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# Port 4.0: a conceptual model for smart port digitalization

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**Abstract**

Port and terminal operators are experiencing growing complexity and rapidly accelerating demands. As a result, the entire port ecosystem — from the seaports to inland intermodal terminals — is under pressure to modernize. Port 4.0 is a port that leverages advanced technologies to digitally transform key business processes, improve security, and increase operational efficiency and port sustainability. This study presents a conceptual framework for Port 4.0. The conceptual framework describes key principles, enabling technologies, and key service areas for port digitalization. The framework is illustrated using digitalization examples in different ports worldwide.


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*Keywords:* Port 4.0; smart port; digitalization; port automation; Industry 4.0.

## 1. Introduction

With increasing trade routes and global sea traffic, and the vast demand of the ever-increasing population, the ports and sea terminals are getting increasingly busy hubs. Due to the growing global trade volume, the (container) vessel sizes have grown exponentially over the past decade as well (Tetteh et al., 2016). To align with these trends, many ports aim to increase the port handling infrastructure capacity (for example, see Maasvlakte 2 project in Port of Rotterdam) or continuously improve the productivity of port operations and processes (van Hassel et al., 2020). At the same time, digital and ICT (information and communications technology) tools and innovations have developed rapidly during the last two decades, providing abundant opportunities for improving port processes and decisions.

Port 4.0 is the conceptual framework to characterize an organized and consistent development of digital tools at ports. It is generally defined as the application of Industry 4.0 tools and concepts to the port sector (de la Peña Zarzuelo et al., 2020). Yet, detailed models and frameworks are needed to guide this development and customize the Industry 4.0 concepts to the port and shipping sector. This study aims to present such a framework, describing the key elements

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of Port 4.0. To develop the framework, we used the existing literature (both scientific and grey literature, including example reports of port authorities and shipping companies as well as of EU-supported projects on port digitalization).

The rest of this paper is structured as follows. Section 2 presents a framework for Port 4.0. The framework describes the primary dimensions as well as the enabling technologies for developing Port 4.0. Section 3 extends the framework and presents the specific services and solutions together with several demonstrative examples of ports worldwide.

Section 4 concludes this paper.

## 2. Conceptual model for Port 4.0

The 4th Industrial Revolution, or Industry 4.0, "describes a new paradigm of digitized and connected industrial value creation" (Kiel, 2017, p.1). It entails completely digitalizing production and service processes using a set of digital technologies and tools. Industry 4.0 has also highlighted some new concepts, including cyber-physical spaces or smart factories. In the port and shipping sector, the transition has been described by different terms like "Smart Port," "Sustainable Smart Port" (Othman et al., 2022), and "Sustainable Digitized Port" (Kumar et al., 2021). Although the concept of Industry 4.0 has been introduced for almost a decade, there is no overall accepted model with key principles and digital enablers for that. This is partly because the concept is rooted in many different scientific domains, such as Computer Science, Robotics and Automation, Mechanical Engineering, and Process Design and Re-engineering. Besides, there has been a need to customize the concept for different sectors and applications. This study presents a conceptual model based on SAP's model for Industry 4.0 (SAP, 2020) and the model for Industry 4.0 pillars, as suggested by Culot et al. (2020). This model aims at customizing industry 4.0 models and principles, considering the specific characteristics and illustrations from the port sector with three main dimensions and seven enabling technologies, as discussed in the following. The model further describes three main areas of application and solutions for Port 4.0 that is discussed in section 3.

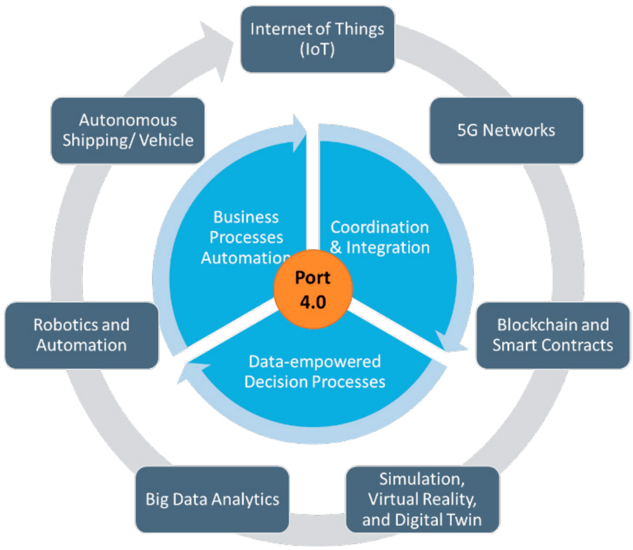


Fig. 1. Conceptual Model for Port 4.0: dimensions and enabling technologies

### *2.1. Key Dimensions of Port 4.0*

The model for Port 4.0 is based on three key dimensions:

- **Business Process Automation (BPA):**

BPA is the use of advanced technology to perform business processes with minimal human intervention (Leshob et al., 2018). The consequence is higher control of the equipment and processes involved, standardization of performance and service levels (by eliminating uncertainty in response times and human errors), and improved safety and security (by reducing direct human contact with the processes). Automation especially calls for standardization in the physical assets and operating procedures (Martín-Soberón et al., 2014). A primary element of this standardization is the standard loading unit (or container) that has been the backbone of significant growth in intermodal door-to-door transport service demand – and, subsequently, the exponential growth in global trade flows over the last three decades. Standardizing cargo handling processes at the port – like material unloading and cargo handling equipment or ship docking and maintenance processes- or standard digitization of ship records can provide a solid foundation for Business Process Automation at the port terminals.

Automating processes at a port may entail relatively high capital investment costs - that are not affordable for every port, especially in under-developed and developing nations. That is a primary reason that in a recent study by International Transport Forum, they reported that no fully automated container terminals do yet exist across the world (International Transport Forum, 2021). The study shows that only 53 container terminals are now automated to a certain degree around the globe, which represents only 4% of global container terminal capacity.

Furthermore, automation minimizes the human factor in the process and, possibly, would lead to loss of employment in the sector (Bottalico, 2022). Therefore, port workers and labor unions mostly don't support automation initiatives. Further automation may highlight the Cyber Security Risks at the ports (de la Peña Zarzuelo, 2021).

- **Coordination and Integration**:

The port sector is a complex network of people and organizations – primarily in different countries or even continents- including shipowners, port and customs authorities, cargo owners or shippers, liner shipping companies, bunkering companies, and other international and local businesses (Brooks et al., 2017). Managing transactions amongst these individual corporations can be a challenge and can directly influence the efficiency of port and shipping processes. At the same time, these transactions generate an enormous amount of information that must be processed, organized, and disseminated (Wiegmans et al., 2018). At the same time, more and more, the ports are framed as part of a broader port-city ecosystem (Van den Berghe, 2018). Also, spatially, for many European ports like the Port of Hamburg or the Port of Rotterdam, the port activities are already incorporated with the city services and directly impact the city's livability. Accordingly, the governance and decisions made by the city actors can directly influence the port operations and strategies. Information and communication technology can facilitate information exchange and coordination of activities and decisions of different players within the port as well as the broader port-city ecosystem.

- **Data-empowered Decision Processes**:

A tradition in the port and shipping sector is to keep extensive data records to track the cargo and container flows (Heilig & Voß, 2017). This data, which primarily includes the sailing data – like speed or time of arrival- or cargo data – like quantity or custom documents- or the data about different transportation assets – like the maintenance of cranes and containers or inspection record of reefers – are frequently collected and used to create regular reports and visualizations to represent and evaluate the business operations and assets' status.

However, with the extensive use of ICT tools and systems, more data from sensors, GPS, RFID, and other traffic management systems are available to improve the decisions at the port or beyond. Besides, external sources of data such as weather or highway traffic data can now be incorporated and used for reactive decision–making and predictive and preventive decision processes. With the advent of Big Data Analytics techniques, the "data" can be used to develop new business models and restructure the port and shipping sector business processes (Yang et al., 2019). Data-driven decision solutions also help to allocate the port resources, such as tugs, pilots, trucks, and service boats, more efficiently and avoid unnecessary journeys. As a result, fuel consumption and emissions from port and shipping activities can be reduced (Munim et al., 2020). Additionally, data-empowered decision-making allows ports to predict potential abnormal conditions and handle last-minute requests, e.g., by reallocating resources in real time if vessels' Expected Time of Arrival (ETA) changes.

### *2.2. Enabling technologies*

The key enabling technologies for Port 4.0 are as follows:

- **Robotics and Automation**:

All repetitive tasks that do not require special creativity or flexibility are subject to possible automation (Kon at al., 2021). Providing an efficient unmanned connection between the harbor quay and the stack yard in terminals, the Automated Stacking Cranes (ASCs) and Automated Guided Vehicles (AGVs) are some early examples of automation at the seaports. Port gate automation – using a Driver identification system (DIS) or License plate identification system (LPIS) – is another common example of automation at a port (Scholliers et al., 2016). Similar to LPIS, several developed ports, like the port of Rotterdam and Singapore, have invested in Container number recognition systems using optical character recognition (OCR) technology to automate the container handling processes (Mi et al., 2021).

- **Autonomous Shipping/ Vehicle**:

The terms autonomous ship and autonomous vehicle are generally used for transportation fleets with the ability to operate independently of a human operator (Xu, 2020). The Society of Automotive Engineers (SAE) defines six levels of driving automation ranging from 0 (fully manual) to 5 (fully autonomous). Level 5 involves full automation whereby the ship or vehicle is able to perform all tasks in all conditions, and no human assistance is required. The development of viable 5G networks is the backbone to achieve this full automation (Höyhtyä & Martio, 2020). This will allow ships and vehicles to communicate with the surrounding infrastructure, like dock sensors or traffic lights.

- **Internet of Things (IoT)**:

The Internet of Things (IoT) describes the network of physical objects that are embedded with Hardware (like sensors), software (like operating systems or firmware), and the communication protocols (like Wi-Fi, IP, or 5G networks) and that enable the exchange data across the internet (Gubbi et al., 2013). IoT is critical in designing and operating automated and connected smart ports (Yang et al., 2018). IoT sensors can be used for asset tracking and warning signals if a container or transportation asset is damaged or tampered with. Furthermore, the data provided by IoT devices can be used to improve asset availability, optimize resource planning, accelerate asset maintenance, and even redesign the entire value chain processes.

- **5G Networks**:

5G network is the fifth and latest technology standard for of technologies and standards for wireless communication. It is designed to increase speed, reduce latency, and improve the flexibility of wireless services (Rodriguez, 2015). Therefore, 5G networks can enable instantaneous connectivity to different devices and is the necessary port infrastructure for other digital solutions like IoT, Digital Twins, and autonomous operations at the port (Porelli, 2021).

- **Blockchain and Smart Contracts**:

The blockchain is a distributed ledger or log, similar to a database, of the transactions and users in a collaborative network (Ahmad et al., 2021). Because of the decentralized digital ledger, all parties in the network can verify new transactions when they occur. Therefore, it is nearly impossible to fake, hack or disrupt the data in the blockchain-based network. Smart contracts are self-executing contracts with terms and conditions between buyer and seller that are stored on a blockchain and run when predetermined conditions are met (Sangeerth & Lakshmy, 2021). Smart contracts are helpful in automating the workflows and communication between devices and are, therefore, a backbone for IoT applications, automation, and autonomous processes at the port (Ahmad et al., 2021).

- **Big Data Analytics**:

Big Data describes the large volume of structured, semi-structured, and unstructured data collected during a system's operation (Yang et al., 2019). Big Data is mainly characterized by high volume, high velocity (the speed of data generation), and high variety (coming from different sources in different structures). Big Data analytics is a process (including a tool set of different algorithms) to extract meaningful insights, such as hidden patterns, potential market trends, potentially fraudulent activities, and customer preferences (Yang et al., 2019). Big Data at port comes from several sources. A primary data source is the Terminal Operating System (TOS). The TOS manages all processes, from documentation to planning and execution at the port (Hervás-Peralta et al., 2019). Also, data can come from the field, like IoT sensors, AGV operations, programmable logic controllers (PLCs) of cargo handling equipment, Position Tracking Systems Data, and Spatial Image Analysis such as AIS (automatic identification system) and LRIT (longrange identification and tracking of ships). Besides, external data sources like weather data or city traffic data can be combined with those above sources and unlock great insights and support the port decision processes.

- **Simulation, Virtual Reality, and Digital Twin**:

The data provided by other digital technologies can be communicated to stakeholders in several ways. It can be used as input for simulation models to perform detailed internal logistics analysis, decision support, risk mitigation, and disruption response (Dragović et al., 2017). Subsequently, the bottlenecks and potential improvement options – like extending the stacking area or the number of berths- can be studied before implementing them in the real world.

The other possibility is developing virtual reality applications (primarily for training purposes). Virtual reality uses computer modeling and simulation to develop an artificial 3D environment that enables users to explore and interact with virtual surroundings in a way that approximates the real experience (Damiani et al., 2018).

Finally, the data from all technical hardware and software settings can be used to develop a Digital Twin of the port. A digital twin is a virtual dynamic representation of physical assets, processes, or the business environment that replicates how the system behaves in the real world (Hofmann & Branding, 2019). Several ports, including Antwerp-Bruges, Port of Abu Dhabi, and Port of Rotterdam, have invested in developing a Digital Twin of port assets, operations, and flows. Digital twins can help ports in improving sustainability and safety processes as well as allow maritime stakeholders to effectively share data (Port Technology, 2021).

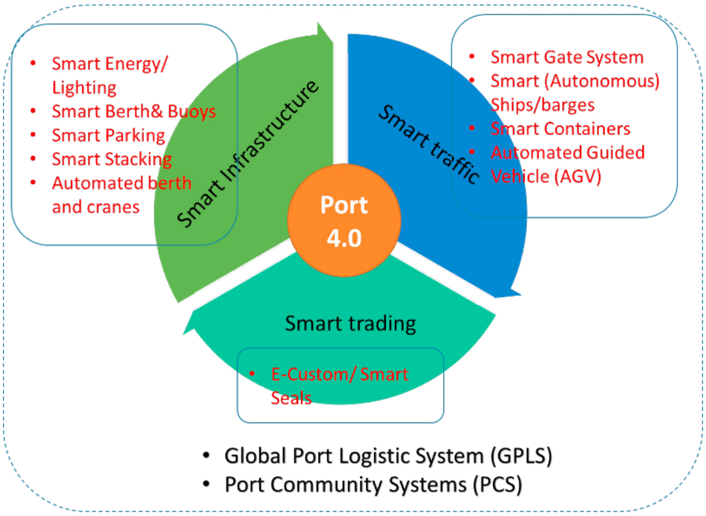


Fig. 2. Conceptual Model for Port 4.0: key services and solutions

## 3. Port 4.0: the portfolio of key solutions

Figure 2 shows the key services and operational modules for transforming a port to a smart port or Port 4.0. These modules are categorized into three main areas:

- **Smart infrastructure** is focused on “fixed assets” in a port, like buildings (e.g., warehouses or stacking areas), cranes, railways, and roads. The aim of Smart Infrastructure modules is: 1) to increase productivity; 2) to increase the asset life through smart maintenance.

- **Smart traffic** is focused on “moving assets” like ships, trucks, trains, and containers. The aim of Smart Traffic modules is: 1) to contribute to the efficient flow of assets and improve productivity; 2) to increase asset utilization and asset availability.

Table 1. illustrative port cases on different Port 4.0 solutions and services

| Smart Solution | | Port Case Description | Key enabling Technologies |
|---|---|---|---|
| **Smart Infrastructure** | **Smart Energy/ Lighting** | Smart lighting at Southampton port using Telensa's PLANet technology to save energy and improve the control of light levels by dividing the port into multiple zones and tailoring the lighting levels for each zone based on the activity taking place within it (IES, 2022) | IoT, Data Analytics |
| | | PIONEERS project to demonstrate clean energy innovations in smartening and reducing emissions in ports including the Port of Antwerp (Smart Energy International, 2021) | IoT, Digital Twin |
| | | Microgrid electricity trading platform jointly developed by S&P Global Platts and Blocklab, the Port of Rotterdam's blockchain subsidiary (Smart Energy International, 2020) | Blockchain |
| | | Smart Grid Management System (SGMS) project at Singapore's ports and installation of Smart energy storage system at the Pasir Panjang Terminal to improve the energy efficiency of port operations by 2.5% (Future IoT, 2022) | Data Analytics |
| | | The PESO project in Port of Portsmouth to integrate local electricity generation, new energy storage and smart energy management (Energy Systems Catapult, 2022) | IoT, Data Analytics, Simulation |
| | | Smart lighting solution at the Port of Casablanca using inteliLIGHT NB-IoT controllers allowing autonomous lighting operation and real-time control (InteliLIGHT, 2021) | IoT, Data Analytics |
| | **Smart Berth& Buoys** | Placing a number of "Digital Dolphins," smart quay walls and sensor-equipped buoys, that support ship-to-ship cargo transfer and generate time-stamped data about their status and direct environment at Port of Rotterdam (IBM, 2018) | IoT |
| | **Smart Parking** | Smart pre-port parking guidance solution in «Tankpark» Moorfleet at Hamburg Port: smart parking sensors transfer the occupancy information to HPA's Port Road Management Center (PRMC) and truckers are guided to available parking near their destination (Nedap, 2019) | IoT, Data Analytics, Simulation |
| | **Smart Stacking** | Fully automated BOXBAY high bay storage concept at the first full-size facility constructed at Jebel Ali port delivers three times the capacity of a conventional and reducing the footprint of terminals by 70 percent (Marine Insight, 2021) | Simulation, Data Analytics, Automation |
| | | DP World's Automated Container Stacking at London Gateway terminal with sixty automated stacking cranes (Port Technology, 2018) | Simulation, Data Analytics, Automation |
| | **Automated berth and cranes** | Automated remote control of the ship-to-shore (STS) and stacking cranes as well as remote monitoring of automatic gates at HHLA Container Terminal Altenwerder (CTA) in Hamburg (ABB, 2022) | Simulation, Data Analytics, Automation |
| | | The installation and operations of remote-controlled Rubber-Tyred Gantry cranes (RTGs) and automated container stacking system by Hongkong International Terminals (HIT) at the Tsing Yi part of the Hong Kong port (Port Today, 2022) | Simulation, Data Analytics, Automation |
| **Smart traffic management** | **Gate automation** | Pilot IoT project in the Port of Valencia based on collaboration of Traxens and MSC Terminal in which trucks were equipped with Traxens IoT devices, allowing for real-time tracking, and predicting/managing potential congestion at the terminal gate (Andrew Lloyd & Associates, 2018) | IoT, Data Analytics |
| | | The Automatic Gate system at Port of Valencia using OCR technology to read the truck plate and container(s) number(s) and validates the information (Ali, 2020) | IoT, Data Analytics |
| | **Smart (Autonomous) Ships/barges** | Using AGT International SmartPort Solution to track barges using RFID tags at Port of Hamburg (Daily Logistics, 2022) | IoT |
| | **Smart Containers** | Remote Container Management (RCM) technology used by Maersk and Hamburg Süd to monitor the condition of refrigerated containers during its voyage (Maersk, 2022) | IoT, Data Analytics, Simulation |
| **Smart Trading** | **Smart Custom** | Blockchain based concepts in cross-border cargo clearance by collaboration of Maersk with IBM (Daily Logistics, 2022) | Blockchain, Data Analytics |
| | | Port of Marseille – Smartbolt digital cargo seal developed by Anatsol and Traxens to makes cargo transit secure and fast. The Smartbolt is scanned for critical information that is digitized and communicated to the clouds thereby eliminating human intervention (World Port Sustainable Program, 2020) | IoT |

- **Smart trading** is focused on the "flow of cargo." The aim of Smart Trading is: 1) to control the speedy, smooth, and efficient flow of goods to and from a port; 2) to avoid the spoilage of perishable goods during operation at a port; 3) to improve the safety and security by an effective custom process.

Each of these three dimensions may include several modules and services, as shown in Figure 2. These modules (which are a combination of hardware and software solutions) can be potentially connected through a centralized Port Logistics System and a Port Community System (which aims at paperless communication and information sharing with the port stakeholders). Accordingly, the interactions between these different elements can be managed in an integrated way. Table 1 summarizes some of the illustrative projects in these different areas in the ports worldwide.

## 4. Concluding remarks

This study presents a conceptual model for Port 4.0. The model aims to formalize the technical competencies for port digitalization in three areas or key dimensions, enabling technologies and key service areas. Although digitalization can dramatically impact the port and shipping industry in terms of improved productivity and safety and the creation of new businesses and services, digitalization at the port should not be considered just as an application of digital technology. Therefore, a possible direction for future research is studying the organizational and managerial competencies for digitalization in the port and maritime industry. Together, these elements can be a basis for developing a maturity model for digital transformation in the port sector.

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