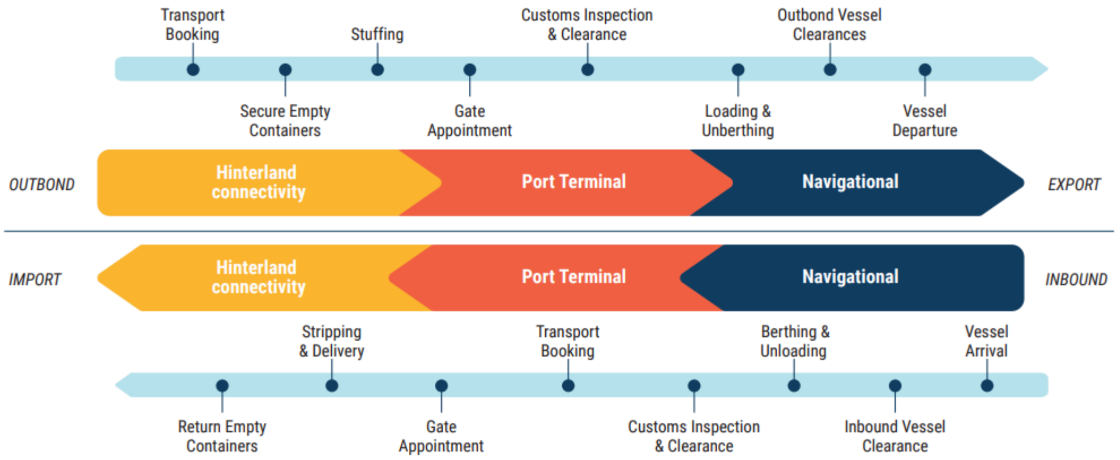


Figure 2.Typical port flows and services (Ollivier et al., 2024).

Digitalization brings substantial benefits, including improved efficiency, cost reductions, better resource utilization, enhanced security, and stronger knowledge management (World Bank, 2025; see Table 2). Automated handling systems, IoT-based monitoring, predictive analytics, and digital documentation reduce congestion, optimize fuel and equipment usage, and streamline customs processes. At the same time, significant challenges remain (see Table 3). These include cybersecurity threats, high initial investment costs, organizational resistance, workforce reskilling needs, system compatibility issues, regulatory complexity, and concerns regarding long-term social and environmental impacts (World Bank, 2025).

Table 2. Key Benefits of Port Digitalization (World Bank, 2025).

Category	Benefits
Improved efficiency Of port operations	• Automated cargo handling, navigation, and vessel management. • Increased productivity, reduced congestion, and faster turnaround times. • Optimized port calls with Just-in-Time vessel arrivals.
Cost reduction & environmental sustainability	• Data-driven decision-making with predictive analytics.• Optimized fuel use, cargo handling, and equipment management.

Better resource utilization	• Real-time monitoring in ships, cranes, and ports using IoT sensors. • Predictive maintenance and improved safety protocols. • Automated tracking for personnel and assets.
Knowledge management	• Streamlined customs and logistics with digital documentation. • Reduced administrative burdens and increased trade traceability.
Digital communication & connectivity	• Real-time tracking and ship-to-shore coordination. • Advanced satellite communication for seamless data exchange.
Enhanced security	• Access control, digital permission management, and 24/7 port surveillance. • Smart gates improve port security.

Table 3. Key Challenges of Port Digitalization (World Bank, 2025).

Category	Challenges
Cybersecurity & data protection	• Impacts of cyberattacks (ransomware, phishing, data breaches). • Need for robust security frameworks and data integrity measures.
Financial & investment barriers	• High initial costs and concerns over Return on Investment (ROI). • Importance of public-private partnerships for funding.
Workforce & organizational adaptation	• Need to upskill workers for digital technologies such as AI. • Resistance to change and need for management adaptation.
Technology integration & compliance	• Compatibility issues between old and new systems. • Challenges in navigating international regulations and data protection laws.
Sustainability & long-term impact	• Balancing efficiency with environmental and social responsibility. • Addressing potential job displacement due to automation.

The change from conventional to modern port operations shows the extent of change (Table 4). Conventional ports are characterized by manual operations and paper-based documentation, and decision-making by experience. On the other hand, digitalized ports are characterized by the use of technology and AI to perform operations and make decisions. In addition, modern ports extend the safety dimension to cover cybersecurity and sustainability to cover resource optimization and reduction of emissions (World Bank, 2025).

Table 4. Conventional port operations vs. current demand (World Bank, 2025).

Aspect	Conventional Port Operations	Modern Port Operations
Process	Mostly manual, labor-intensive tasks	Automated processes, minimal manual effort
Technology	Paper-based, face-to-face communication	AI, IoT, blockchain, cloud-based, autonomous systems
Efficiency	Subject to delays and bottlenecks	Streamlined, reduced delays, optimized management
Decision-making	Based on human experience	Data-driven analytics guide decisions
Connectivity	Local/regional focus	Globally integrated, part of a connected supply chain
Safety	Physical safety only	Includes cybersecurity, remote monitoring, and automated security
Sustainability	Limited, higher emissions	Sustainable operations with resource efficiency
Resource Management	Conventional, no real-time tracking	Real-time tracking and analytics optimize resources
Global Role	Siloed stakeholders	Fully integrated in global supply chains

In view of this complexity, the digital transformation process must therefore be executed in a strategic and step-by-step manner. Based on the World Bank (2025), the development of ports would generally involve short-term, medium-term, and long-term strategies (see Table 5). Short-term strategies would involve the development of digital infrastructure, regulatory requirements, and cybersecurity. Medium-term strategies would concentrate on operational optimization, Port Community Systems, and port call optimization. Long-term strategies would target the complete transformation of ports to smart ports through the integration of cutting-edge technologies like IoT, AI, and blockchain, ultimately establishing a completely interconnected and sustainable port ecosystem.

Table 5. Phased Digital Transformation Measures for Ports (World Bank, 2025).

Time Horizon	Focus Areas	Key Measures
Short-term (0–2 years)	Digital foundations, regulatory compliance, and cybersecurity	• Implement a Maritime Single Window (MSW) for efficient information exchange • Establish robust cybersecurity frameworks • Prioritize scalable, secure digital infrastructure
Medium-term (2–5 years)	Operational efficiency, supply chain resilience	• Introduce Port Community Systems (PCS) and Port Management Systems (PMS) • Adopt Port Call Optimization practices such as Just-in-Time (JIT) arrivals • Strengthen coordination and data sharing across the port ecosystem
Long-term (5+ years)	Smart port transformation, cross-sector integration	• Integrate advanced technologies (IoT, AI, blockchain) and automation • Create a fully interconnected, sustainable port ecosystem • Align operations with national and global digital strategies

2.1.3 Strategy and Sustainability in Smart Ports

Beyond digital transformation, sustainability has emerged as a critical factor in determining the competitiveness of a port. Environmental sustainability is no longer a choice but has become a part of the overall strategic positioning of a port. This is due to the fact that green strategies such as mitigating carbon emissions, adopting renewable energy sources, and adhering to international environmental agreements have become imperative in the current maritime environment (Lam & Li, 2019; Raimbault, 2019, as cited in Nguyen et al., 2026). Furthermore, investments in energy-efficient technology have a dual positive impact on the competitiveness of a shipping alliance that has adopted sustainability strategies in line with ESG reporting (Boullauazan et al., 2023; Eom et al., 2023; Tang & Wang, 2025, as cited in Nguyen et al., 2026).

The strategic planning of ports is the context in which digitalization and sustainability strategies are combined. As Notteboom et al. (2022) state, port planning is not a one-off activity but a dynamic process that reacts to technological change, market uncertainty, and policy pressure. Port planning may cover the whole port system (for example, through master planning) or concentrate on particular terminals and operational zones. Significantly, port authorities differentiate between three planning horizons.

Short-term planning primarily focuses on the optimization of existing resources, which is usually for the operational period (one year) and the tactical period (one to three years), with no significant structural infrastructure improvements. Medium-term planning includes the financial dimension combined with the strategic dimension, which is usually achieved through the formulation of business plans and strategic plans for a period of three to five years. This helps in improving competitiveness through budget allocations, market positions, etc. Long-term planning includes master plans for infrastructure improvements, technological improvements, sustainability improvements, etc., which are usually aligned with economic and environmental objectives (Notteboom et al., 2022).

The different governance models used affect the way these plans are developed. Three different planning models may be distinguished (Notteboom et al., 2022). Top-down planning is mostly based on the initiative of the government or the port authority. Bottom-up planning is based on input from the port community. The hybrid approach is a combination of both. Goals are set top-down, while plans are developed in cooperation with the port community. This approach is important to ensure that there is an alignment between macro-level economic goals and the micro-level operational needs. More recently, the strategic planning process may also take network considerations into account. Some activities may be performed more efficiently in the network than in the port itself.

In the aforementioned governance framework, the process of strategic development in the port industry normally follows a five-phase model, as discussed in Notteboom et al. (2022) and presented in Figure 3. In the first phase, the formulation of a well-defined vision is necessary, where the vision is integrated with economic, social, and environmental considerations. This ensures that the process is not incremental.

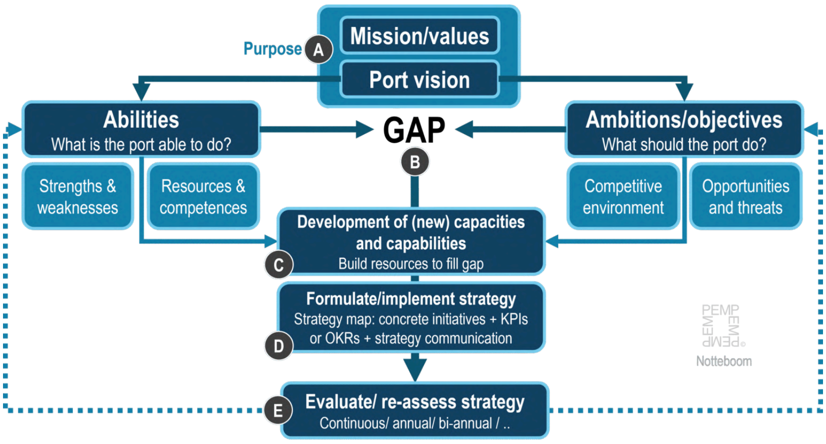


Figure 3.The strategic port planning process (Notteboom et al., 2022).

The second phase involves the assessment of the gap that exists between the current and future capabilities. This entails the evaluation of internal strengths and weaknesses as well as the assessment of opportunities and threats that the organization might face in the future. Analytical tools that can be used in this phase include PESTEL analysis, Porter’s Five-Force Analysis, and benchmarking.

The third phase is about the creation of resources as well as the development of capabilities. There is a need for the port to develop its financial capital, technological base, human expertise, and organizational processes in order to bridge the gap. Integration of resources improves efficiency in port operations.

The fourth phase involves the translation of vision and resources into strategies that are actionable. The process of strategy formulation entails utilizing an organization's competencies in a manner that addresses both environmental and competitive issues. The implementation of strategies entails aligning an organization's systems of governance, investment, and performance management, often in relation to KPIs and objective-setting systems.

Finally, continuous evaluation will help to ensure that all actions taken are still aligned with the long-term goals. By monitoring performance outcomes and making adjustments to strategies as necessary to respond to changes in technology, regulation, and/or market conditions, greater adaptability and competitiveness will be achieved.

Overall, strategy and sustainability are deeply intertwined within smart port development. Digital technologies enable efficiency and emission reductions, but strategic planning ensures that these innovations are embedded within long-term economic, environmental, and social objectives. A smart port, therefore, is not only digitally advanced but strategically governed and sustainability-oriented.

2.2 Digital Twins

2.2.1 Concept and Theoretical Foundations of Digital Twins

The concept of the Digital Twin (DT) emerged from the convergence of modeling and simulation methodologies with contemporary information and communication technologies. The DT idea was first introduced in 2002 at the University of Michigan by Michael Grieves, even though the underlying logic dates back further than the term itself (Grieves & Vickers, 2017; Homayouni et al., 2025). The fundamental idea behind the DT is the creation of a virtual replica of a physical object or system that is always connected to the real-world object or system through bidirectional data flows. This connection between the physical and the digital is dynamic in nature (Li et al., 2024).

This is unlike static simulations or 3D models, which cannot be replicated using real-time data, computational models, or analytics to mimic the state of a physical system. By using Industrial Internet of Things (IIoT) technologies, sensors, data flows, and algorithms, a digital twin can be created, which is dynamic in nature and not only capable of showing the current state of a system but also its future state. This can be achieved using the integration of historical and real-time data for predictive maintenance, optimization, or decision-making (Li et al., 2024).

A commonly cited definition of a DT is provided by IBM (n.d.) as “a virtual representation of a physical object or system that uses real-time data to simulate and mirror its behavior, performance, and operating conditions.” The key factor is that DTs cover the entire lifecycle of an asset, from its initial design and production to its eventual retirement. The key characteristic of a DT is that it involves a constant interchange of data that allows the DT and reality to mirror each other. DTs can operate on various levels of granularity, such as a component, asset, system, or process level.

Despite the changes in terminology, the core framework of the Digital Twin has remained the same since its inception. According to Grieves and Vickers (2017), the Digital Twin can be defined as a “complete digital information model that exists simultaneously with a physical system as a separate but integrated entity.” Their original model, introduced in 2002 with the title “Conceptual Ideal for PLM,” already contained the three core components of the Digital Twin: the physical space, the virtual space, and the data flow between the two. The basic assumption is that all information available from the physical system must also be available from the digital system.

To better understand the structure of the digital twin, Grieves & Vickers (2017) proposed the distinction between the Digital Twin Prototype (DTP), the Digital Twin Instance (DTI), and the Digital Twin Environment (DTE). The Digital Twin Prototype is the design phase of the digital twin, where all the information necessary to develop the physical product is incorporated. On the other hand, the Digital Twin Instance is related to the physical object throughout its life cycle. It is always in connection with the physical object, including information about the object in real time. Both the DTP and the DTI operate in the Digital Twin Environment, where data from multiple digital twins can be aggregated in order to perform predictive analytics, probability of failure assessment, and strategic decision support.

In the past, the basic notion or idea of relating a physical system with a corresponding monitoring counterpart can be traced back to the Apollo missions carried out by NASA.

In the past, the Apollo program involved the use of a “living model,” which was a physical counterpart, and the counterpart was used in space. The use of the “living model” was primarily used to analyze the conditions in a controlled environment (Madusanka et al., 2023; Homayouni et al., 2025). Similarly, in the development of the aerospace industry, the use of the “Iron Bird,” which is a ground test facility used by Airbus, involved the use of hardware simulators and virtual cockpit systems in the analysis of the system (Madusanka et al., 2023). Therefore, the use of synchronized physical and virtual systems is not new, and the basic idea or notion has always existed.

Overall, the Digital Twin represents a shift from static modeling toward dynamic, data-driven lifecycle integration. By combining IIoT connectivity, computational analytics, and continuous feedback loops, digital twins provide a theoretical foundation for intelligent system management. Their ability to mirror, simulate, and predict system behavior positions them as a key enabler of digital transformation across industries.

2.2.2 Digital Twin Architecture and Operational Workflow

According to the research paper by Hakimi et al. (2024), there is a general DT framework consisting of four environments: the physical environment, virtual environment, analytical environment, and connection environment. The environments are connected and supported by a central data environment (Figure 4).

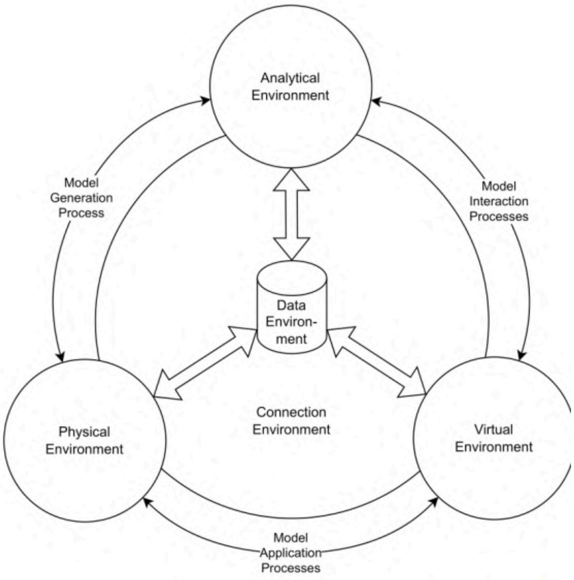


Figure 4. The key components of a digital twin (Hakimi et al., 2024).

The physical environment refers to the physical world and its elements, whereas the virtual environment refers to the virtual representation of the physical elements.

The analytical environment deals with processing and evaluating data with the help of algorithms and simulation models. The connection environment deals with the communication between the elements.

This architecture may be of particular interest for container terminals, which are characterized by dynamic and interdependent operations. In fact, as shown by Hakimi et al. (2024), as described in Figure 5 below, the container handling process starts with trucks or trains carrying containers to the container terminals. The containers are then scanned and registered; next, they are transported to specific yard blocks by the terminal's transport vehicles. The stacking cranes will then place the containers according to their row, bay, and tier numbers before being picked up by the quay cranes and transported to the vessel. The reverse process occurs for import containers. This process involves several coordinated resources and may be described by uncertainty and congestion risks.

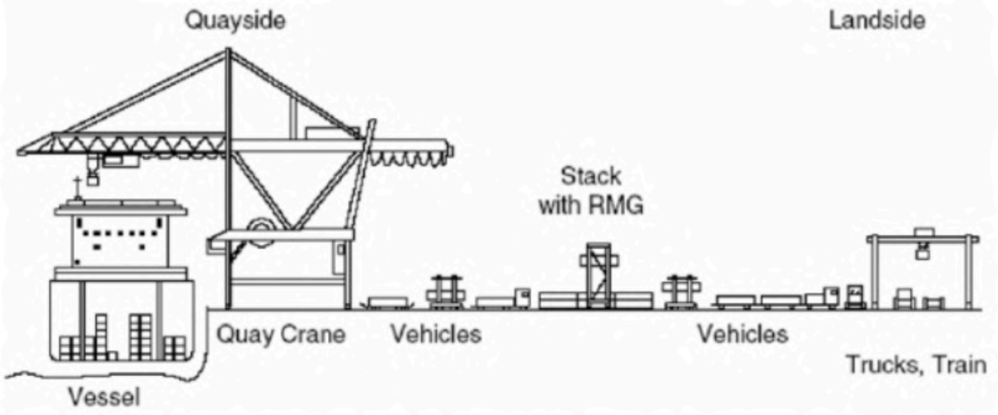


Figure 5. The schematic side view of a container terminal illustrates how the terminal's components are laid out and organised (Steenken et al., 2004, as cited in Hakimi et al., 2024).

To address this complexity, Hakimi et al. (2024) propose a structured digital twin workflow for container terminals (see Figure 6). The system collects both real-time and historical operational data from Terminal Operating Systems (TOS) and Gate Operating Systems (GOS), including container movements, equipment positions, vessel schedules, rail operations, and truck arrivals. These data streams are processed into Key Performance Indicators (KPIs) and predictive forecasts, which feed the digital twin model.

In the virtual world, the digital twin mimics the terminal operations and produces simulated results for the TOS and GOS. Using these simulated results, the virtual KPIs can be calculated, such as the crane travel distance or unproductive moves. Therefore, the gaps in the terminal operations can be identified, and the strategies can be tested in the virtual environment, which is risk-free. In this way, the terminal operations can be optimized, and the decisions can be taken in an advanced and proactive manner. Instead of responding to the disturbances, the terminal operations can be evaluated in real-time, and the best solution can be chosen(Hakimi et al., 2024).

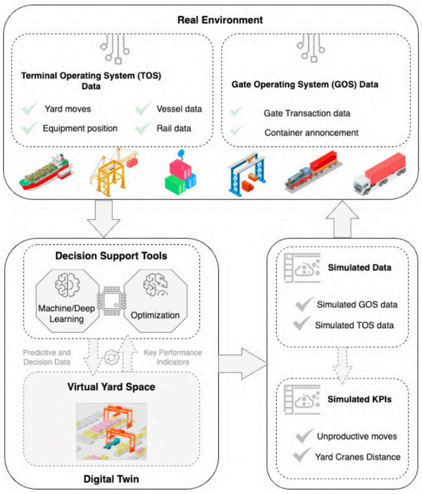


Figure 6. Diagram of the proposed terminal's digital twin (Hakimi et al., 2024).

However, the effective implementation of DT in seaports is not limited to the technical aspects. Rather, it is more about the integration and harmonization of heterogeneous data sources, the integration of physical operational systems with virtual simulation, and the interoperability with external stakeholders such as shipping companies, regulatory bodies, cargo owners, and customs authorities (Homayouni et al., 2025).

Homayouni et al. (2025) describe several frameworks for the implementation of the Digital Twin in seaports. One such architecture is based on a five-layer model, which includes the physical, data, model, service, and application layers. Another such architecture is the hybrid bi-level DT framework, which was implemented at the Qingdao Port. This framework is based on the integration of the physical and digital twin. The DT architecture implemented at the Yangshan Port in Shanghai is based on a five-layer model, which includes the Internet of Things, simulation, visualization, and decision support. All these frameworks demonstrate the structured and scalable approach to the management of the operational complexities in smart ports.

In summary, the architecture of Digital Twin in a port environment is marked by system integration, data exchange, and optimization through feedback. By incorporating analytics into the system, digital twins enable container terminals to evolve from reactive to predictive and adaptive infrastructure.

2.2.3 Applications of Digital Twins in Ports

Digital Twin (DT) technology has now become a major facilitator of digital transformation in contemporary ports, given its capabilities for facilitating real-time monitoring, simulation, and optimization of port operations. Indeed, through the integration of IoT technologies, DTs have been able to replicate the mapping of real-time operational data, including equipment conditions, cargo movements, and environmental factors, in a virtual environment, which enables port managers to monitor port operations, detect inefficiencies, simulate alternative scenarios, and minimize downtime. The capabilities of DTs in ports have been demonstrated in the optimization of loading, unloading, transportation, and storage activities, including emergency simulation, risk identification, and 3D visualization for management purposes (Li et al., 2024).

DTs help to improve transparency and control in maritime logistics through the analysis of historical and real-time data using advanced analytics techniques. This helps to make effective resource allocation, optimization of workflows, risk management, and scenario testing more effective. For instance, Hakimi et al. (2024) have suggested a framework of DTs for the optimization of stacking crane operations in container terminals using the creation of a virtual model of the terminal environment similar to the real conditions of its operation.

At a systemic level, the implementation of DTs is dependent on the integration of various data sources, which are considered to be heterogeneous, such as IoT sensors, monitoring systems, weather data, and operational systems. The data sources provide information related to environmental factors (such as emissions, energy use, air quality, and water quality), asset and infrastructure performance (such as cranes, vehicles, and berths), logistics operations (such as cargo and personnel movement), safety and security incidents, and system reliability as a whole (Homayouni et al., 2025).

A significant contribution of the applications of DT is the achievement of the goals of sustainability. Homayouni et al. (2025) present ten main DT applications that can be classified under the three pillars of sustainability: economic, social, and environmental dimensions (see Figure 7). The economic dimension of the applications of DT is related to efficiency in operation and the optimization of assets. The social dimension of the applications of DT includes safety improvements, training, and communication with stakeholders. The environmental dimension of the applications of DT includes the reduction of emissions, optimization of energy consumption, and monitoring of the environment.

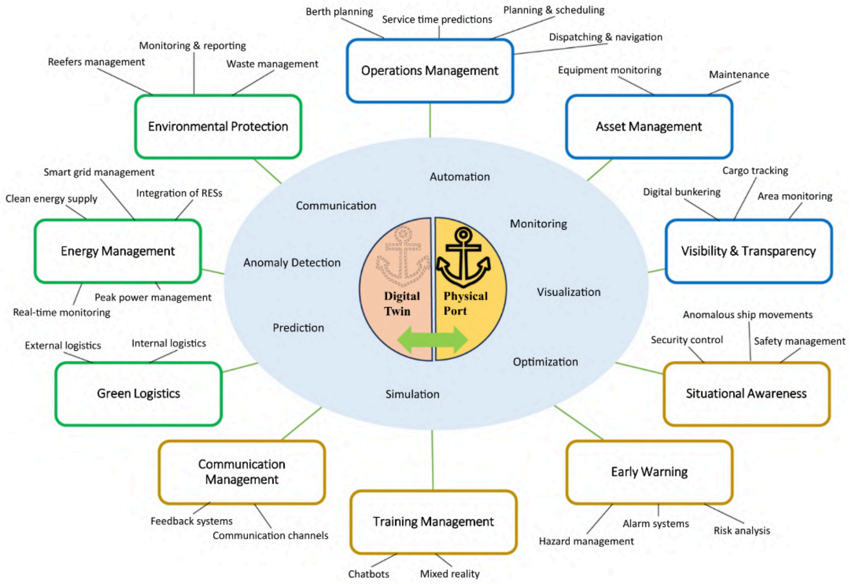


Figure 7. Digital twin applications to improve sustainability in seaports operations and logistics (Homayouni et al., 2025).

Table 6 provides a summary of some important DT global applications in seaports around the globe (Homayouni et al., 2025). This includes efficiency enhancement in ports such as Shanghai and Esbjerg; prediction in Belfast and Hamburg; visibility enhancement in Singapore and Rotterdam; safety innovations in Antwerp and Barcelona; DT training innovations in Livorno; and environmental optimization innovations in Rotterdam, Pusan, and Abu Dhabi. Overall, DTs have been found to increase efficiency, transparency, safety, cooperation, and sustainability through real-time data integration.

Table 6. Applications of Digital Twins in Seaports (Homayouni et al., 2025).

Core Application	Purpose / Use Case	Global Examples
Operational Efficiency	Optimize vessel scheduling, berth planning, cargo handling, and AGV routing.	Port of Esbjerg (wind turbine logistics), Shanghai Port (terminal optimization), Port of Leith (docking navigation).
Asset Management	Real-time monitoring, predictive maintenance, and infrastructure health management.	Belfast Harbour (equipment monitoring), Port of Hamburg (mooring monitoring), and automated quay crane maintenance.
Visibility & Transparency	Enhance cargo tracking, environmental monitoring, and operational oversight.	Port of Singapore (digital bunkering), Port of Rotterdam (real-time container tracking), Port of Hamburg (intelligent containers).
Safety & Security	Improve situational awareness, emergency preparedness, and risk assessment.	Port of Antwerp (autonomous drone network), Port of Barcelona (intelligent surveillance), Royal Naval Dockyard (sea-level monitoring).
Training & Communication	Worker training, knowledge transfer, and stakeholder collaboration.	Port of Livorno (VR/AR training), Popeye chatbot for terminal staff, Blue Visby solution (stakeholder coordination).
Environmental Goals	Reduce emissions, optimize energy consumption, and improve sustainability.	Port of Rotterdam (Routescanner), Pusan Newport (green berth scheduling), Abu Dhabi Terminals (digital energy tracking).

Further empirical evidence is provided by the work of Neugebauer et al. (2024), which explores the implementation of DTs in Germany, Belgium, Spain, and China, as presented in Table 7. This includes the Weserport terminal in Bremen, where satellite positioning and sensor data from forklifts are used to predict transport movements in near real-time; the Valencia terminal, which uses simulation and forecasting techniques; the Antwerp Bruges terminal, which has developed an extensive 3D and IoT-integrated digital twin; and the Shanghai and Dalian terminals in China, which also use multi-layer digital twins for real-time monitoring and predictive planning. Although the level of technological development varies from the use of model-based digital twins to the more advanced "strict" digital twins, all share the benefits of better resource utilization, greater operational transparency, and better support for strategic decisions.

Table 7. Key practical digital twin implementations in seaports (Neugebauer et al., 2024).

Port / Terminal	Country	Digital Twin Features	Data Sources	Key Benefits	Implementation Stage
Weserport (Steel Coil)	Germany	Near real-time integration, ML for transport prediction.	Satellite positioning, forklift sensors, TOS.	Improved resource use, reduced search orders.	Partial / Model-based
Valencia Terminal	Spain	Simulation models, ship forecasting APIs, and 3D visualization.	TOS, internal data lake.	Enhanced transparency, optimized vehicle flow.	Early stages
Antwerp-Bruges	Belgium	Full 3D/VR twin, predictive analytics, and environmental tracking.	BIM, AIS, radar, IoT, wind turbines.	Proactive management, high visibility.	Strict Digital Twin
Hamburg Testbed	Germany	Federated twins, traffic management, and structural health.	Traffic sensors, structural health sensors.	Operational planning, cross-twin coordination.	Partial / Federated
Shanghai Terminals	China	Multi-layer strict twin, simulation & optimization.	ECS, vehicle/crane positions, 3D rendering.	Real-time monitoring, process redesign.	Advanced / Strict Twin
Dalian Terminals	China	Multi-layer digital twin, lifecycle representation.	ECS, vehicle/crane sensors.	Process monitoring, predictive insights.	Developing / Near real-time

Overall, the reviewed applications demonstrate that Digital Twins in ports extend beyond operational optimization. They function as integrated platforms for predictive management, sustainability enhancement, stakeholder coordination, and long-term strategic planning. While implementation approaches vary according to port size, governance structure, and technological readiness, the overarching trend indicates a shift toward data-driven, adaptive, and interconnected port ecosystems.

2.2.4 Challenges and Adoption Barriers in Maritime Digital Twins

The development of the Digital Twin (DT) idea is motivated not only by technological capabilities but also by significant organizational and computational challenges. As Michael Grieves and John Vickers (2017) explain, "While the promise of improved prediction, simulation, and integration is compelling, the adoption of Digital Twins is hindered by organizational 'silo structures,' challenges in modeling complex physical systems, and the significant computational requirements to simulate the myriad states a system can be in." These challenges have created fragmented data, inconsistent Bills of Materials, and poor collaboration across domains. Yet, DTs also hold promise for transformative change, such as using real-time data for future designs or "front-running" simulations of system failure before critical issues occur.

Grieves & Vickers (2017) have summarized the main challenges and opportunities associated with DT implementation in their work (Tables 8 and 9). Some of the challenges include organizational silo effects, a lack of understanding of physical phenomena, and the vast number of possible states associated with a system. On the other hand, some of the opportunities include feedback from in-use data and simulations in real-time. This is a collection of insights that shows how DTs can be used to reduce uncertainty and increase the accuracy of predictions despite the challenges.

Table 8. Key Obstacles to Digital Twin Implementation (Grieves & Vickers, 2017).

Obstacle	Description	Implications

Organizational Siloing	Separation between departments (design, engineering, manufacturing, support) and even within disciplines.	Fragmented data, inconsistent Bills of Materials, lack of cross-domain integration, and cultural resistance.
Limited Understanding of Physical Phenomena	Incomplete knowledge of how materials, structures, and forces behave under real-world conditions.	Reduced accuracy in simulation models and predictive analysis.
Large Number of Possible System States	Systems operate under thousands of variable parameters over time.	High computational requirements; difficulty detecting undesirable emergent behaviors.

Table 9. Emerging Possibilities of Digital Twin Technology (Grieves & Vickers, 2017).

Possibility	**Description**	**Potential Benefit**
Feedback from In-Use Data	Capturing operational and production data to inform future design phases.	Early identification of complexity issues and undesirable behaviors before deployment.
Real-Time “Front-Running” Simulation	Running simulations in parallel with live systems using real-time data feeds.	Anticipation of crises, improved decision-making, mitigation of failures, and enhanced safety.

DT technology in the maritime sector is still in its infancy, far from the state of other industries such as aerospace, manufacturing, and urban planning. Several challenges have been identified for the adoption of DT technology in the maritime sector, including infrastructural challenges, connectivity challenges, and challenges related to skills, knowledge, and organizational readiness, among others, as cited by Madusanka et al. (2023) in their study. Some of the challenges include limitations in maritime infrastructure, data transmission at sea, software and hardware expertise, unwillingness to change from manual to computerized systems, cyber-physical challenges, and security of data, among others (Table 10).

Table 10: Key Challenges and Bottlenecks for Digital Twin Implementation in the Maritime Industry (Madusanka et al., 2023).

Category	Key Bottlenecks

Infrastructure & Connectivity	Limited maritime infrastructure, restricted data transmission at sea, and challenges in connecting underwater vehicles (submarines, UAVs) to shore-based DT systems.
Skills & Knowledge	Lack of software and hardware expertise among stakeholders, knowledge gap about DT technology and benefits, low industry engagement beyond academia.
Adoption & Culture	Reluctance to move from long-established manual hardware to digital systems, limited collaboration among researchers and institutes.
Technology & Readiness	Cyber-physical fusion challenges, technology readiness lagging behind conceptual development, handling of large data sets, and insufficient research on the decommissioning phase.
Security & Data Management	Data security concerns, including confidentiality, authentication, and non-repudiation; challenges in storing, accessing, and visualizing large datasets.

In particular, seaports are faced with additional hurdles to overcome for DT implementation to be successful. Challenges identified by Homayouni et al. (2025), which affect seaports, are investment and maintenance expenses, scarcity of data, interoperability problems, conflicting stakeholder goals, change resistance, data security concerns, and returns on investment. Figure 8 below, according to Homayouni et al. (2025), shows seaports and the challenges they face regarding DT adoption and implementation, with emphasis on the hurdles to be overcome for DT to be successfully adopted and implemented.

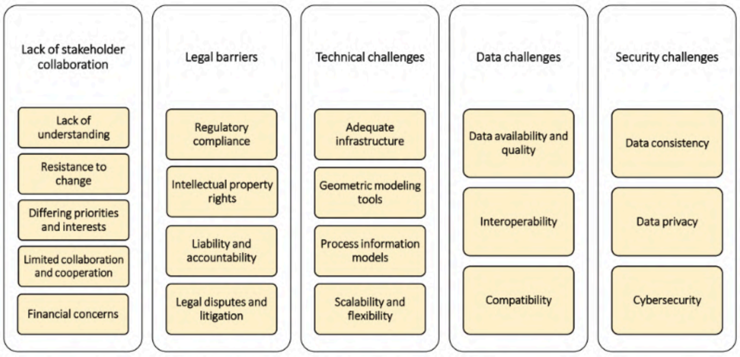


Figure 8. Main challenges and barriers for DT implementation in seaports(Homayouni et al., 2025).

2.3 Energy and Sector Coupling

2.3.1 Renewable Energy and Energy Transition in Ports

Ports are being considered as important hubs for renewable energy development and transition. The geographical location of ports provides good conditions for various forms of renewable energy development and transition, including geothermal heat plants using seawater with heat pump technology to produce energy for ports with great potential, but which requires careful assessment of its impacts (Acciaro et al., 2014).

A good example of proactive engagement in renewable energy is the Port of Hamburg. The port has been supporting the development of wind energy since the early 1990s. The Hamburg Port Authority (HPA) has been able to align its strategic goals with the vision of the city's energy transition. The presence of Hamburg Energie, a city-owned energy company that is involved in renewable energy and electric mobility, is an added advantage (Acciaro et al., 2014).

In general, ports possess a unique advantage for the deployment of RE due to their geographical position and space. For example, wind energy plants can be deployed in coastal ports such as Rotterdam, the Netherlands, and Kitakyushu, Japan; wave energy plants are deployed at Port Kembla, Australia, and Mutriku, the Basque Country; tidal energy plants are also considered for Dover, the UK, and Digby, Nova Scotia, Canada; and finally, geothermal energy plants are deployed at the Hamburg port. Additionally, flat land, such as storage areas or warehouse roofs, can host solar energy plants, such as those deployed at the Tokyo Ohi terminal, the administrative buildings at the San Diego port, although not sufficient for solar energy deployment. Biofuels also offer promising opportunities, as not only can the handling of biofuels be expanded, but also their production, storage, and distribution, which can support the expansion of alternative bunkering services.

A comprehensive literature review undertaken by Buonomano et al. (2023) has highlighted that the energy demands in ports are varied and include electricity, gas, thermal energy, cold energy, conventional fuels, and alternative fuels such as hydrogen, ammonia, and biofuels. Therefore, due to the increase in energy demands and stringent regulations on emissions, polygeneration plants with the potential to offer different energy carriers through renewable energy sources have been developed. For efficient energy production with low emissions, advanced models such as optimization models and simulation tools play a vital role. Ship-port interaction is also a critical aspect for the decarbonization of ships, with ports providing shore-side electricity supplies through alternative fuels such as biofuels; however, biofuel production is relatively expensive.

The energy transition of Norwegian ports until 2050 is further investigated by Gabrielli et al. (2025), with emphasis on the integration of energy systems and sector coupling. By mapping nineteen Norwegian ports, the energy transition of the Norwegian ports until 2050 is investigated, including the analysis of the energy transition of four case studies, considering different techno-economic and socio-technical scenarios. Although the shore power supply (OPS) is considered the most effective solution for decarbonization, additional emission reductions are subject to the characteristics of the ports. Ports where offshore wind farms or heat-intensive industries are located are characterized by high potential for hydrogen production. Multi-energy systems are crucial for the flexible energy transition of the Norwegian ports, although the feasibility of such systems is subject to different scenarios.

2.3.2 Power-to-X and Energy Conversion Technologies

"Power to Heat" (P2H) technology converts electric power to heat energy by utilizing electric boilers (EBs) and heat pumps (HPs), as shown in Figure 9. Besides domestic usage like water heaters, it has applications in district heating, industrial usage, and supplying negative control energy. In power integration systems, the waste heat of gas-based power plants may be converted back to electric power by utilizing steam turbines, as shown by the versatility of power conversion (Wang et al., 2023).

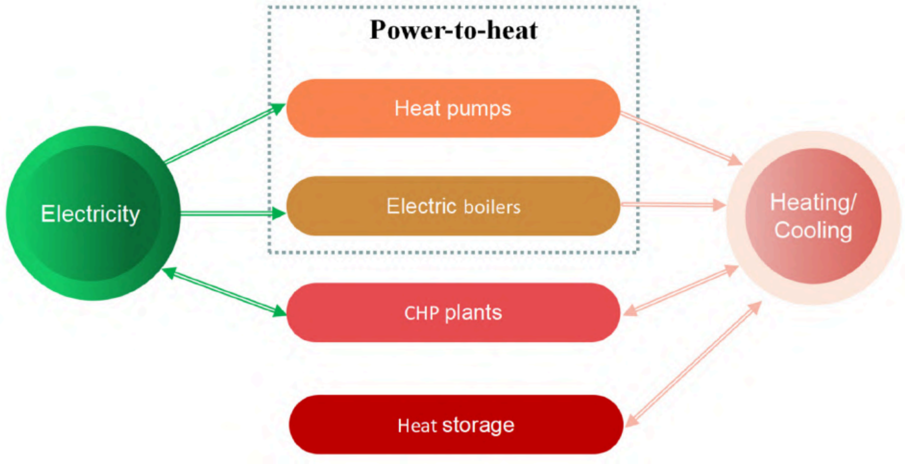


Figure 9. Schematic diagram of P2H (Wang et al., 2023).

However, hydrogen has some challenges in the transportation sector due to its low energy density. To begin with, hydrogen would only be feasible for small ships or those with a short range, although research and development are expected to improve this situation. On the other hand, seaports are adopting Alternative Maritime Power (AMP), or “cold ironing,” which enables ships to use shore-based electricity rather than diesel engines, thus encouraging environmentally friendly seaports (D’Amico et al., 2024).

Power-to-X (P2X) plays a vital role in the sector coupling of renewable electricity using P2G, P2H, and P2L. P2G generates hydrogen gas using electrolysis or synthetic methane gas. P2H generates heat using the electrolysis process. P2L generates liquid fuel using the reaction of H2 gas with CO2. P2L can be used in hard-to-electrify sectors like air travel and deep-sea shipping (Wang et al., 2023).

However, energy system modeling is critical in comprehending and optimizing these interactions between different sectors. Research indicates that the integration of renewable electrification with flexible technologies, such as electrolyzers and heat pumps, as well as cross-border transmission, can lower costs, emissions, and enhance system resilience. These findings underscore the significance of P2X and energy system modeling in facilitating a transition to fully renewable and low-carbon energy systems (Wang et al., 2023).

Sector coupling requires the use of various enabling technologies that can combine renewable electricity in the transport, industry, and building sectors. These enabling technologies can be categorized into three main areas: direct electrification, Power-to-Gas/Liquids (P2G/P2L), and Power-to-Heat (P2H). Direct electrification involves the substitution of fossil fuel-based uses with electric counterparts, such as battery electric vehicles and electric arc furnaces in the steel industry. Nevertheless, not all sectors can be addressed through direct electrification. In the case of difficult-to-abate sectors, such as air transport, maritime transport, and industrial processes, Power-to-X technologies can transform electricity into hydrogen or synthetic fuels that have defined chemical and thermodynamic properties. In addition, Power-to-Heat technologies, such as heat pumps and electric boilers, can facilitate the flexible conversion of electricity into thermal energy, especially when there is excess renewable electricity production (Ramsebner et al., 2021).

Table 11. Overview of key enabling technologies for sector coupling (Adopted from Ramsebner et al., 2021).

Technology Category	Main Principle	Key Applications	Advantages	Limitations / Considerations
Direct Electrification	Replacement of fossil-fuel technologies with electric alternatives.	BEVs (power-to-move), Shore Power, electric cranes.	High efficiency; mature technology; immediate emission cuts with RES.	Limited to specific processes; increases peak demand on the grid.
Power-to-Gas (P2G)	Electricity is converted to hydrogen via electrolysis.	Heavy industry, shipping fuels, gas grid injection, seasonal storage.	Enables long-term storage; suitable for hard-to-electrify sectors.	Conversion losses (60–80% efficiency); high capital costs (CAPEX).
Power-to-Liquids (P2L)	Hydrogen combined with CO2 to produce synthetic fuels.	Aviation, deep-sea shipping, heavy transport.	High energy density; uses existing engine technologies.	Highly energy-intensive; not yet commercially mature.

Power-to-Heat (P2H)	Electricity is converted to heat via pumps or boilers.	District heating (port-city), residential heating.	High flexibility; heat pumps are highly efficient (COP 3–5).	Infrastructure and thermal storage integration are needed.

The maritime industry is in the middle of a structural change towards a climate-neutral future. In view of the joint assessment of the European Environment Agency and the European Maritime Safety Agency (2025), a wide range of alternative fuels, propulsion systems, and operational methods are being considered to lower greenhouse gas emissions. The study shows that no single technology can alone decarbonize the maritime industry, but rather a mix of renewable fuels, electrification, efficiency gains, infrastructure development, and policy measures will be needed. Each of these options has its own set of benefits in terms of technical feasibility and emissions reduction potential, but also its own set of limitations.

Table 12. Summary of Alternative Maritime Decarbonization Options (EEA & EMSA, 2025).

Technology / Fuel	Key Advantages	Main Challenges
Biofuels	Compatible with existing engines; effective short-term solution.	Limited sustainable biomass; competition with other sectors (Urban et al., 2024).
Methanol	Easier storage than H2; existing supply chain; retrofit potential.	Requires low-carbon production (Green Methanol) for real climate benefits.
Hydrogen (H2)	Zero direct CO2; high decarbonization potential.	Low energy density; storage complexity; infrastructure gaps (IRENA, 2022).
Synthetic Fuels	"Drop-in" compatibility; near-zero lifecycle emissions.	Extremely high renewable electricity demand; high production costs.
Ammonia (NH3)	Zero-carbon potential; ideal for deep-sea shipping.	Toxicity; safety concerns; NOx emissions; high electricity demand.
Wind Propulsion	5–30% fuel savings; mature auxiliary technology.	Weather dependence: supplementary rather than a standalone solution.
Batteries	Zero-emission operation; ideal for short-sea/ferries.	Limited energy density; weight/space constraints; route limitations.
Fuel Cells	High efficiency; zero air pollutants (local).	Technology scaling; integration complexity within ship architecture.

Nuclear Propulsion	High energy density; zero operational CO2.	Regulation, public acceptance; high initial capital costs.
Onboard CCS	Transitional emission reduction for fossil-fuel ships.	Space and storage requirements; safety and additional energy costs.
Onshore Power	Eliminates at-berth emissions; growing EU regulatory support.	Grid capacity requirements; limited global deployment (Gabrielii et al., 2025).

2.3.3 Conceptual Foundations of Sector Coupling

Sector Coupling is a strategic approach to increase the efficiency, flexibility, and reliability of energy systems through the use of electricity in different sectors of energy consumption, either directly or indirectly. This allows for the integration of a larger fraction of VREs, such as solar and wind energy, thus paving the way for a fully renewable energy system (IRENA Coalition for Action, 2022). Sector Coupling can be achieved directly through electrification using devices such as heat pumps, electric boilers, or electric vehicles. On the other hand, it can be achieved indirectly through Power-to-X (P2X) technologies that convert electricity to fuels such as hydrogen, fuels, or heat, thus providing energy services in sectors that cannot be electrified (IRENA et al., 2018; Robinius et al., 2017). Figure 10 shows how electricity can be utilized in different sectors to increase efficiency.

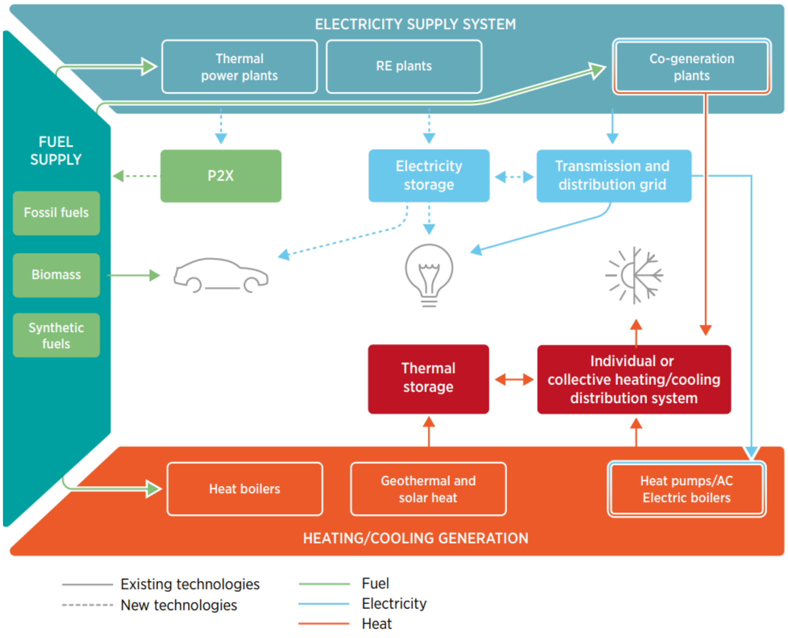


Figure 10. Sector Coupling (IRENA, IEA, & REN21, 2018).

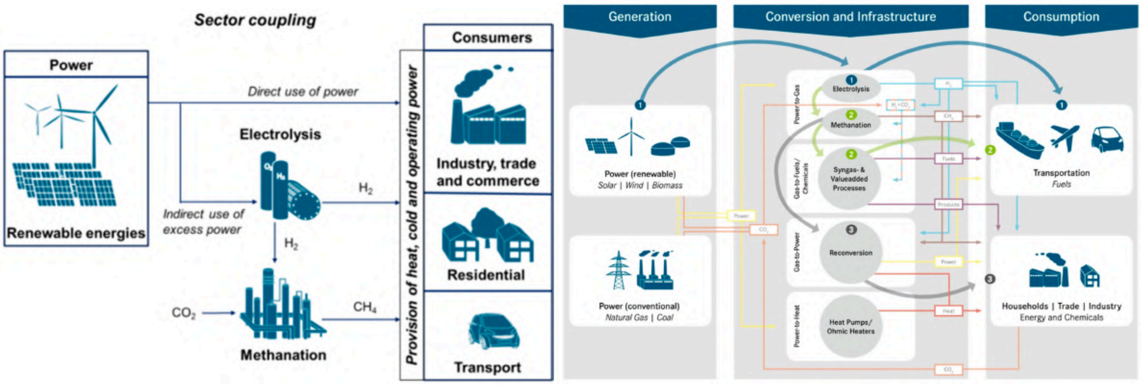
This concept is based on the co-production, conversion, and substitution of energy types, including electricity, heat, and fuels. In this way, the surplus VRE can be used in an efficient manner without curtailment. Sector coupling helps in the synchronization of electricity demand with the supply of renewable energy. This reduces the need for conventional power plants, optimizes the use of conventional fuels, and maximizes the flexibility in the overall system. Sector coupling can be seen in the use of heat pumps, which, when used in conjunction with thermal storage, can help in shifting the demand for heat to the supply of renewable energy, thus avoiding curtailment and ensuring the stability of the grid. Similarly, in the transportation sector, electric vehicles can be used to maximize the flexibility in the overall system.

The industrial applications of sector coupling are also quite significant. For example, the P2X technologies can be used for the production of hydrogen or hydrogen-based fuels, which can be used for the decarbonization of industries that cannot be decarbonized through electrification. The flexible industrial loads, such as aluminium or steel production, can be adjusted according to the availability of renewable electricity. For example, the HYBRIT project in Sweden uses renewable electricity for the production of hydrogen, which can be used for the decarbonization of the steel industry (IRENA et al., 2018).

Although the terminology of “sector coupling” is of recent coinage, the idea has long been realized through fossil fuel-based sector coupling. CHP plants, for instance, have long been providing electricity while using the surplus heat for industrial or domestic applications. Likewise, natural gas infrastructure has long been facilitating the intersectoral use of methane gas for electricity, transport, and industrial applications. The transfer of such existing sector couplings to renewable-based sector coupling is, therefore, a paradigm shift that demands digitalized energy management (Robinius et al., 2017; IRENA, 2021).

For effective sector coupling, clear identification of relevant sectors is also necessary. As per Robinius et al. (2017), "electricity end-use applications such as heating or lighting should not be seen as separate sectors. Relevant sectors are industry, trade and commerce, residential/households, and transport, with agriculture being a sector that deserves attention but often remains hidden from view." Sector coupling of these sectors using renewable energy, P2X technologies, and demand response measures provides flexibility through sector coupling, which is critical for the grid. This enables the efficient supply of renewable energy for satisfying heating, cooling, and transportation needs without any wastage, thus providing stability to the grid (IRENA, 2021; Robinius et al., 2017).

On the global level, the strong growth in renewable electricity, especially in solar PV and wind, has led to more than double the capacity since 2009. The share of renewable electricity is expected to meet up to 86% of global electricity demand in 2050, with 74% contributed by solar and wind power, according to the 1.5°C scenario. This high share of renewable electricity demands a highly flexible power system, which is achieved through sector coupling. Sector coupling connects several end-use sectors to electricity and allows the coordinated use of direct electrification, thermal storage, and P2X. This is shown in Figures 10 and 11, which describe the integration of Power-to-X applications in sector-coupled energy systems.



Figures 11 & 12. Sector Coupling, Power-to-X applications (Robinius et al., 2017).

2.3.4 Implementation of Sector Coupling in Ports

However, the effectiveness of the implementation of sector coupling in ports depends on the use of digitalization, smart energy management, advanced weather forecasting, and new business models such as energy-as-a-service, aggregation, peer-to-peer electricity trading, community ownership, pay-as-you-go, and urban energy planning (IRENA, 2021). Demand response flexibility in buildings, transportation, and industry has the greatest potential, whereas supply response solutions, such as Power-to-Gas, can be used to further support the flexibility of the system. Figures 10 and 11 below show the use of sector coupling in enhancing the flexibility in the sector.

On the one hand, the role of digitalization is significant in balancing VRE production and demand in a cost-effective way. Through the use of smart meters, grid sensors, IoT, and advanced algorithms, it is possible to monitor the production and consumption of energy in real-time, forecast the demand, and optimize the flow of energy based on the time, weather, and prices (State of Green, 2024). The use of big data and AI-based control systems helps in the development of cross-sector flexibility markets, which can be used for demand response and trading in energy storage. However, cybersecurity, data protection, and high costs are major challenges.

Sector Coupling connects renewable electricity supply with transport, space heating and cooling, and industrial applications, which conventionally use fossil resources (Ramsebner et al., 2021). Sector Coupling in the transportation sector includes battery electric vehicles, hydrogen fuel cell vehicles, synthetic electrofuels (Power-to-Gas/Power-to-Liquids), and shore power, which not only facilitate the decarbonization of the transportation sector but can also be used to optimize the grid. The decarbonization of the residential sector is achieved through Power-to-Heat technologies, which can be used to optimize the grid. Similarly, the decarbonization of the industrial sector is achieved through the electrification and integration of renewable hydrogen supply, which can be used to decarbonize the production of steel and other hard-to-abate sectors. Table 13 below summarizes the sector-specific applications and the technologies, system roles, and challenges involved (Ramsebner et al., 2021).

Table 13. Overview of sector coupling applications (Adopted from Ramsebner et al., 2021).

Sector	Main Decarbonization Pathways	Key Technologies	System Role	Main Challenges
Transport	Direct & indirect electrification	BEVs, FCEVs (hydrogen), synthetic electrofuels (P2G/P2L), shore power.	Reduces oil dependence; provides grid flexibility (V2G, H2 storage).	Battery weight (shipping); infrastructure gaps; electrofuel costs.
Residential (Heat & Cool)	Power-to-Heat (central & decentralized)	Heat pumps (HPs), electric boilers, district heating, thermal storage.	Absorbs surplus renewable electricity; increases demand-side flexibility.	Building refurbishment, grid peak demand, and high infrastructure investment.
Industrial	Electrification & renewable hydrogen integration	Electric arc furnaces, renewable H2 (electrolysis), on-site RES generation.	Enables deep decarbonization of hard-to-abate sectors via hydrogen.	High energy intensity; cost competitiveness; massive green H2 demand.

The practical application of sector coupling in ports is shown in the study by Buonomano et al. (2023) through the dynamic simulation models of Energy Hubs (EHub). EHub is used for hourly energy balance calculations for electricity, thermal energy, and fuels to meet the energy needs of the port facilities as well as the ships in the port. EHub is also used for the production of clean fuels from renewable energy resources. Biomass is obtained from ships or port facilities and is processed in biodigesters to produce biogas for Combined Heat Power (CHP) plants in the port microgrid. Thermal energy is used for the biodigester, space heating, and cooling through absorption chillers. Battery energy storage is used to balance excess electricity. Grid connection is used to meet the remaining energy needs, while excess energy is supplied back to the grid. Figure 13 shows the energy fluxes in the EHub in the port.

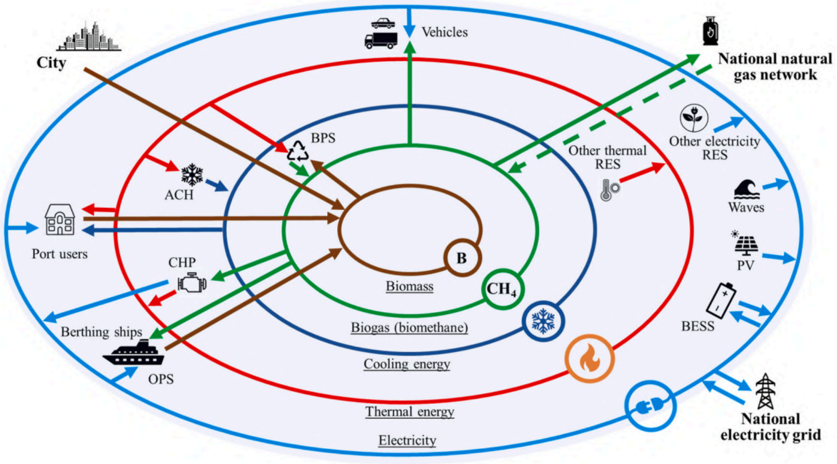


Figure 13. Energy fluxes of the port energy hub. (Buonomano et al., 2023).

Despite the technological developments in the field, there are still major barriers to sector coupling in maritime environments. Urban et al. (2024) have identified the structural, economic, and organizational barriers to sector coupling in maritime environments. The barriers include the "silo-character" in shipping activities, the lack of cooperation between different sectors, the absence of integrated business models, the high cost premiums for green compared to conventional fuels, the lack of transparency in reporting, the lack of integrated planning, and the competition for scarce resources in the form of advanced biofuels, to name a few. The barriers to sector coupling in the maritime industry need to be addressed through the development of regulatory frameworks, economic incentives, the use of standardized frameworks, the development of partnerships based on trust, and the development of governance structures.

3 The Port of Vaasa: Context, Infrastructure, and Role

The Port of Vaasa is a key component in the region, especially regarding the local economy and the energy shift. The port is a hub that caters to cargo, passenger, and energy-related activities. Its location, along with its infrastructure, makes it a vital component in the transportation of goods, thus enhancing the competitiveness of the local industries. This section gives an overview of the port, its infrastructure, development strategies, and the technical requirements necessary to incorporate a new technology, such as a Digital Twin, to improve sustainability.

3.1 Overview of the Port of Vaasa

The Port of Vaasa is the gateway for the Energy Vaasa cluster, which is the largest cluster for energy technology in the Nordic countries. A substantial amount of transport of energy technology products occurs through the Port of Vaasa, thereby serving the needs of the industry. The Port of Vaasa is planned for multiple purposes, including passenger transport, energy transport, and cargo transport that includes bulk cargo as well as heavy cargo (Port of Vaasa, n.d.).

Figure 14. The strategic location of the port (Wasaline, 2025).

The Port of Vaasa is in a strategic location for trade as it is close to an international airport and is well connected by road and rail. This is important for the smooth transport of fuels, agricultural products, and project cargo. The port has also been able to gain experience in dealing with project cargo, especially in relation to energy, engineering, and metal production in the region. Further, the Vaasa-Umeå connection is recognized as the northernmost year-round international maritime connection between two countries, as shown in Figure 14 linking the E12 transport corridor from eastern Finland to Norway and the Atlantic coast.

However, the environment in which the port operates does not experience major disruptions in its operation due to ice. This is because, in this environment, sea ice usually sets in during January and melts in April, and the vessels operate throughout the year, supported by Finnish state icebreakers, and Vaasan Hinaus Oy provides icebreaking services in the port area. There might be temporary restrictions on vessel movements depending on the weather, ice class, and deadweight tonnage of the vessels.

In addition to this, the port has been connected to land transport facilities. The port has about one kilometre of railway tracks that connect it to the Finnish rail network. This has helped in the transportation of goods by train to warehouses, storage, and the port. This has been essential for the transportation of goods in an environmentally friendly manner, which has also enabled the use of specialized trains for the transportation of heavy goods. Moreover, there is a weather station located at the coal berth, and the winds come from the southwest (Port of Vaasa, n.d.).

The city of Vaasa is also set to achieve its goal of carbon neutrality by 203X, in line with the EU’s enhanced 2030 climate policy, which targets a reduction of at least 55% in carbon emissions, and also in line with Finland’s Climate-Neutral Finland 2035 program. The Port of Vaasa is also crucial in ensuring that not only is carbon neutrality achieved in Vaasa city, but also in the region’s industry as it works towards carbon emission reduction targets. The project starts off by examining and analyzing the ecosystem of the port and its needs, as well as its potential role in carbon neutrality and how it could be part of a larger ecosystem of carbon neutrality through concepts such as energy concepts and sustainable solutions. The project will be a roadmap for long-term efforts and strategies towards carbon neutrality, with a flexible and resilient port infrastructure being key in such developments and strategies (VASEK, 2024).

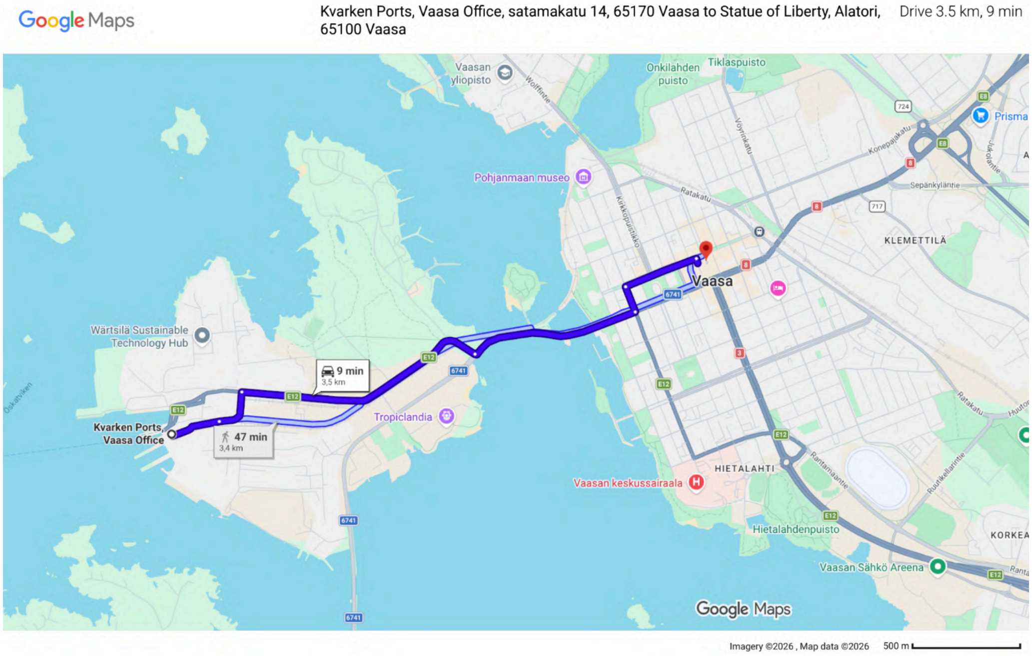


Figure 15. The distance between the port of Vaasa and the city center (Google Maps, 2026).

The Port of Vaasa is an essential logistics hub in regional trade in western Finland. According to statistics provided by the Finnish Port Association, international cargo volumes through the Port of Vaasa have been between 0.77 million tonnes and 1.18 million tonnes between 2016 and 2025 (Finnish Ports Association, n.d.). The highest volume was recorded in 2022 when international transport volumes through the port were 1.18 million tonnes due to a surge in imports. As shown in Figure 16, in 2025, the international cargo volumes through the port were 937,118 tonnes, with 611,709 tonnes being imports and 325,409 tonnes being exports. In comparison to other international cargo volumes in Finland in 2025, which were above 90 million tonnes, it is clear that although it is a small portion in comparison to other ports in Finland, it plays an important role in regional trade in western Finland.

The amount of transit transport via the Port of Vaasa has also been extremely small over the given time period. The amount of transport via the port on an annual basis has generally not exceeded a few hundred tonnes. This implies that the port mainly handles regional imports/exports rather than acting as a transit port. The amount of container transport via the Port of Vaasa has also been extremely small. Only sporadic container transport was noted in some years, while over 1.4 million TEU was handled collectively by Finnish ports in 2025. This can be explained by the specialized logistics infrastructure of the Vaasa port, which mainly handles bulk materials, transport related to energy, etc., rather than containers (Finnish Ports Association, n.d.).

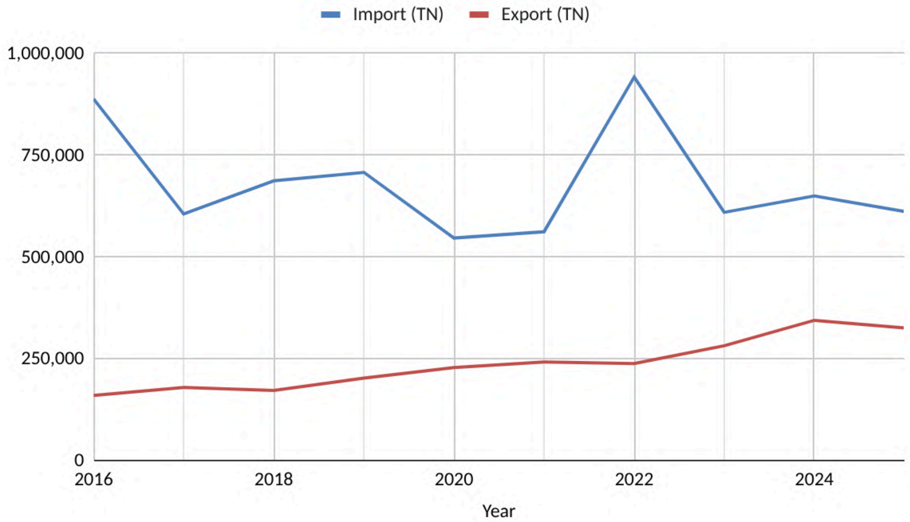


Figure 16. The international transport from and to the port of Vaasa (Finnish Ports Association, n.d.).

Domestic water transport via the port has exhibited a declining trend over the last decade. The amount of total domestic cargo transported decreased from 360,450 tonnes in 2016 to 61,206 tonnes in 2025, showing the move away from domestic water transport via Vaasa harbor. At the same time, there has been a decrease in domestic water transport in Finland, though not significantly.

Passenger traffic is another significant activity of the port, primarily because of the ferry route that connects Vaasa to Umeå across the Gulf of Bothnia. The number of passengers has risen from 184,191 in 2016 to over 209,000 in 2019 before the COVID-19 pandemic hit the world, causing a sharp decline in 2020 before gradually improving to 259,280 in 2025, as shown in Figure 17 below.

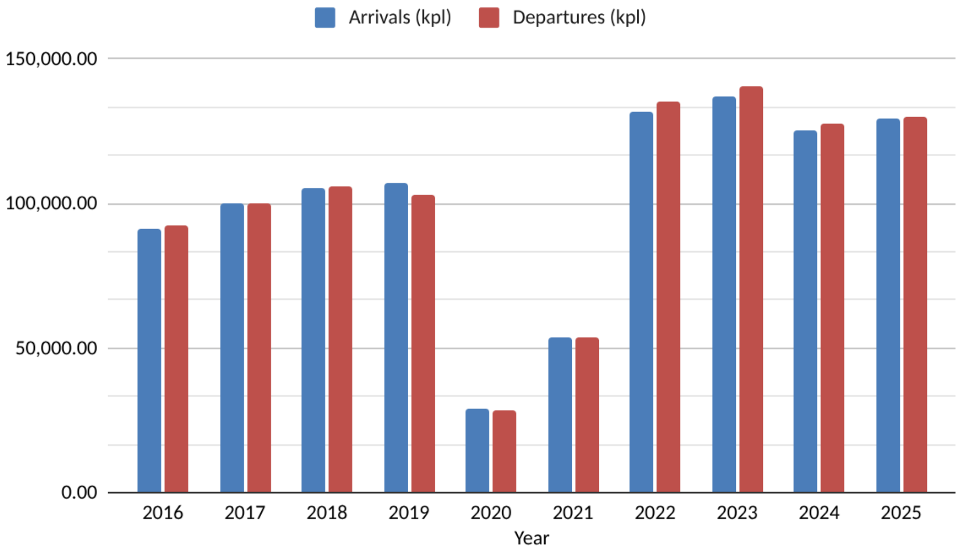


Figure 17. The number of passengers departed from and arrived at the port of Vaasa (Finnish Ports Association, n.d.).

3.2 Current Infrastructure and Energy Systems

The infrastructure of the port includes seven quays, totaling 1,343 meters in length, to support various shipping activities, including LoLo, RoRo, bulk, liquid bulk, container, and passenger. The water depth along the quays varies from 6.8 to 9 meters, and access to freshwater and electricity is available along most of the quays. Facilities for discharging wastewater for passenger vessels are also available. The access to the port is guaranteed by two fairways, one from the north and one from the south, for vessels of a draft of up to 9 meters. The fairways, which are 32 nautical miles (60 km) in length, have a minimum width of 140 meters, and there are no air draft limitations. The size of the vessel for which the fairway was designed was 242 meters in length and 35.2 meters in beam (Port of Vaasa, n.d.).

The handling of the cargo in the Port of Vaasa is improved by the use of modern equipment, such as mobile harbor cranes provided by Blomberg Stevedoring. The machines available in the port include the Liebherr LHM 600, the Liebherr LHM 400 machines, and the Mantsinen MSK 100-8 material handling machines. The machines have the capacity to lift cargo of up to 200 tonnes each, but the machines can work in pairs to lift cargo of up to 300 tonnes. The port also has paved storage spaces of 8 hectares, as well as field storage spaces for large and heavy cargo. Special spaces are also provided for the handling of dangerous goods (Port of Vaasa, n.d.).

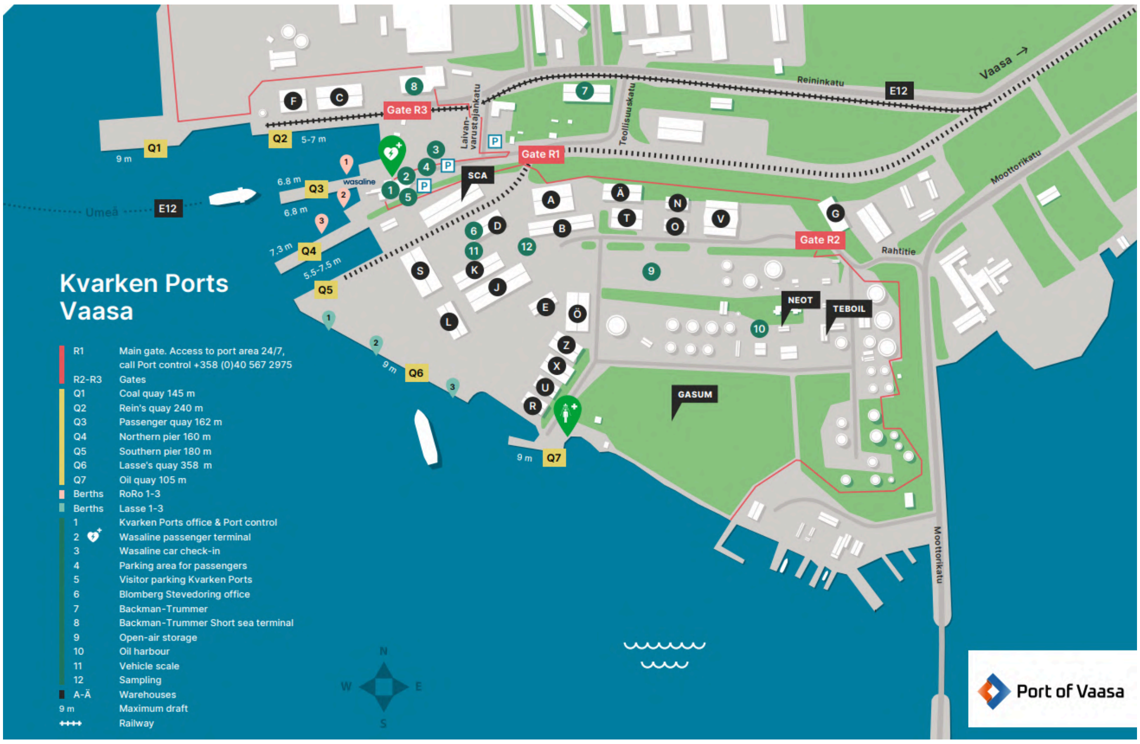


Figure 18. Layout and facilities of the Port of Vaasa (Port of Vaasa, 2025).

3.3 Future Development and Strategic Goals

The development strategy of the Port of Vaasa is closely related to the general strategic goals of Kvarken Ports, with a focus on reinforcing the competitiveness of industries in the region, as well as supporting their transition toward carbon neutrality. Under this perspective, the role of the Port of Vaasa is not only related to being a logistics center, but also to being a facilitator of the sustainable development of industries in the Vaasa region. For this purpose, some of the main development priorities of the Port of Vaasa include increasing the quay and fairway’s capacity to accommodate larger vessels, as well as increasing storage areas to accommodate the increasing need for storage space, both for industrial purposes and for the increasing volumes of cargo passing through the region. Additionally, the development of a roadmap toward carbon neutrality is also being pursued by the development of solutions related to energy, as well as positioning the Port of Vaasa as an energy hub in the region(LiMoWa, 2024).

The development of the innovation system in the Port of Vaasa is key to realizing the strategic objectives of the region’s industry, logistics sector, and city. The Sustainable and Smart Port of the Future project (2025–2027) was established by VASEK in collaboration with Kvarken Ports and Vaasa University of Applied Sciences. The project has established key priorities in green logistics, port infrastructure and energy solutions, charging systems, improved cooperation and communication, and digital development. The project is focused on piloting an innovation platform and a cooperation model that can boost the development and commercialization of sustainable logistics, energy, and real estate solutions in the port. By using the best methods for piloting an innovation platform and a cooperation model, the project aims to increase the port's efficiency and productivity. Additionally, the project is focused on enhancing collaboration between different players in the ecosystem. The key results of the project include a cooperation model, a value proposition for the innovation ecosystem, an investment plan for clean transition projects, and piloting plans for demonstrating strategic initiatives (VASEK, 2025).

The Port of Vaasa has recently seen organizational and infrastructural developments in enhancing its position as a key contributor to regional development and energy transition (Coastline, 2025). Kvarken Ports Vaasa is a standalone entity in Finland, while Vaasan Satamainfra is focused on developing the port’s infrastructure. The port, located close to the largest energy technology cluster in Northern Europe, has completed several key projects in enhancing its capacity and expanding its facilities. Notable developments include an extension of the port's main cargo quay, thereby almost doubling capacity for large vessels. Further developments include widening the fairway and expanding the port's land area by seven hectares. Through ecosystem development programs in collaboration with VASEK businesses and funding bodies, the port is working on energy concepts, logistics, and digital solutions to enhance sustainable development and energy security in Finland.

In another similar initiative, the Future Ready Harbour Concept – Towards Sustainable Maritime Ecosystem (August 2020-January 2021) project, led by the University of Vaasa in partnership with VASEK and Kvarken Ports, aimed to enhance the port's role in the sustainable maritime ecosystem. The project's main objectives were to develop a co-innovation platform, set R&D priorities, and develop project ideas to facilitate decarbonization, renewable energy, and integrative ship-port-ecosystem development. Acknowledging the city's importance in the ecosystem, the project also emphasized the significance of the development of the entire system in the ports and industries, as the major ports in Europe have already developed digitalization ecosystems, although the development of new technologies such as 5G, energy IoT, smart grids, etc., is in the initial phase (University of Vaasa, 2021).

3.4 Technical and Data Requirements

After referring to multiple sources, Zhu et al. (2025) classify the essential data sets for the Digital Twin of the ports into various categories, which include waterside and landside operations. On the waterside, the data sets related to the vessels play an important role in the Digital Twin of the ports, which include the arrival time of the vessels, the volume of the cargo, and the technical parameters of the vessels, such as the dead weight tonnage and the power of the engines. Traditionally, the data sets related to the vessels are obtained from the operational records of the ports, but the use of Automatic Identification System (AIS) data sets is becoming more popular. AIS data sets provide continuous information related to the positions of the vessels, the velocity of the vessels, and the course of the vessels. This data set is highly popular for the development of the predictive model of the vessels.

On the landside, information about the equipment and infrastructure is necessary. This includes information about quay cranes, trucks, reach stackers, forklifts, storage yards, silos, and rail infrastructure. For all of this information, details about the dimensions, capacity, working speed, and power consumption of the equipment are necessary for the simulation of the Digital Twin. IoT technology can be utilized for the monitoring of the assets in the ports in real-time. However, this technology requires substantial investments in hardware, communication infrastructure, and storage capacity. In the absence of IoT technology, the records of the operations of the assets can be utilized for simulation.

Finally, environmental and building data are also important for the simulation of the results related to the use of energy and the sustainability of the system. For instance, the geographical information available through CAD or GIS enables the Digital Twin to consider the routes of vessels, the dimensions of the berths, and the areas for storing cargo. Moreover, the information related to the weather is important for considering the constraints related to the operations of the port, as well as the consumption of energy for the buildings. In the context of building information, the integration of Building Information Modeling (BIM) information enables the simulation of the entire system related to the use of energy in the port, as discussed in Zhu et al. (2025).

In addition to the above-stated layers of data, to support the creation of the Digital Twin, which specifically focuses on energy and sector coupling, it is also important to consider the following layers of data:
the consumption and production of energy, the energy storage, the connection to the main electrical grid, the type of vessels, the type of fuel, the working hours, cargo handling equipment, vehicles, buildings, and environmental factors such as the local weather, etc. Such an extensive range of data enables the planning of the entire operations of the port, considering the theme of the management of the energy.

4 Case studies

This section has presented two case studies that provide examples of the use of digital twins and smart energy systems within a contemporary port setting. The case studies of the Port of Oulu and the MAGPIE project provide examples of the use of digital twin technology within a port setting. The Port of Oulu case focuses primarily on the use of a digital twin for operational understanding and visualization within a port setting. The MAGPIE project case focuses primarily on the use of digitalization as a means of enabling the energy transition through various solutions such as shore power, renewable energy, and energy storage. These case studies provide examples that are useful for informing a concept for an energy-focused digital twin at the Port of Vaasa.

4.1 Case study 1: Port of Oulu

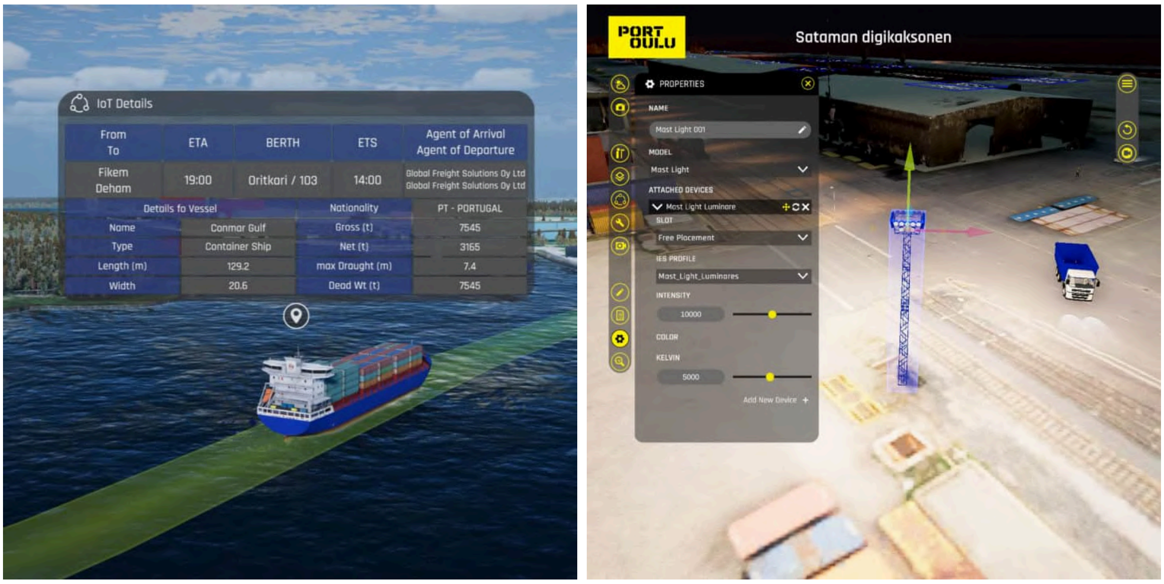
The Port of Oulu is one of the largest general cargo ports in the Bay of Bothnia and is significant in the development of trade and commerce in Northern Finland. The port is in operation throughout the year and is located in the fastest-growing city in Northern Europe. The port's infrastructural facilities are divided into three main harbor areas: Oritkari, Nuottasaari, and Vihreäsaari. These three harbor areas are for the different operational purposes of the port. Containers and forest industry products are mainly located in the Oritkari area, while Nuottasaari is used for the handling of the raw materials of the forest industry. Vihreäsaari is mainly used for the handling of liquid fuels and bulk cargo. The maritime history of the port is long and dates back to the 14th century. Today, the port has a fairway depth of 12.5 meters and 1,460 meters of quays. Additionally, the port is well connected with the transport routes of Northern Finland and the rest of the world by means of road, rail, and the Oulu airport. The port has large land areas available for future flexibility based on the customer's demands (Port of Oulu, n.d.).

As the complexity of logistics chains increases, as well as the expectations of companies in terms of efficiency, transparency, and sustainability, the port has sought digitalization as a means of optimizing its services for its partner network. One of the main initiatives in this digital transformation is the creation of a digital twin of the port. The digital twin is considered a digital platform in constant evolution, representing the state of port activity, giving stakeholders a comprehensive overview of port activity. The digital twin enables stakeholders to access different types of data available in the port area, allowing for the visualization of this information in images, videos, or simulations. The stakeholders can access information in real time about weather conditions, vehicle movement, or changes in transport routes. The digital twin also enables stakeholders to access planning and monitoring of sea, rail, and road traffic, tracking the movement of ships, trains, and vehicles in the port area (Oulu.com, 2021).

Figure 19. Digital twin of the port of Oulu (Oulu.com, 2021).

From a technical point of view, the digital twin concept was developed as a platform that could unify spatial data, infrastructure information, and IoT sensor data. This enables the development of a detailed 3D model of the port environment where information could be monitored in near real time. In the past, the operational information was scattered across several different systems before the implementation of the digital twin concept. This made it more difficult to coordinate the different teams involved in the operation. The integration of the different systems into a single platform enables the digital twin to provide better visibility for the operators.

It also allows for simulation and planning activities to be carried out, which can be useful for daily operations. The simulation of various scenarios can be carried out based on the data and information collected. This would be useful for better decision-making. The second advantage of the digital twin platform is that it allows for better collaboration among various stakeholders involved in the operations of the port. These include logistics providers, maintenance providers, security providers, and the port authorities. The digital twin would allow these various parties to have access to the same data and information. Therefore, it would not only be used for monitoring but would also be a platform for collaboration for the various parties involved in the operations of the port (Blare Tech, n.d.).



From To	ETA	BERTH	ETS	Agent of Arrival Agent of Departure
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Details fo Vessel		Nationality	PT - PORTUGAL
Name	Conmar Gulf	Gross (t)	7545
Type	Container Ship	Net (t)	3165
Length (m)	129.2	max Draught (m)	7.4
Width	20.6	Dead Wt (t)	7545

NAME: Mast Light 001
MODEL: Mast Light
ATTACHED DEVICES: Mast Light Luminare
SLOT: Free Placement
IES PROFILE: Mast_Light_Luminares
INTENSITY: 10000
COLOR
KELVIN: 5000

Figures 20 & 21. Overview of the Digital twin of the port of Oulu (Blare Tech, n.d.).

Apart from the above, the digital twin will be significant in the future digital development strategy of the port. It will act as a major interface for accessing and sharing information. This will help stakeholders better manage the data they have. It will help in addressing the issues of connectivity and network capacity within the port environment. This will ensure that digital services within the port function effectively despite the evolution of the port infrastructure. In the future, the digital twin will be significant in the technological advancements that will be experienced in the port. Some of the advancements will be in the areas of autonomous transport systems, the use of drones, and the application of artificial intelligence in the efficiency of the decision-making process.

4.1.1 Key insights for the port of Vaasa digital twin

The case of the Port of Oulu offers a series of useful lessons in terms of developing a digital twin for the Port of Vaasa. First of all, there is the importance of integrating different types of data, including spatial data, infrastructure data, and operational data, into a single platform that supports monitoring, management, and visualization. This shows how digital twins can be useful in terms of situational awareness, operational planning, and collaboration. The aforementioned lessons can be summarized in Table 14 and can be useful in developing a digital twin for the Port of Vaasa, especially in relation to energy-related aspects and sector coupling.

Table 14. Key insights from the Port of Oulu digital twin relevant to the Port of Vaasa

Key Insight from Port of Oulu digital twin	Relevance for the Port of Vaasa digital twin
Integration of spatial, infrastructure, and IoT data in a single platform	Supports the creation of a unified digital twin environment for energy and operational data
Real-time monitoring and visualization of port activities	Enables better understanding of energy consumption and operational patterns
Simulation capabilities for planning operations	Can support energy system analysis and sector coupling scenarios
Improved collaboration through shared data access	Facilitates coordination between port operators, energy providers, and logistics stakeholders
Scalable digital infrastructure for future technologies	Allows integration of future smart port technologies and energy solutions

4.2 Case study 2: The MAGPIE Project

The MAGPIE project has the objective of assisting in the transition to greener and more sustainable ports by facilitating the use of clean energy carriers as well as enhancing energy efficiency within port-related transportation. The project hopes to hasten the decarbonization of ports by implementing innovative solutions that are mainly related to digitalization, automation, and smart energy. The results from this innovative solution implementation will form part of a master plan that will be created for European Green Ports, which will include a roadmap as well as guidelines for other ports within Europe to implement sustainable solutions (MAGPIE Consortium, n.d.).

As ports and cities change in relation to their connections with the broader system of the local, regional, and global, a new interface has appeared. Thus, ports have the ability to adjust relatively fast in relation to changes in technology, infrastructures, and global trade, while the city and the system of local governance adjust more slowly. Consequently, port cities are often subject to substantial change. The spaces where the port and the city meet are often understood as contested spaces; however, they can also function as dynamic interfaces where different activities, stakeholders, and urban functions interact and adapt to ongoing change (MAGPIE Consortium, 2025).

Managing this transition also requires addressing the interests of a wide range of stakeholders associated with the port system. Different actors, both in business and government, as well as the city, are all part of the processes of influencing the development of ports and the associated energy transition strategies. In the last few years, there has been a greater emphasis by ports on enhancing the relationship between the ports and the city by focusing on the link between city development and port development. There is a need for communication, especially due to environmental and associated city dweller concerns, and the need for them to be made aware of the potential impacts of the processes and strategies of the ports, as they need to be part of the decision-making processes regarding their environment, as highlighted by the MAGPIE Consortium (2025).

One of the main technological demonstrations of MAGPIE is the shore power systems. This technology provides the ability for ships to use electricity from the shore while in the port rather than using diesel power. This reduces greenhouse gas emissions and improves the quality of the air. However, the shore power systems have challenges because of the fluctuating demand and the high peak demand of the ships. To solve the challenge of the fluctuating demand of the ships, the MAGPIE project uses the energy storage systems (ESS) (Wiggelinkhuizen et al., 2025).

In this regard, a Smart Energy System developed by Distro is utilized to regulate and optimize the flow of energy from the grid, renewable sources, storage devices, and vessels. The system is scheduled to provide energy according to the capacity of the grid, availability of renewable sources, and operational needs, such as storage when vessels are docked. The initial plan was to incorporate a battery storage system as part of the shore power system; however, owing to budget and time constraints, it was decided to deploy it on a crane vessel called Thialf operated by Heerema Marine Contractors. In this case, the battery is connected to the shore power system only when the vessel is docked and is utilized for peak shaving to relieve pressure from the electricity grid while serving the vessel's needs (Wiggelinkhuizen et al., 2025).

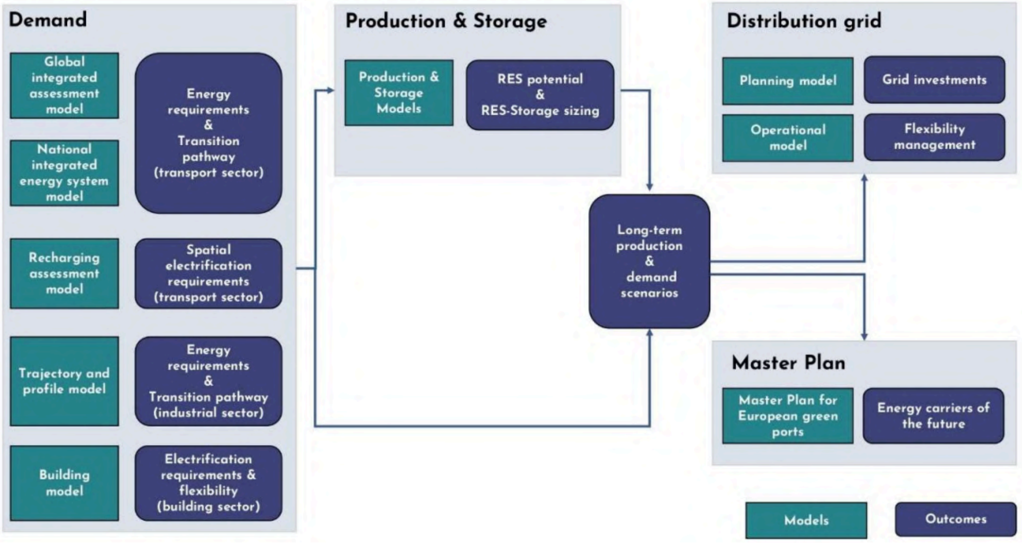


Figure 22. High-level vision of modelling architecture (Silva et al., 2023).

The planning of energy systems in ports is related to the level of electrification of the activities that take place in ports. As the electricity requirement grows, it is necessary to plan the production and storage of energy. The availability of renewable energy sources depends on the storage, and the sizing of storage depends on the surplus of energy produced. Therefore, the MAGPIE framework proposes a combined modelling method for estimating renewable energy potential, determining the optimal sizes of renewable energy systems and storage, and developing hourly production profiles for energy planning in port ecosystems, as proposed by Silva et al. (2023).

A practical example of the application of these concepts is the shore power system installed at the Port of Rotterdam, which serves the Heerema facility in the Rozenburg area. The system provides power to the vessels through a connection to the grid and a nearby wind farm. The system consists of voltage and frequency conversion equipment and a cable management system that provides a connection from the shore to the vessels (Punt et al., 2024).

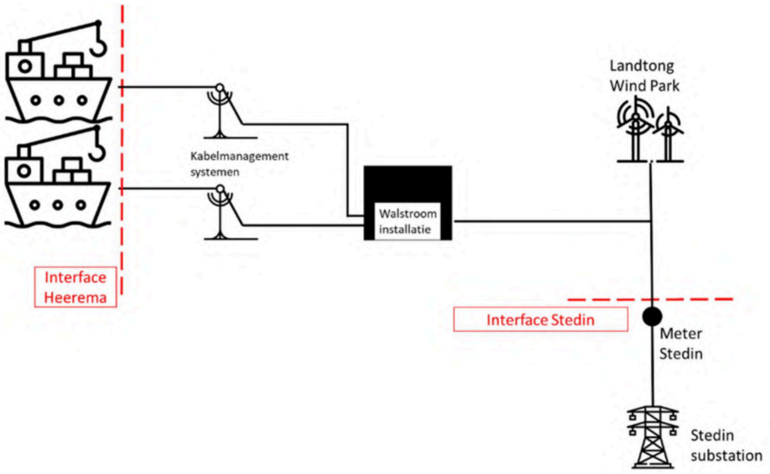


Figure 23. Concept of Heerema shore power installation (Punt et al., 2024).

The nearby shore power facility in the Port of Rotterdam is assisted by a wind farm with nine turbines with a total capacity of 40.5 MW, situated between the Nieuwe Waterweg and the Calandkanaal in the industrial area of the Port of Rotterdam. The shore power facility itself has a capacity of 20 MW and can supply power to up to two ships and two cranes at a time. It can meet a base load of up to 5 MW, which may rise up to 10 MW during crane operations. It meets an estimated electricity demand of around 20 GWh annually for Heerema operations. It comprises a series of important components, including an electrical house with converters and controls, transformers, and a cable management system connecting ships with the power supply on land. Under the MAGPIE project, the facility is further developing the concept of connecting the shore power facility with battery storage and energy management solutions. It may even be connected with an electricity marketplace using Artificial Intelligence technology.

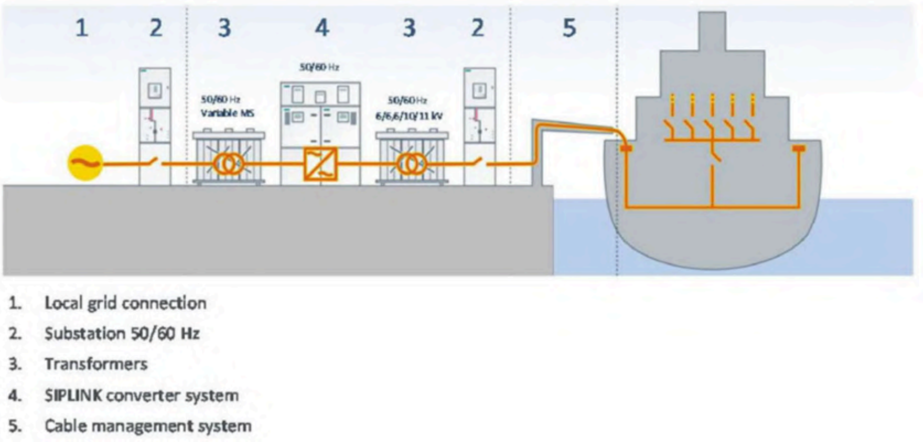


Figure 24. Schematics of Heerema shore power installation (Punt et al., 2024).

In addition to energy system innovations, MAGPIE also investigates the potential of digital twins in managing complex port ecosystems. The backend architecture of the digital twin allows for data sharing among stakeholders in the port ecosystem in a secure and efficient manner using International Data Spaces (IDS). Each digital tool and data source is connected via an IDS connector, which handles data processing and ensures compatibility between different data types. Users interact with the digital twin via a graphical interface, where multiple digital tools are integrated, and the results are presented in interactive dashboards. Interoperability is also facilitated by a vocabulary provider and domain ontologies, where data is presented in a knowledge graph. Due to its modularity, other digital tools may be integrated into the system provided that data is compatible with the established ontology framework (Ziaei et al., 2022).

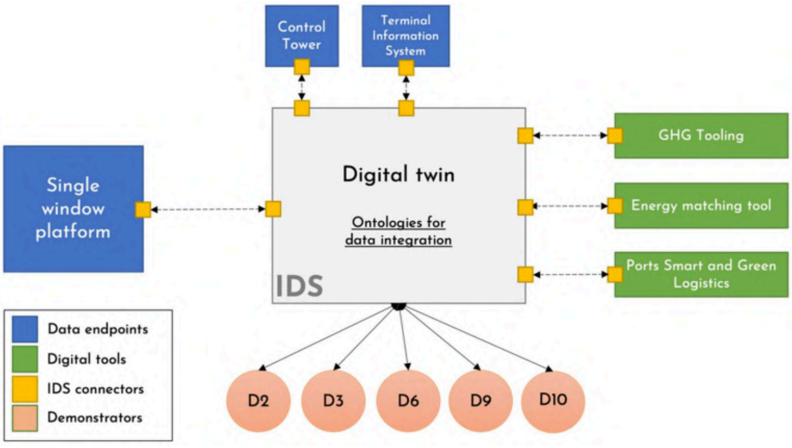


Figure 25. The conceptual system architecture for the Digital Twin (Ziaei et al., 2022).

4.2.1 Key insights for the port of Vaasa digital twin

The MAGPIE project also has some useful lessons for the creation of a digital twin for the Port of Vaasa, especially in relation to energy systems and sector coupling. This is particularly in relation to the integration of renewable energy sources, energy storage, shore power, and data. In addition, the MAGPIE project also has some useful lessons on the role of smart energy management systems and digital technologies in facilitating the use and consumption of energy in a more efficient manner. This is in addition to the potential for greater collaboration between port stakeholders. This is presented in Table 15.

Table 15. Key insights from the MAGPIE project relevant to the Port of Vaasa

Key Insight from the MAGPIE project	Relevance for the Port of Vaasa digital twin
Integration of renewable energy, storage, and shore power systems	Supports the development of an energy-focused digital twin capable of managing port electrification and sector coupling
Use of energy storage for peak shaving and grid flexibility	Demonstrates how storage can reduce grid pressure and improve energy system efficiency
Smart energy management systems coordinate energy flows	Enables optimization of energy supply between the grid, storage, renewable sources, and port operations
Scenario modelling for electrification, production, and storage planning	Can support long-term planning of energy infrastructure and renewable integration in the port
Digital twin architecture enabling secure data sharing across stakeholders	Facilitates collaboration between port authorities, energy providers, and logistics operators

5 Prototyping a Flexible Digital Twin

This chapter presents the development and implementation of a flexible digital twin prototype for the port environment. It covers the technical foundation, system architecture, and logic design that enable the digital twin to integrate data, simulate processes, and support decision-making. The chapter also highlights the tools, platforms, and programming environments used to build the prototype, followed by the implementation and visualization strategies that bring the digital twin to life. Together, these sections demonstrate how a practical, interactive, and adaptable digital twin can be developed to model complex port operations and support energy management and sector coupling initiatives.

5.1 Development Environment and Technical Tools

The development of the digital twin prototype necessitates the utilization of a number of software tools and technical environments, which provide support for modeling, programming, and data processing. The technological foundation of the proposed approach consists of these software tools, which make it possible to develop, manage, and visualize the digital twin. The chosen development environment integrates web technologies, 3D modeling tools, data analysis tools, and external data sources through APIs. All these components make it possible to develop a flexible and interactive digital twin prototype that can work with different types of data and provide a dynamic view of the port environment.

5.1.1 Digital Twin Platform

Cesium is an open and interoperable 3D geospatial platform that is meant to enable developers to create high-performance applications using the industry-leading implementation of 3D Tiles. By using a high-precision rendering engine and prioritizing data compatibility, it can stream and analyze large and complex data sets across various industries (Cesium GS, Inc., n.d.).

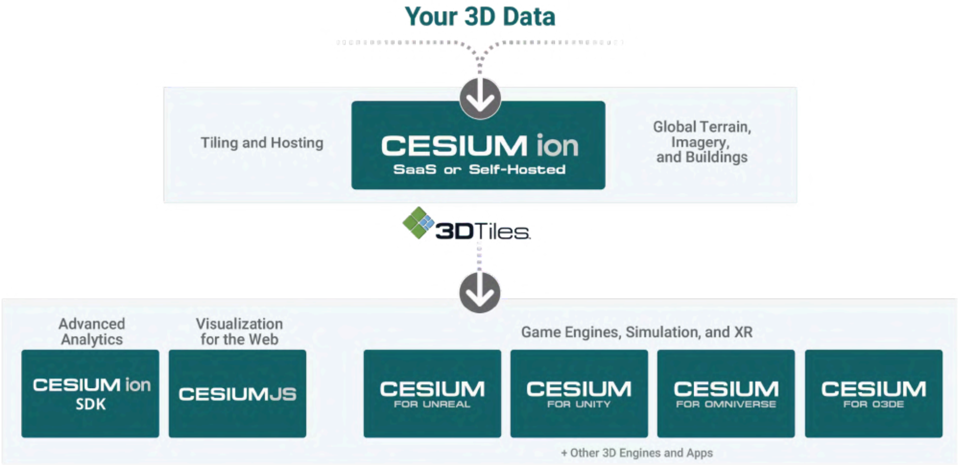
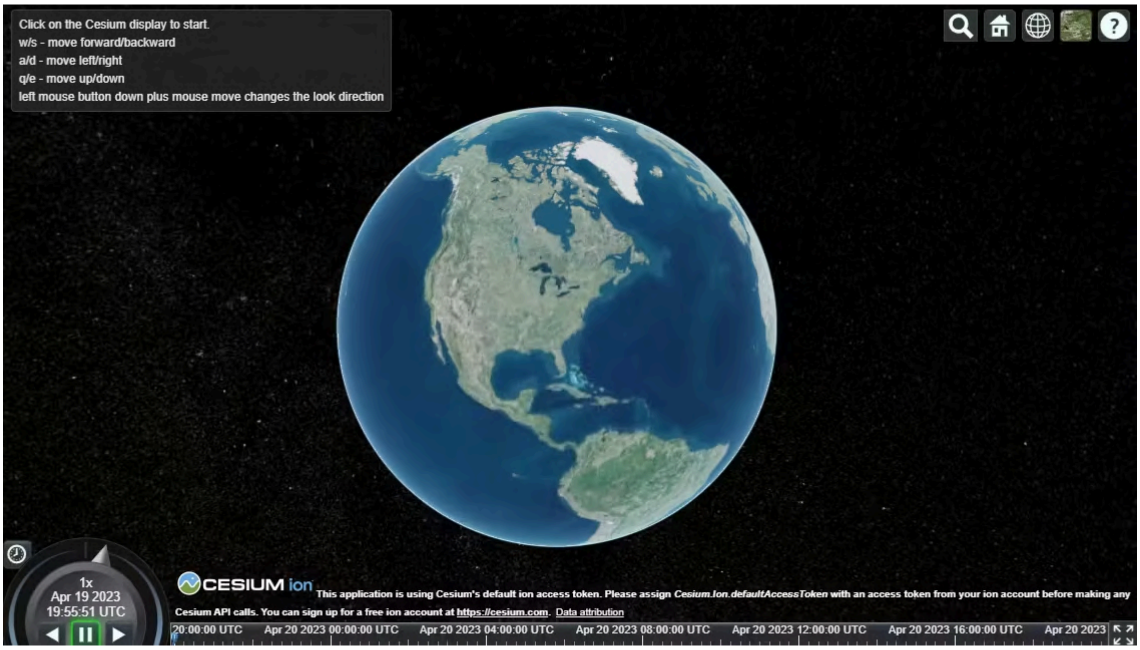


Figure 26. The Cesium ecosystem (Cesium GS, Inc., n.d.).

Acting as an open-source ecosystem, Cesium fills the space between photorealistic computer graphics and geospatial precision. It has originated from the aerospace industry's precision demands for tracking and visualization. By advocating for open standards like 3D Tiles and offering specialized plugins for game engines like Unreal, Unity, and NVIDIA Omniverse, the platform makes it possible to integrate diverse data into a high-precision WGS84 world. This open-standard approach and the emphasis on cross-industry innovations have made it possible for the seamless integration of massive 3D data in web and game engines (Cesium GS, Inc., n.d.).



Click on the Cesium display to start.
w/s - move forward/backward
a/d - move left/right
q/e - move up/down
left mouse button down plus mouse move changes the look direction

This application is using Cesium's default ion access token. Please assign *Cesium.Ion.defaultAccessToken* with an access token from your ion account before making any Cesium API calls. You can sign up for a free ion account at https://cesium.com. Data attribution

Figure 27. CesiumJS user interface (Cesium GS, Inc., n.d.).

CesiumJS is a JavaScript library that is developed to be a high-performance, web-based 3D geospatial visualization library. This library is used for developing interactive applications that can be used for large datasets. By using this library, developers can leverage the benefits of open formats and the WGS84 ellipsoid, creating a high-precision environment for streaming 3D tiles and dynamic content on desktop and mobile platforms. Its strong interoperability and usability features have made it a core library for sharing complex geospatial information in industries such as aerospace and urban planning. (Cesium GS, Inc., n.d.)

CesiumJS was chosen mainly because it is inherently web-based, which removes the need for a host game engine such as Unity or Unreal Engine, as well as the need for specific software installations. Being inherently web-based, it improves the accessibility of the digital twin prototype by being able to integrate well with current web technologies. Moreover, the web-based approach makes it easier to manage the digital twin prototype in terms of scalability across various devices, as it does not require local high-performance computation resources.

5.1.2 GIS Software

The development of a port's digital twin demands an effective GIS framework that can efficiently handle location-based information. A GIS tool is vital in this context because it facilitates the precise extraction of geographical features and site-specific information processing before exporting it to the host platform where the digital twin is built. This ensures that the bridge between raw spatial information and visualization is maintained so that the digital twin remains an accurate representation of the port's physical landscape.

As an open-source powerhouse, QGIS plays the role of a versatile hub in processing and visualizing geographic information. QGIS gives its users the ability to easily edit, analyze, and map all sorts of different data types, ranging from standard imagery like rasters to more complicated geometric shapes like vectors. QGIS's greatest strength is its compatibility with different formats. Through the use of different libraries like GDAL and OGR, QGIS can natively read all sorts of different formats, ranging from more complicated spatial databases to ESRI shapefiles, to more standard formats like GeoTIFF or JPEG (United Nations Office for Outer Space Affairs, n.d.).

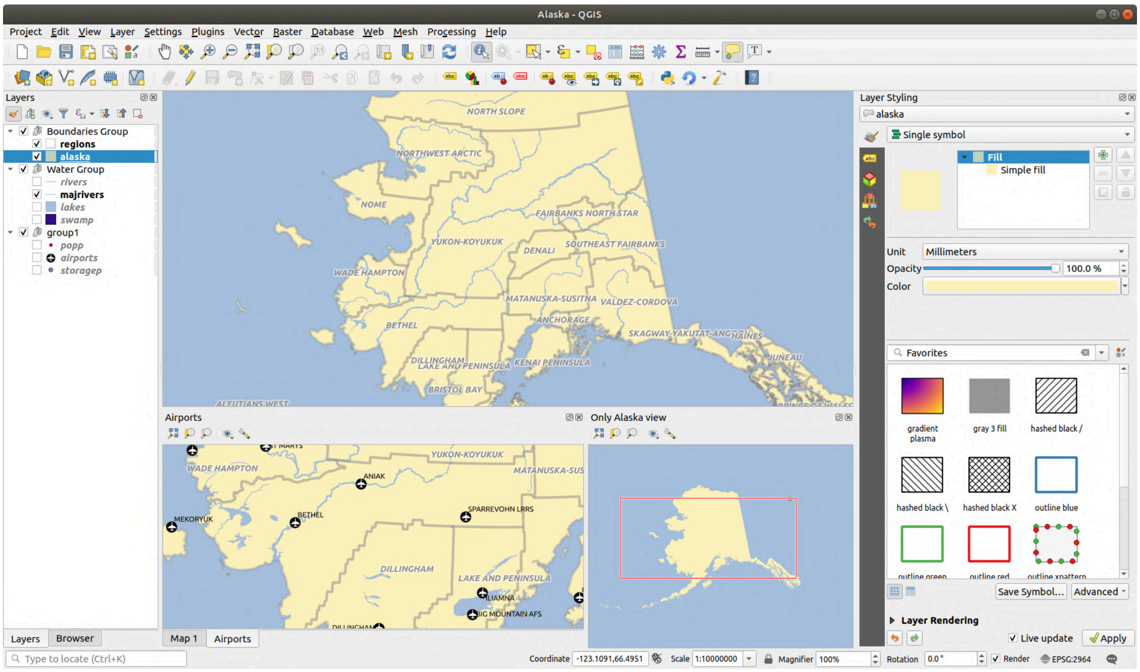


Figure 28. QGIS user interface (QGIS Project, 2024).

5.1.3 Data Analysis

In terms of data processing and analysis, Python and Google Sheets were utilized as the primary tools in cleaning, processing, analyzing, and interpreting the collected data. Python was primarily utilized in the processing, cleaning, and generation of results in analyzing the collected data, while Google Sheets was utilized in providing a conducive environment in organizing the collected data. The use of these tools was instrumental in the development of the digital twin prototype.

5.1.4 3D Modeling

The software that was selected for this project is Blender. Blender is used for creating 3D models. This software is used for creating and editing 3D models. After creating and editing 3D models using Blender, they can be exported in formats that can be used with CesiumJS. This is because Blender is a powerful 3D creation and editing software that is free and open-source. Moreover, Blender can export 3D models in various formats that can be used in web-based 3D applications. This makes it suitable for use with other tools that can be used in creating a digital twin.

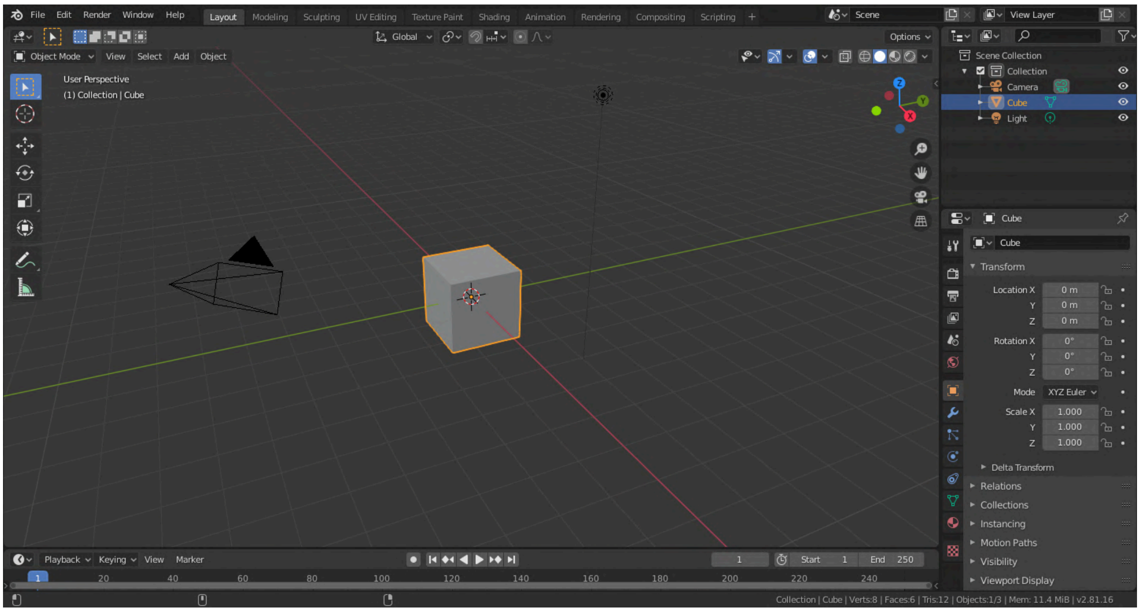


Figure 29. Blender user interface (Blender Foundation, 2019).

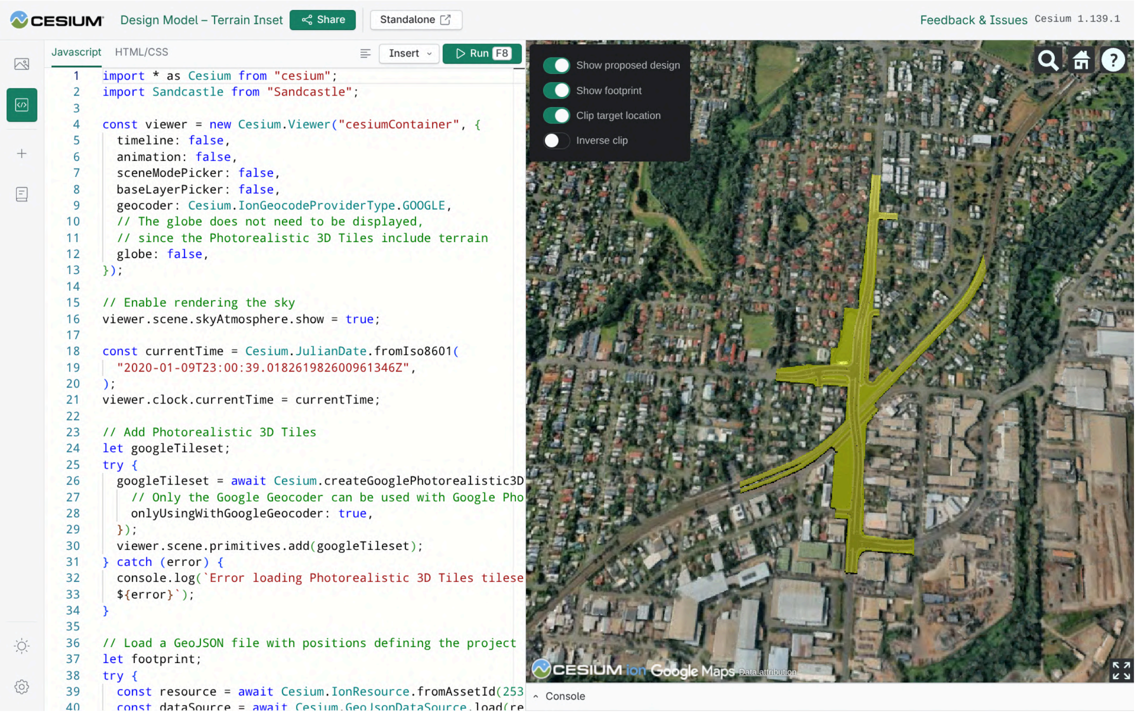
5.1.5 APIs

An Application Programming Interface (API) is a virtual bridge that enables the interaction between two different software components through a set of rules or protocols. API may be viewed as a "service contract" where one side of the contract makes a request, and the receiving end makes a specific response in compliance with the guidelines set in the contract (Amazon Web Services, n.d.).

During the development of the digital twin, APIs (Application Programming Interfaces) were used to connect the system with external data sources. For this digital twin, the OpenWeather API was incorporated to retrieve weather information relevant to the port area. The digital twin can retrieve weather information relevant to the port area at any given time, making it possible to perform simulations based on the weather. Through the use of live information, the digital twin becomes more dynamic.

5.1.6 Programming

JavaScript is the main programming language used in this project, as it is the core language of the CesiumJS library and enables the development of the interactive features of the digital twin. In addition to this, the programming languages HTML and CSS were used in the development of the interface of the digital twin-based web platform, which helps the end user in interacting with the digital twin using the interface. Moreover, the programming language Python was used in the development process in some cases, as it helps in the analysis of the data before it is integrated into the system. All the programming languages used in the development process helped in the creation of a functional prototype of the digital twin.



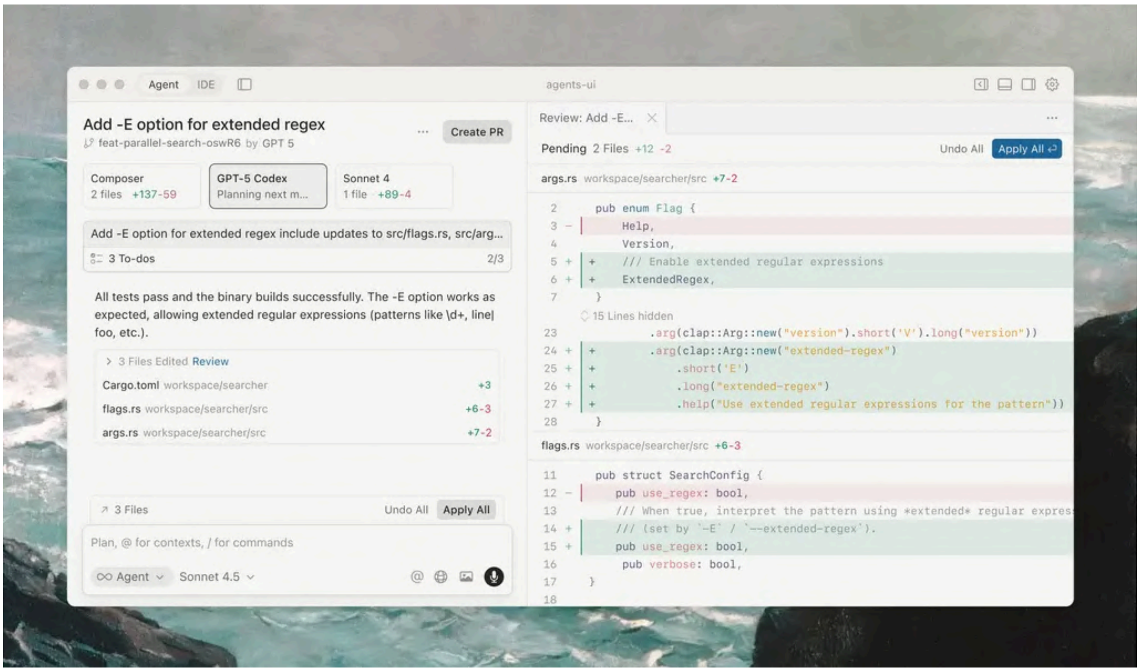
```javascript
import * as Cesium from "cesium";
import Sandcastle from "Sandcastle";

const viewer = new Cesium.Viewer("cesiumContainer", {
  timeline: false,
  animation: false,
  sceneModePicker: false,
  baseLayerPicker: false,
  geocoder: Cesium.IonGeocodeProviderType.GOOGLE,
  // The globe does not need to be displayed,
  // since the Photorealistic 3D Tiles include terrain
  globe: false,
});

// Enable rendering the sky
viewer.scene.skyAtmosphere.show = true;

const currentTime = Cesium.JulianDate.fromIso8601(
  "2020-01-09T23:00:39.018261982600961346Z",
);
viewer.clock.currentTime = currentTime;

// Add Photorealistic 3D Tiles
let googleTileset;
try {
  googleTileset = await Cesium.createGooglePhotorealistic3D
    // Only the Google Geocoder can be used with Google Pho
    onlyUsingWithGoogleGeocoder: true,
  });
  viewer.scene.primitives.add(googleTileset);
} catch (error) {
  console.log(`Error loading Photorealistic 3D Tiles tilese
  ${error}`);
}

// Load a GeoJSON file with positions defining the project
let footprint;
try {
  const resource = await Cesium.IonResource.fromAssetId(253
  const dataSource = await Cesium.GeoJsonDataSource.load(re
```

Figure 30. JavaScript coding in the CesiumJS example (Cesium GS, Inc., n.d.).

5.1.7 Developing environment

The development environment is where various stages of coding, testing, and debugging occur during the prototype implementation. In this project, we started development using Visual Studio Code, a popular code editor that offers great support for web technologies like JavaScript, HTML, and CSS. We managed version control and collaboration through GitHub and GitHub Codespaces. This setup allowed us to develop and test the project in a cloud-based environment when necessary.

However, as the code base grew in size and complexity, the development process moved to Cursor, which is an AI-assisted development environment developed on top of Visual Studio Code. This environment enabled the improvement of coding efficiency, debugging, and code navigation, all while being fully compatible with the JavaScript-based architecture required for the CesiumJS digital twin platform.



Add -E option for extended regex

feat-parallel-search-oswR6 by GPT 5

Add -E option for extended regex include updates to src/flags.rs, src/arg...

All tests pass and the binary builds successfully. The -E option works as expected, allowing extended regular expressions (patterns like \d+, line|foo, etc.).

```
    pub enum Flag {
-       Help,
        Version,
+       /// Enable extended regular expressions
+       ExtendedRegex,
    }
```

```
              .arg(clap::Arg::new("version").short('V').long("version"))
+             .arg(clap::Arg::new("extended-regex")
+                 .short('E')
+                 .long("extended-regex")
+                 .help("Use extended regular expressions for the pattern"))
    }
```

```
    pub struct SearchConfig {
-     pub use_regex: bool,
      /// When true, interpret the pattern using *extended* regular expres
+     /// (set by `-E` / `--extended-regex`).
+     pub use_regex: bool,
       pub verbose: bool,
    }
```

Figure 31. Cursor user interface Cursor (n.d.).

5.2 System Architecture and Logic Design

This section will cover the architecture, data integration logic, and working process of the digital twin prototype of the Port of Vaasa. The developed digital twin is intended to reflect the physical infrastructure of the Port, integrate data, and offer an interactive environment for analysis and evaluation. The architecture of the developed digital twin is based on a layered approach.

5.2.1 Overall System Architecture

The digital twin of the Port of Vaasa is designed with the aim of meeting the needs of the port, based on the analysed context of the port, and also the literature review conducted in this research and other case studies that have been analysed in the previous section.

As presented in Figures 32 and 33, the digital twin architecture will comprise three layers, which are integrated with each other. The Physical Infrastructure and Sensing Layer will provide the foundation for this system, which will comprise a representation of all physical assets, facilities, and infrastructure within the digital twin of the port. This layer will ensure that all physical aspects, such as cranes, storage facilities, and transportation routes, are digitally connected to the system. Collected data from port facilities related to the status, condition, and activities of these physical assets will be connected to this layer so that the digital twin has a realistic and current representation of the physical environment of the port.

Decision, Interaction & Visualization Layer

This layer consists of visualization tools, simulation interfaces, operator dashboards, and automated control mechanisms that convert intelligence into actionable decisions and strategic insights.

Digital Twin & Intelligence Layer

This layer consists of the digital twin models, algorithms, and optimization engines that transform raw data into system understanding, prediction, and operational intelligence.

Physical Infrastructure & Sensing Layer

This layer consists of real-world physical assets, operational entities, and embedded sensing devices that capture real-time data and represent the actual state and behavior of the system.

Figure 32. Hierarchical Framework for Digital Twin Integration.

Above this layer is the Digital Twin and Intelligence Layer. It is the “brain” of the system. It processes the data collected from the physical layer using algorithms, computational models, and predictive logic. It simulates the operations, predicts possible issues, and optimizes the operations of the port. The topmost layer is the Decision, Interaction, and Visualization Layer. It is the interface through which the stakeholders can interact with the digital twin. It interprets the results produced by the digital twin and provides the stakeholders with the required insights. It enables them to monitor the activities, make decisions, and interact with the operations of the port.

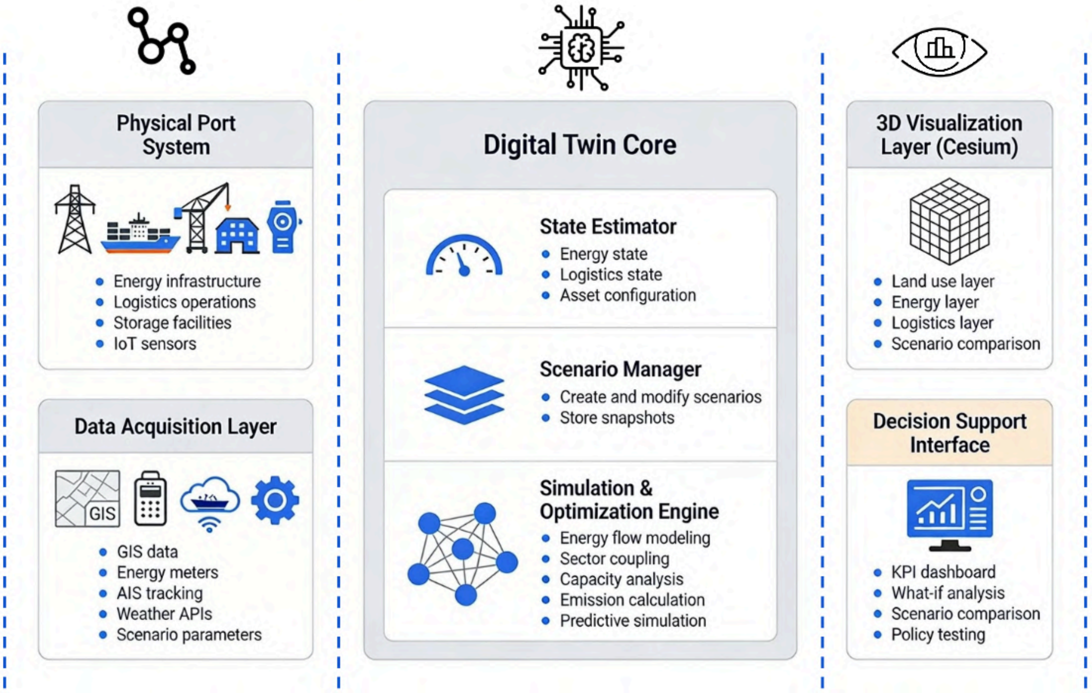


Figure 33. Three main layers of the digital twin.

5.2.2 Data Integration and System Logic

The starting point for a strong digital twin is the integration of data, and this is where the gap is closed between the actual port and its virtual connection. The best-case scenario is that the system is a living mirror, maintained through a constant flow of data from sensor networks, logistics, and weather stations. The information is a holistic overview of the pulse of the port, including everything from the exact movement of cargo to the changing levels of energy consumption and the weather.

In this project, the lack of direct access to actual live operational data at the Port of Vaasa required the use of artificially created data. Such artificially created inputs were designed to closely replicate the actual operational loads and system activities present in the real world. Through the use of this data, the prototype was successfully able to validate the actual system architecture and the data and logic paths present within the system.

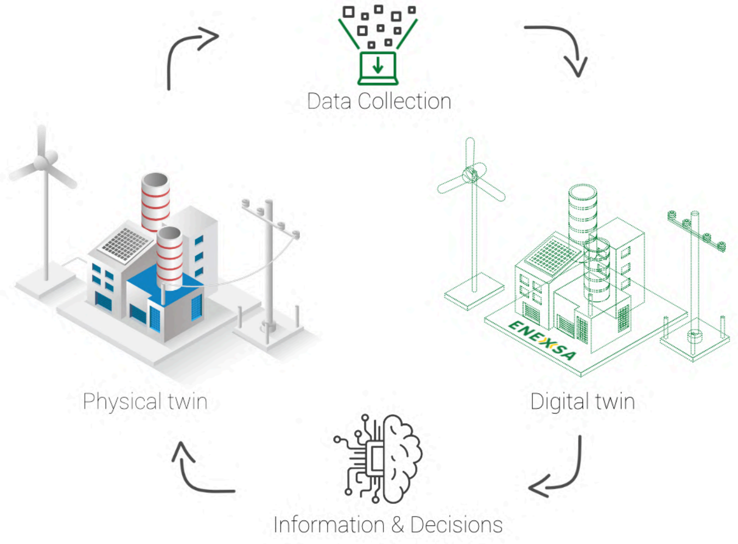


Figure 34. The role of data in connecting physical and digital twins (Enexsa, n.d.).

As shown in Figure 35, the internal architecture of this system manages this information through a structured, multi-layered process. First, the data enters a state management layer, in which the status of all port assets is recorded, and this information is then processed through a computational logic to obtain system behavior, and this behavior is then sent to a visualization environment, ensuring that the virtual model remains synchronized with this data. This modular approach to building a digital twin also means that a smooth transition from simulated to actual operational data can be made, allowing for a fully realized digital twin in a live environment.

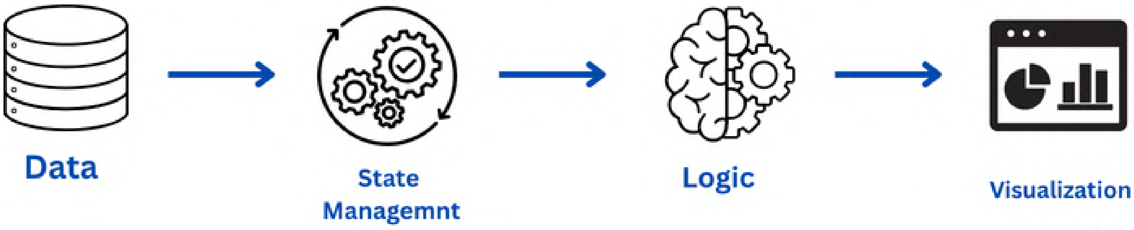


Figure 35. The general workflow of the digital twin prototype.

5.2.3 User Interaction and Visualization Environment

The digital twin prototype offers an interactive environment for users to explore, analyze, and evaluate the operations and development scenarios of the Port of Vaasa.

As depicted in Figure 36, this interaction layer can be seen as a communication interface between the digital twin system and users, providing users with spatial information and operational insights in an intuitive visual environment.

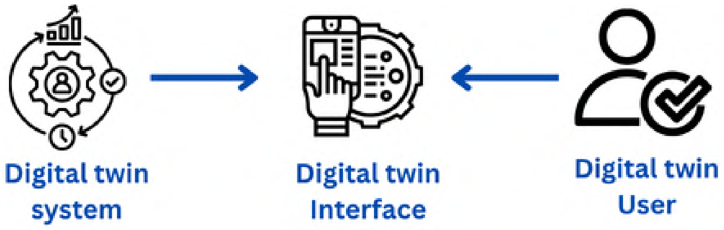


Figure 36. The interaction between the user and the digital twin prototype's system.

The platform used for visualizing and interacting with the digital twin environment is CesiumJS. This platform facilitates the development of a web-based three-dimensional model of the port infrastructure, where the terrain, infrastructure components, operational assets, and zones of land use can be spatially presented in the geospatial environment. Within this platform, the user has the flexibility to navigate the spatially presented port infrastructure and get insights and information from it. Various information components, such as logistics assets, energy infrastructure, transportation routes, and zones of land use, can be presented separately in the platform. This helps stakeholders understand the spatial and functional interaction of the components in the port infrastructure.

This interactive environment will also allow users to explore specific infrastructure elements within the digital twin. Users will have the option to select individual assets, such as crane systems or storage facilities, to obtain additional information on their operational status or role within the port infrastructure. This will increase transparency and promote a better understanding of relationships between different infrastructure elements.

Additionally, the interface can facilitate exploratory analysis in various ways. For instance, it can help users evaluate different development configurations and planning scenarios. In this way, the interface can help the user evaluate the potential effects of proposed changes in infrastructure, logistics, and energy systems on the general functioning of the port. In this way, the digital twin can function as a decision-support tool in which spatial understanding, system exploratory analysis, and scenario evaluation can be performed within a unified digital platform.

5.3 Prototype Implementation and Demonstration

Following the definition of the system architecture and the system interaction framework, a functional prototype of the digital twin was developed to reflect the application of the proposed approach to the Port of Vaasa. The main aim of the developed prototype was to create a digital environment where the spatial structure of the port and the infrastructure components and zones, as well as the possible development areas, would be presented in a manner allowing for exploration and interactive experience. The developed prototype represents a practical application and implementation of the proposed digital twin concept. By using the developed prototype, the spatial structure of the port and the infrastructure components would be presented in a three-dimensional virtual environment.

Following the definition of the system architecture and the system interaction framework, in order to validate the proposed digital twin framework, a functional prototype has been developed for the Port of Vaasa. This prototype aims to demonstrate the potential of the proposed conceptual architecture discussed in the previous sections in terms of its capability for being implemented into a digital platform. It is important to note that the prototype does not seek to emulate the full complexity of the Port of Vaasa in terms of its operations; instead, it aims at validating the feasibility of the digital twin concept and its potential for being used for spatial analysis, infrastructure understanding, energy matters, and development planning. The implemented prototype for the digital twin platform provides an interactive environment for visualizing the infrastructure of the Port of Vaasa and its different operational zones.

5.3.1 Prototype Implementation Overview

The prototype was created as a web-based application, utilizing common technologies such as HTML, CSS, and JavaScript, as shown in Figure 37. This allows for access to the digital twin through any web browser, as well as flexibility for future system expansion with more data sources. As mentioned earlier in the previous sections, the geospatial visualization component of this prototype was created using CesiumJS, which allows for the creation of an interactive 3D world based on geographic coordinates. This platform allows for visualization of terrain, infrastructure, and spatial data within a virtual world.

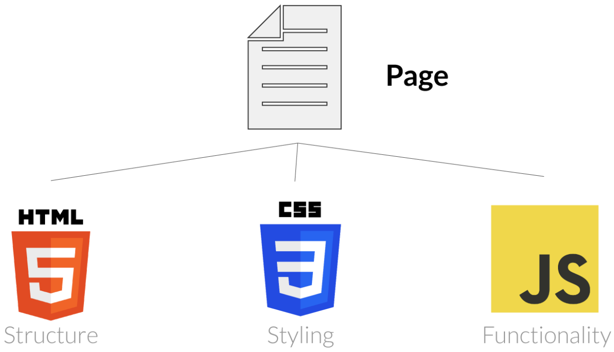


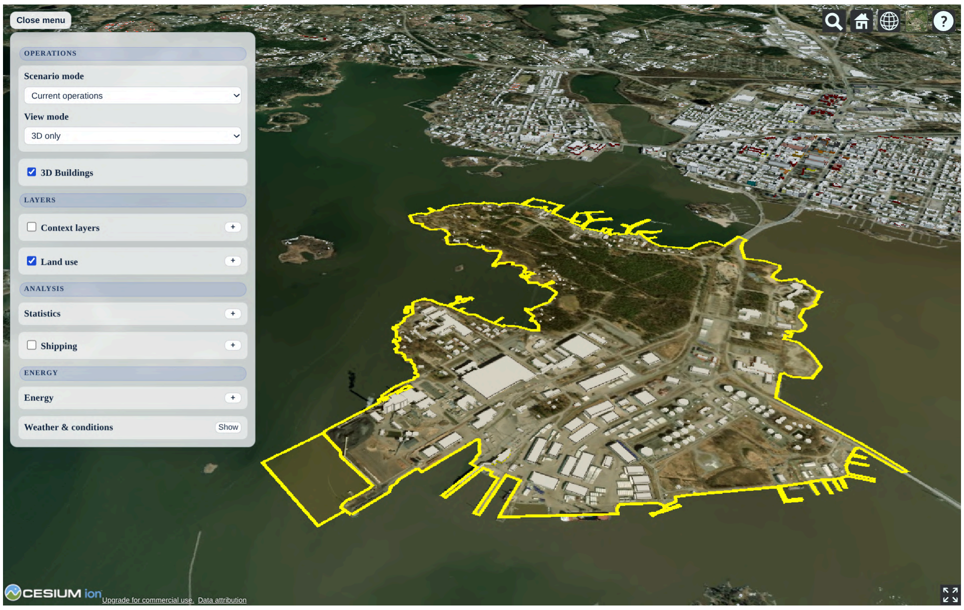
Figure 37. The three building blocks of a web page (Kononenko, 2018).

5.3.2 Demonstration of the Digital Twin Prototype

During the development of the digital twin prototype, one of the main goals of designing the system was to make sure that it was simple to understand, use, and maintain. The user interface of the system was specifically designed to make the interaction with the digital twin model as easy for the user as possible, without any significant need for technical knowledge. Figure 38 shows an overall depiction of the port area and its surrounding environment as seen in the digital twin model. As shown in Figure 38, the prototype includes three-dimensional buildings; the visibility of 3D buildings can be easily toggled in the side menu.

Figure 38. An overview of the port in the prototype.

As is illustrated in Figure 39 below, the basic functions and possibilities of the prototype can be found via the side menu that serves as the key point of contact when interacting with the software. Through this menu, users can handle the different scenarios, control the view, and manage a number of layers. These include the possibilities to show/hide 3D buildings, land use layers, and weather conditions. Users can also get access to historical data and statistics concerning the port capacity, as well as the layers related to the energy systems and sector coupling.



Scenario mode: Current operations

View mode: 3D only

☑ 3D Buildings

☐ Context layers +

☑ Land use +

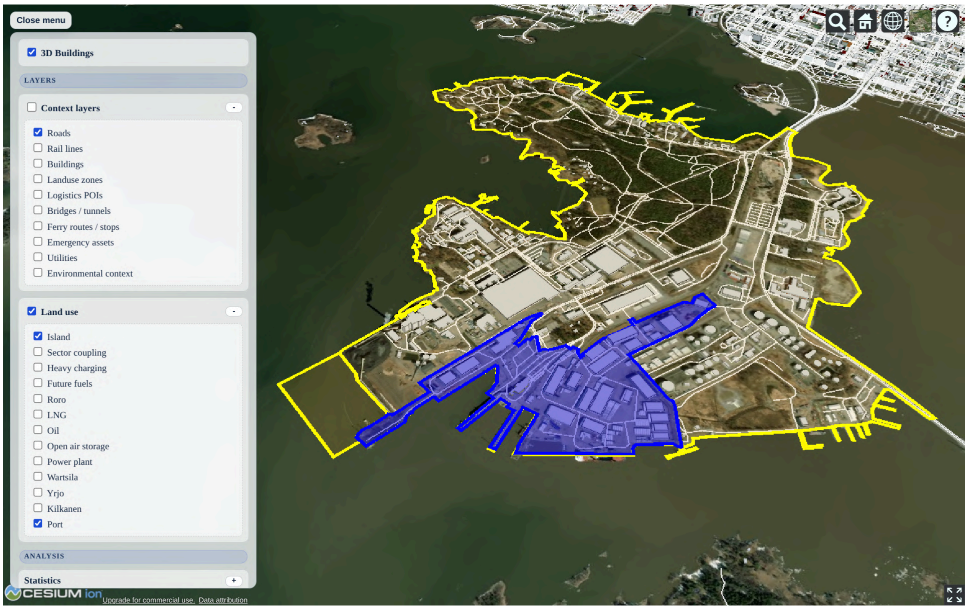
Statistics +

☐ Shipping +

Energy +

Weather & conditions

Figure39. The side menu and main functionalities of the prototype.



☑ 3D Buildings

☐ Context layers -
- ☑ Roads
- ☐ Rail lines
- ☐ Buildings
- ☐ Landuse zones
- ☐ Logistics POIs
- ☐ Bridges / tunnels
- ☐ Ferry routes / stops
- ☐ Emergency assets
- ☐ Utilities
- ☐ Environmental context

☑ Land use -
- ☑ Island
- ☐ Sector coupling
- ☐ Heavy charging
- ☐ Future fuels
- ☐ Roro
- ☐ LNG
- ☐ Oil
- ☐ Open air storage
- ☐ Power plant
- ☐ Wartsila
- ☐ Yrjo
- ☐ Kilkanen
- ☑ Port

Statistics +

Figure 40. Context-related layers of the prototype.

Data related to the context contributes significantly towards enhancing the understanding of the system as well as making decisions. Hence, this information can be accessed easily via the prototype's menu. As depicted in Figure 40 above, the system has been designed with two major layers: the context layer and the land use layer. The context layer is generated from the OpenStreetMap, which acts as the base map for the digital twin and comprises various elements of the infrastructure found within the surrounding areas. Conversely, the land use layers have been developed using QGIS with reference to the port map before being incorporated into the prototype.

Statistics on the port for the last ten years are available directly through the main menu of the prototype under the Statistics category, as shown in Figure 41. These statistics are based on data from the Finnish Port Association and reflect various dimensions of port operations. Clicking on each statistics category shows the relevant statistics on screen in the form of graphs, accompanied by explanations that assist in interpreting the data. This will make information about past trends readily available and support better decision-making.

International transport

Port of Vaasa international cargo volumes by year (tonnes). Import covers inbound sea freight, export covers outbound.

Trend (2016–2025): Overall **downward** (-10.6%).

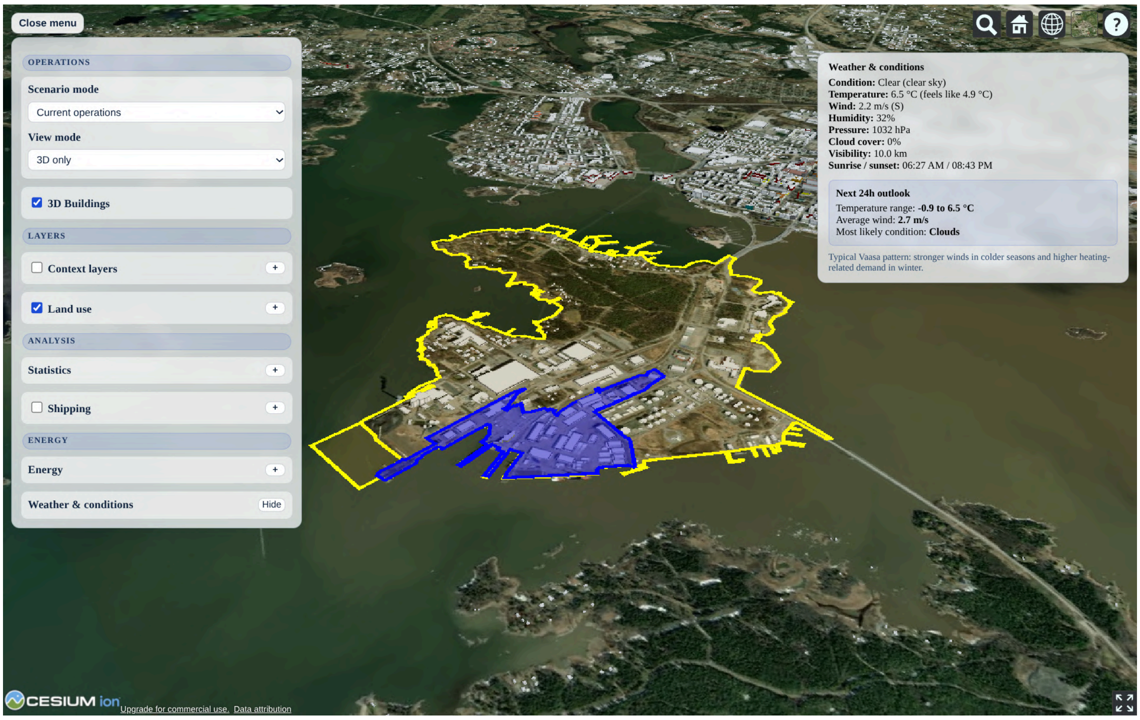
Import declined by 276,370 (-31.1%).
Export grew by 165,834 (+103.9%).

Peak year: **2022** (1,180,127 TN). Lowest: **2020** (774,573 TN).

Combine with scenario assumptions for planning conclusions.

Figure 41. Showing the statistics of the port inside the prototype.

Another available feature of the prototype is the weather update section, where weather data is fetched using the integrated OpenWeather API, as depicted in Figure 42. The weather data includes such details as temperature, wind speed, humidity, among others, in addition to weather forecasts for the next 24 hours. Given the absence of on-site sensor data at the moment, weather data can still find applications in several digital twin use cases, especially those relating to energy management and shipping operations at the port.



Scenario mode: Current operations
View mode: 3D only
☑ 3D Buildings
☐ Context layers
☑ Land use
☐ Shipping

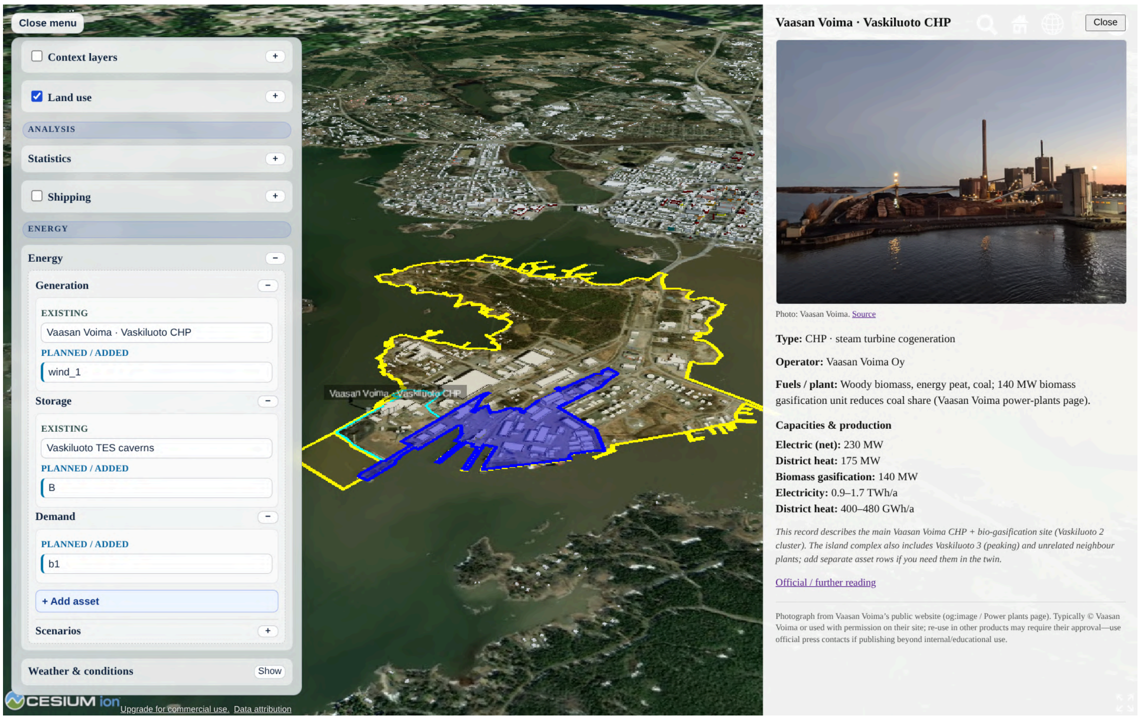
Weather & conditions
Condition: Clear (clear sky)
Temperature: 6.5 °C (feels like 4.9 °C)
Wind: 2.2 m/s (S)
Humidity: 32%
Pressure: 1032 hPa
Cloud cover: 0%
Visibility: 10.0 km
Sunrise / sunset: 06:27 AM / 08:43 PM

Next 24h outlook
Temperature range: **-0.9 to 6.5 °C**
Average wind: **2.7 m/s**
Most likely condition: **Clouds**

Typical Vaasa pattern: stronger winds in colder seasons and higher heating-related demand in winter.

Figure 42. The weather feature of the prototype.

Lastly, the energy section is among the most important aspects of the prototype. This component gives the decision makers the ability to generate multiple development scenarios based on various energy assets. Different existing components can be chosen within the energy production, storage, or demand categories, or new ones could be created and added, which would enable the users to try and evaluate different combinations. An example of this combination could be having wind farms in the energy production sector, lithium-ion battery storage, and a certain level of energy demand. The results of such combinations are shown in Figures 43, 44, and 45.



Vaasan Voima · Vaskiluoto CHP

Photo: Vaasan Voima. Source

Type: CHP · steam turbine cogeneration

Operator: Vaasan Voima Oy

Fuels / plant: Woody biomass, energy peat, coal; 140 MW biomass gasification unit reduces coal share (Vaasan Voima power-plants page).

Capacities & production

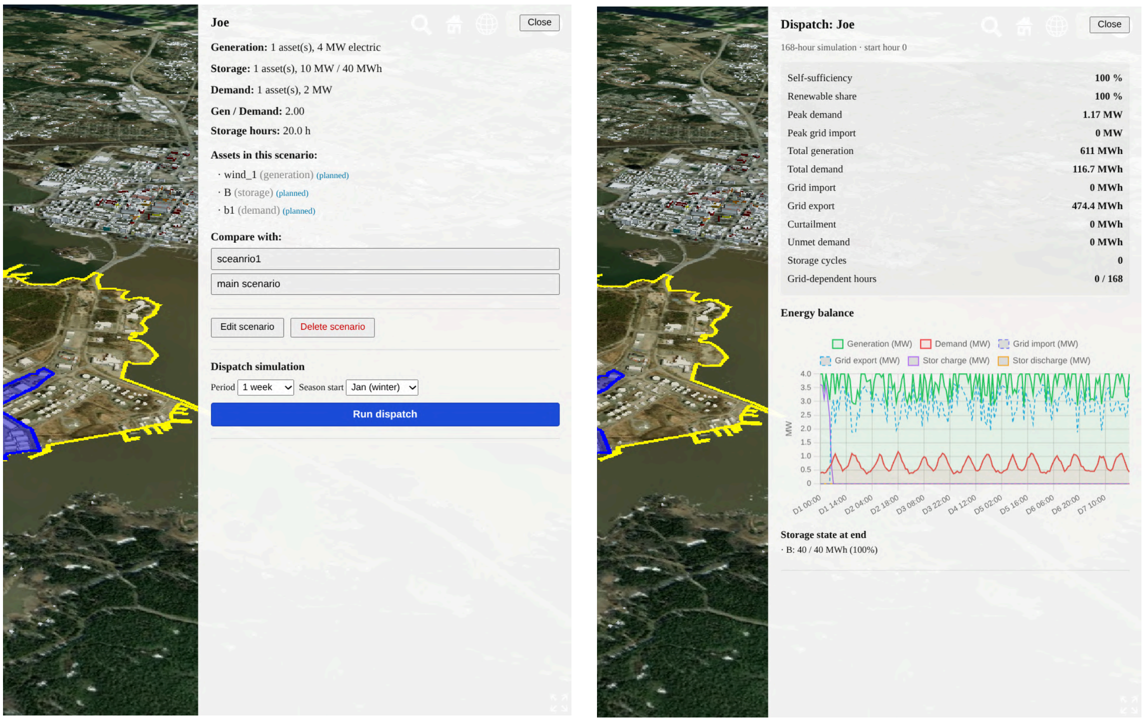
Electric (net): 230 MW
District heat: 175 MW
Biomass gasification: 140 MW
Electricity: 0.9–1.7 TWh/a
District heat: 400–480 GWh/a

This record describes the main Vaasan Voima CHP + bio-gasification site (Vaskiluoto 2 cluster). The island complex also includes Vaskiluoto 3 (peaking) and unrelated neighbour plants; add separate asset rows if you need them in the twin.

Official / further reading

Photograph from Vaasan Voima's public website (og:image / Power plants page). Typically © Vaasan Voima or used with permission on their site; re-use in other products may require their approval—use official press contacts if publishing beyond internal/educational use.

Figure 43. Selection and creation of different energy assets.



Joe

Generation: 1 asset(s), 4 MW electric
Storage: 1 asset(s), 10 MW / 40 MWh
Demand: 1 asset(s), 2 MW
Gen / Demand: 2.00
Storage hours: 20.0 h

Assets in this scenario:

· wind_1 (generation) (planned)
· B (storage) (planned)
· b1 (demand) (planned)

Compare with:

sceanrio1
main scenario

Dispatch simulation

Period 1 week Season start Jan (winter)

Dispatch: Joe

168-hour simulation · start hour 0

Self-sufficiency	100 %
Renewable share	100 %
Peak demand	1.17 MW
Peak grid import	0 MW
Total generation	611 MWh
Total demand	116.7 MWh
Grid import	0 MWh
Grid export	474.4 MWh
Curtailment	0 MWh
Unmet demand	0 MWh
Storage cycles	0
Grid-dependent hours	0 / 168

Energy balance

Storage state at end

· B: 40 / 40 MWh (100%)

Figure 44 & 45. Scenario creation and evaluation

5.3.3 Prototype Capabilities and Future Steps

The developed prototype of the digital twin of the port presents several important features that show great promise for its future use as an analysis and decision support within the port setting. Firstly, it provides the possibility for intuitive exploration of spatial information using the 3D model of the port and its environment. Secondly, it incorporates numerous layers of data, such as land use, infrastructure, meteorological conditions, and historical statistics, in order to provide a more complete picture of how the port works. Also, basic scenario analysis is possible using the energy module, where various components are combined into an integrated system.

Another important capability is the use of external data sources, for example, meteorological data, which is also important, since it will increase the dynamics of the model and enable the application to be more representative of reality. Despite its early state, the prototype demonstrates the potential that digital twins have for improving awareness, planning, and initial decision-making without necessitating technical expertise on the part of the user.

The prototype currently in use is still a basic model that serves mainly as a proof of concept. There are several areas where improvement can be made in the next versions and future developments. First, the inclusion of real-time data captured by the sensors in port activities can greatly improve the accuracy of the predictions. Second, enhancing the energy modeling through further simulation and optimization techniques, and improving the interoperability with other port management systems like Terminal Operating Systems (TOS). In addition to that, the inclusion of advanced analytics and machine learning would greatly benefit the decision-making process within the digital twin.

The future development direction will need to concentrate on improving the prototype in terms of functionality and practical applicability, rather than complicating the system itself. In particular, incorporating real data from the port logistics process, such as vessel schedules, berth allocation, and cargo flows, will enable the creation of an accurate digital twin that will enable coordination among various processes. The next area worth exploring is the association of the energy part of the prototype with demand profiles and electricity prices that change over time to allow the user to test how well the scenarios fare in a dynamic setting. Moreover, including some user-imposed conditions, such as maximum emissions, minimum capacities, or other policy goals, would make the scenario analysis even more relevant to practical situations. Finally, enabling multiple users to interact and view things from their perspective could convert the tool into a collaboration platform for various stakeholders, such as port authorities, energy planners, and operators.

6 Strategic Roadmap and Discussion

The discussion in this chapter aims to address the manner in which the ideas discussed in the entire thesis will contribute to the further development of the Port of Vaasa. Based on the theoretical approach used as well as the prototype development and transition to smart sustainable ports, a roadmap is proposed for the adoption of digital twin technology, energy systems, and sector coupling. Furthermore, the chapter evaluates the way in which the prototype developed can be incorporated into the trends of future smart ports.

6.1 Phased Implementation Plan for the Port of Vaasa

The transition to smarter and sustainable development at the port can only be done through phased approaches. This is because there needs to be an assessment of technological readiness, cost implications, and other issues before any move is made to enhance the port facilities. From this research, a three-phased plan of action is suggested for implementation at the port of Vaasa.

6.1.1 Short-Term Phase (2026–2028)

In the short-term phase, it is important to pay attention to laying the digital and organizational groundwork that will be necessary for the future implementation of smart solutions at the port. Therefore, the emphasis in the near future is on ensuring better data access and situational awareness related to port facilities and energy system operation.

Key actions of this phase could include:

- Developing basic digital infrastructure and data integration systems.
- Expanding GIS-based port mapping and visualization.
- Including and integrating operational and environmental data into a centralized platform.

- Starting pilot digital twin of the port for visualization and monitoring.
- Implementing operational weather and energy monitoring systems (sensors).

This phase will focus more on improving transparency and information availability, enhancing digital readiness, while keeping things simple and risk-free for investors.

6.1.2 Medium-Term Phase (2028-2032)

The medium-term phase should aim to enhance the operational intelligence capabilities and incorporate real-time systems within the digital twin ecosystem. At this level, the prototype may be developed further to become an interactive operational support system.

Key actions of this phase could include:

- IoT sensor integration and real-time operations data feed.
- Port logistics and operation system connectivity.
- Creating predictive maintenance and monitoring capabilities.
- Energy module expansion to include dynamic energy consumption profiling.
- Sector coupling solutions testing, such as shore power, batteries, and renewables integration.
- Scenario evaluation for energy management and operations optimization.

By this point, the digital twin should provide a platform for more sophisticated decision-making and scenario evaluation of operations and energy use.

6.1.3 Long-Term Phase (2032–2040)

The long-term phase denotes the beginning of the shift towards an interconnected and adaptive smart port environment. It may involve the use of the digital twin as the main operating platform, bringing together the logistics, infrastructure, energy systems, and sustainability factors.

Among other possible developments, the following may be expected:

- Complete incorporation of renewable energy systems and technologies related to sector coupling.
- AI-based optimization and predictive decision-making.
- Synchronization between ships, port infrastructure, and energy systems.
- Connection to the smart regional energy networks and industrial ecosystems.
- Creating a port with the ability to function as a multi-energy hub for electricity, hydrogen, heat, and other energy sources.

In the long term, the Port of Vaasa can move from its current role as a conventional logistics hub to a future state as an interconnected and energy-linked smart port.

6.2 Alignment with Future Smart Port Development

The designed prototype fits well with the trend towards making more advanced and sustainable decisions related to modern port operations. Contemporary ports tend to go far beyond their conventional scope and transform into connected ecosystems, which rely on digital and automated solutions as much as possible.

Among the main advantages of the prototype created during the course of this study can be mentioned its flexibility and modularity. As opposed to the idea of recreating complicated industrial systems immediately, the prototype shows how a digital twin might develop in small steps over time. The described approach appears to be relevant for such ports as the Port of Vaasa, where scalability, cost-effectiveness, and adaptability matter most of all.

The use of visualization means that contextual data, weather forecasts, statistics, and analysis of energy scenarios are some of the features that demonstrate how the prototype fits into the concept of modern smart ports. More specifically, the design of energy-related functions proves the growing relevance of ports as energy hubs in the future.

However, there are still various challenges associated with the adoption of digital twin technology in ports. For example, one of the issues is connected to the availability of data. The other challenge is the interoperability issue between the existing systems. Other problems relate to cybersecurity issues, investments in such projects, and cooperation of numerous parties. In addition, smaller ports may have some technical restrictions. Nevertheless, open-source software and modularity may mitigate some of the issues mentioned above.

In conclusion, this research shows that digital twins can do more than just visualize the information. When combined with the energy system and other data integration technologies, digital twins may contribute significantly to the efficient management of port operations. Moreover, they may be useful in making long-term decisions and planning sustainable strategies. In the conditions of environmental, technological, and economic changes in port operations, a flexible digital twin platform may serve as the basis for future developments.

7 Conclusion

This thesis has examined the use of digital twins in the development of smart ports and the phenomenon of sector coupling in relation to future sustainable port systems. The methodology used in the thesis has been based on both theoretical analysis and prototyping of a flexible digital twin solution for the Port of Vaasa. The purpose of the thesis was to explore the potential uses of information technologies and energy integration approaches in future sustainable port operations.

The findings from the theoretical analysis revealed that ports are gradually transforming into interconnected digital and energy networks. Modern ports are not simply logistical structures, but become an integral part of data exchange, renewable energy systems, and digital infrastructure. In this sense, the introduction of digital twins was shown to be a relevant technology that would help to combine physical and digital worlds and ensure monitoring, simulation, visualization, and optimization of operations. Moreover, the phenomenon of sector coupling was found to be of great significance for future energy systems, which would involve electricity, heat, transport, and alternative fuels.

A digital twin prototype has been created from these principles, based on web-based and open-source solutions. This prototype combines several features such as 3D visualization, contextualization, weather conditions, statistical analysis, and energy scenario generation. The simplicity of use, adaptability, and accessibility are considered key in this concept because anyone will be able to interact with the digital twin without any complicated processes.

The contribution of this research can be regarded in different ways; however, the main conclusion here is that the digital twin may serve as a tool for future smart port development and its transformation from visualization towards increased situational awareness, data integration, and scenario-based decision-making. In addition, energy functionalities incorporated in digital twin environments allow for transforming ports from passive entities to actively participating elements in regional energy landscapes.

In addition to this, the research points out some of the difficulties that arise when implementing a digital twin concept, such as the availability of data, interoperability issues, cybersecurity threats, financing needs, and stakeholder coordination. These problems are especially pertinent to small-scale ports due to their limited access to funding and technology. Still, the research shows that the adoption of modular and scalable solutions, utilizing open-source tools, makes the process more feasible.

The present thesis makes a theoretical contribution to the field of smart port research. It establishes a connection between the theories of smart ports, digital twins, renewable energy systems, and sector coupling. Also, it makes a practical contribution by introducing a versatile prototype designed specifically for the Port of Vaasa and presenting a roadmap for its future application.

Even though it is beneficial, there are some weaknesses in the study. The prototype itself lacks integration into real-life operations within the port environment. Besides, the energy scenarios considered within the research are theoretical and simplistic because of a lack of data about operations. However, further studies could be aimed at the use of sensors and analytics tools, including artificial intelligence, as well as more advanced modeling of energy systems. Greater collaboration with stakeholders and interoperability of a digital twin platform with existing port systems could improve its efficiency even further.

In conclusion, this thesis shows that the application of digital twins is quite promising for addressing the issues that ports will face in the future. Flexible platforms coupled with sector coupling can be used by ports to create resilient digital port environments in the near future.

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