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# Digital Twins in the Context of Seaports and Terminal Facilities

**Julian Neugebauer**[1] **Leonard Heilig**[1] **Stefan Voß**[1]

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**Abstract**
Increasing freight volumes and challenging environments in seaports and container terminals worldwide require streamlined and reliable operations. Digital twins are seen as important drivers of the digitalization in seaports by providing a basis for higher transparency, control and data-driven decision making. In this context, however, the concept is rarely studied, and implementation issues are not comprehensively discussed. The paper presents an exploratory study of digital twins in seaports based on a literature review and case studies. The analysis reveals a standardization deficit for digital twin implementations, an inflationary and improper use of the term digital twin, and fields of research that need to be explored further. The application of optimization methods and the integration of simulation-based optimization in the field of seaports and container terminals is examined, due to its relevance for digital twins. Important lessons learned can be taken from the most advanced implementations, integrating simulations and emulations with optimization methods. An in-depth examination of multiple case studies and discussions with global port leaders yields valuable perspectives on the varied levels of digital twin implementations being applied today, including insights into the most advanced implementations currently being used in ports and container terminals. As a result of the analyses conducted, various research directions and a research agenda are presented.

**Keywords** Digital twin · Maritime logistics · Seaports · Container terminal · Use cases · Literature review

Julian Neugebauer
julian.neugebauer@uni-hamburg.de

[1] Institute of Information Systems, University of Hamburg, Von-Melle-Park 5, 20146 Hamburg, Germany

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## 1 Introduction

Besides integrating new and improved infrastructure and equipment, digital transformation is seen as a key component for planning and improving operational processes in seaports (Karas 2020; Heilig et al. 2017a). The need for further optimization measures has grown steadily in parallel with the worldwide increase in container throughput (The World Bank 2020). After decades of streamlining port processes and operations, the potential of further improvements are seen especially in automation and the utilization of data to facilitate (near) real time and data-driven decision making (Heilig et al. 2017b). The digital twin is considered a key concept of Industry 4.0 (Lasi et al. 2014) and strives to meet the increasing practical requirements. It enables physical systems to be mapped in the digital world. Digital twins combine multiple technologies and differ in the scope of the physical entity being digitized. From the representation of individual parts or components to the mapping of entire seaports or cities, digital twins can be used for creating digital models of objects and their processes as well as environments (Fuller et al. 2020).[1]

In recent years, digital twins have become increasingly important in the port industry (Port Technology 2021) and in research (Madusanka et al. 2023). By increasing efficiency and helping to restructure logistical processes, digital twins are seen as a part of future ports and the maritime sector in general (Lind et al. 2020). They can be viewed as a tool for connecting a variety of research methods and areas, such as simulation or machine learning (ML) and technologies, thus facilitating the combination of the two. Offering a common platform for analyzing data from multiple sources allows researchers as well as practitioners to gain a deeper understanding of the system and its behavior and to identify patterns and trends that may not be immediately apparent from a single data source. Combined with comprehensive models, the behavior of the system under various conditions can then be simulated and analyzed to explore and test new designs or configurations and to identify as well as solve potential problems before they occur in the real world. Solving problem before they occur with a digital twin is similar to prescriptive analytics and is enabled by automated data exchange in (near) real time as part of the digital twin (Bertsimas and Kallus 2020; Tian et al. 2023). Prescriptive analytics is focused on the optimization of processes, while digital twins focus on the optimization of complete physical objects with the underlying processes. Both fields are worth discussing, however, due to length limitations, prescriptive analytics will not be considered further below.

As for the basic theories about digital twins, much has already been contributed to the body of knowledge (Jones et al. 2020; Barricelli et al. 2019), even to the extent of questioning whether definitions of digital twins are too broad (VanDerHorn and Mahadevan 2021). Nonetheless, focusing on a single technology is not part of these definitions. However, this is exactly what is usually described in the context of digital twins for seaports in the literature. Digital twins have many functions, which makes it

[1] Due to the scope of the paper only digital twins in ports and terminal operations are discussed. For other applications in industry and manufacturing the reader is referred to Jiang et al. (2021); Qi and Tao (2018); Tao et al. (2019a).

difficult to develop a unified understanding. As a result, there is neither a common definition nor a clear analysis of this research area in the context of seaports.

This paper analyzes how far the current research on digital twins as well as practical applications have progressed in the field of seaports and container terminals. This is done as part of an exploratory study to help identify opportunities for using digital twins to improve container terminal and port operations, understand the potential and limitations of digital twins, identify challenges and barriers to their implementation or use and generate new ideas and concepts for their research and application. As such, this study can provide information about the development based on the current state and use of digital twins in container terminals. A dual focus is presented on the research area explored in the literature review and the application area examined in the literature, as well as through several case studies. The exploratory research focuses on four main areas: assessing underlying methods, technologies and approaches for creating and maintaining digital twins and their components and improving their accuracy and functionality; understanding the potential and limitations of digital twins in different contexts; identifying best practices for implementing and using digital twins in container terminals; and evaluating the impact and effectiveness of digital twins. For this approach, it is important to start with a brief introduction to the topic. Based on the available research, a clear definition is provided forming the basis for the following literature analysis and being the starting point for identifying problems and exploring them. These problems are later analyzed through interviews and by discussing real-world case studies. For this purpose, various international seaports are considered and interviews are conducted with decision makers from the port sector. The result of the examination of the practical applications is an overview of the state of the art with respect to digital twins in seaports. This yields new insights into hurdles that must be overcome and opportunities that arise from implementing digital twins. Furthermore, a contribution is made to the theoretical but also practical understanding of digital twins and an overview is given of current hotspot studies to support port operations, management and research. To this end, a detailed overview is provided using a structured approach, followed by an extensive analysis in terms of decision support. The result is an analysis of discrepancies and research gaps.

The remainder of the paper is organized as follows. Starting with an introduction to the concept of digital twins in Sect. 2, this section elaborates on how research and practical implementations in the field of digital twins are interrelated. Afterwards, a literature review and major research contributions based on the methods used and the technologies employed for digital twins are presented in Sect. 3. Based on this, use cases are combined with a series of interviews involving port leaders from around the world to provide a practical perspective and discuss key findings. Through these assessments, the current scientific and practical state as well as the technologies and methods used are described in Sect. 4. The paper concludes by identifying potential areas for future research and development of digital twins in ports, with a particular focus on container terminals. It also offers practical insights and reflections for the utilization of digital twins in these fields and shows how different research areas and methods could foster the advancement of digital twins.

## 2 Background

It is crucial to establish what a digital twin actually is. Although often also referred to as a "cyber-physical system" (CPS), a digital twin according to VanDerHorn and Mahadevan (2021) can be described as "virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual system." The definition is derived from a review of many definitions in the literature and represents the current state of research. In this context, a digital twin differs from a generic CPS by a higher degree of integration, synchronization and intelligence. It also represents a one-to-one relationship with the physical system (Tao et al. 2019b). In addition, digital twins enable a continuous feedback loop between the physical and virtual systems. They provide various functions such as simulation, optimization, prediction, diagnosis or control (Grieves and Vickers 2017; Boschert and Rosen 2016). The digital twin definition originates from Michael Grieves in 2002, who was the first to describe the idea of "dual systems in nature" in a way that the physical version and the digital or information version exist with each thing or system as a digital twin (Grieves 2019; Jones et al. 2020). The use of this definition by NASA in 2012 for describing the simulation model of complex parts manifested the term digital twin and led to the widespread adoption of the concept (Tao et al. 2019b).

Over the course of the last decade the definitions for digital twins developed and led to misconceptions regarding the scope of digital twins, resulting in the common distinction of digital support systems, digital shadows and digital twins.

As shown in Fig. 1, the flow of information between the physical and the digital object of a digital twin is fully integrated and automated in all directions, which in turn describes the characteristics of a digital twin. Thus, all three domains, the physical, the digital and the information domain are bilaterally connected. Each digital twin, therefore, contains a model of unspecified complexity that can imply a representative behavior of the twinned physical system or operation (Fuller et al. 2020). Complexity in the context of a mathematical model implemented in a digital

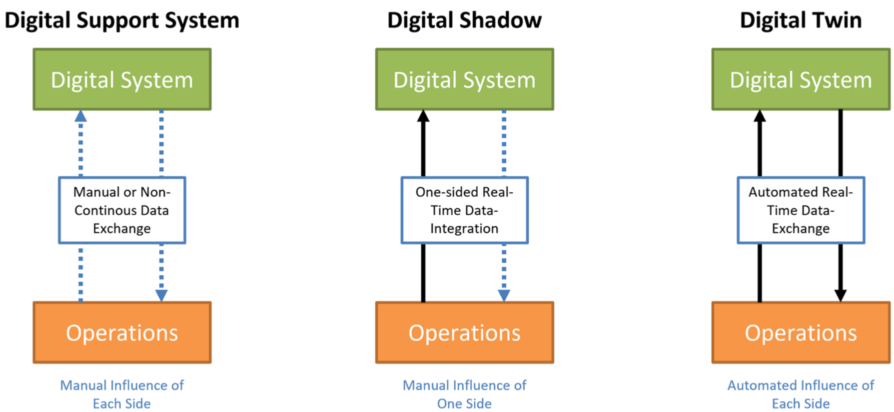


**Fig. 1** Differentiating the digital twin levels based on Fuller et al. (2020)

twin refers to the level of detail and, e.g., the number of variables and equations included in the model.

A digital twin is only realized when the underlying processes and changes from the operation automatically change the twin in (near) real time as well as when the twins' behavior and learning are automatically adopted in the physical operation. However, such systems with intermediate steps, such as a person reviewing the learnings of the digital twin and then automatically applying the results, can still be classified as a digital twin. Digital twins satisfying those definitions are referred to as strict digital twins in the following, in particular to illustrate the state of implementation. A simple example would be optimized route planning for an autonomous vehicle based on (near) real-time position monitoring and simulation of all other vehicles at a container terminal based on a model of the operations. Another example would be a model of a quay crane that tracks the crane's movements in (near) real time and can also simulate the crane's operation for many future shifts, so that wear and tear can be predicted and thus any parts that may be needed can be ordered in advance automatically.

In contrast, a digital shadow is described as one-way integration, assuming the implied model. Since the digital shadow of the strict definition is often referred to as a digital twin in practice, it can also be considered a digital twin in a broader sense. An example is the integration of (near) real-time data that is enriched by the model, visualized in 3D and then manually analyzed. Practically, the model of a vehicle transporting containers could show, based on (near) real-time data, that continuing operation at the same speed could lead to overheating, whereupon the technical staff would tell the driver to slow down. Based on these definitions, the digital support system could be, e.g., a 3D model or a technical documentation file or just a static database record which is manually maintained. This means that there is no automated data flow or update between the digital model or system and the physical object or process. Digital twins generally form the basis for a (near) real-time and highly effective digital representation of objects or systems for further use in the context of optimization approaches, simulation or for other technological applications (Zheng et al. 2019). This is particularly advantageous because previous applications, such as (near) real-time analysis or simulation, were not technically feasible, due to the high computing requirements, or could not be sufficiently distinguished in research.

In addition, for understanding the overarching concept of a digital twin, it is important to further differentiate the types of digital twins. Fundamentally, a distinction can be made according to the development as described by Grieves and Vickers (2017) or the type of thing that is digitally twinned. The types of digital twin modeling start with component or part twinning, where only a specific object is twinned, extending to product or asset twinning, which can include a combination of materials and parts, to the highest-level twinning, where entire systems or processes are represented by the digital twin. In terms of observation level, system or process twins can also be found in seaports and potentially in applications such as port community systems (PCS). Both of these systems consist of a variety of components, including infrastructure and superstructure, as well as various participants and their processes.

As seaports face high demands, many are undergoing digital transformation, although the extent of digitization varies.[2] Some key digital technologies that are being utilized in this process relate to the internet of things (IoT), big data, simulation and cloud computing, among others. The list of applicable technologies and concepts includes countless others, resulting in use cases such as port monitoring or smart maintenance of the terminal (Terziev et al. 2020). All of these support digitalization and continuous improvement, but are costly regarding the implementation time and the finances needed (Pavlić Skender et al. 2020). Furthermore, without having a meaningful human and machine interface the benefits of the digitalization in seaports are minor. Properly implemented, however, the benefits of reducing costs and creating new revenue opportunities outweigh the difficulties that must be overcome in implementation (Min 2022). In addition, simulations in seaports based on the digitized systems can help to evaluate, improve and even generate more data to help replicate complex systems and advance them in the long term (Zhou et al. 2018). This will provide resources for automation and thus for further development in the seaport sector (Li et al. 2021c).

The use of advanced IoT technologies and methodologies such as simulation, optimization, and mathematical modeling are essential components in the creation of digital twins. These tools allow for the construction of virtual representations of physical systems or processes, enabling the analysis and improvement of their performance in a virtual environment. While the combination of these technologies and methods is crucial for the creation of digital twins, it is important to note that digital twins represent more than just the sum of their parts.

The combination and integration of the components of a digital twin are shown in Fig. 2, highlighting the importance of connecting technologies with scientific methods. A digital twin provides a holistic approach to understanding and improving complex systems and processes, by offering a comprehensive view that incorporates multiple technologies and methods. While the primary focus of digital twins is on improving processes and efficiency, they can also be useful for understanding and optimizing complex systems like ports. In fact, the position of vehicles, containers and ships can have an impact on the model contained within a digital twin of a port, making it a valuable tool for managing and improving the various processes and tasks that take place within this specialized area.

In the context of seaports and container terminals, digital twins provide a framework to address specific challenges that are central to seaport or terminal operations and overall efficiency. These problems include, e.g., optimizing vehicle allocation, quay crane allocation, berth allocation, container storage, and traffic management. Research in this area is, e.g., focused on developing algorithms and models to efficiently address these challenges. Due to the large amount of work in these areas, only a few papers are described or cited below, mostly focusing on providing an overview. One of the most important areas of research is the

[2] Digitization is the process of transforming analog data into digital formats, digitalization is the process of using technologies to improve business processes, and digital transformation is the process of creating new business processes as well as new models and value propositions based on digital technologies (Heilig et al. 2017a; Vrana and Singh 2021). All three have to be applied to facilitate the creation of a strict digital twin.

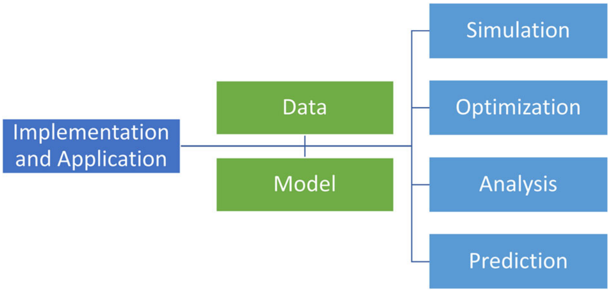


**Fig. 2** Digital twin connecting applications and methods

optimization of vehicle allocation and scheduling within the terminal as, e.g., described by Chen et al. (2021). Efficiently allocating terminal vehicles such as automated guided vehicles (AGVs) and straddle carriers to different tasks is critical to reducing waiting times, minimizing congestion, and streamlining overall operations. To achieve this, researchers are exploring dynamic allocation strategies that take into account factors such as container location, priority, and driving distances (Böse et al. 2000; Gao et al. 2023). In addition, efficient allocation of berths is important for terminal and port operations. Optimal berth allocation ensures smooth vessel traffic and minimizes waiting times for ships. For these problems various constraints and parameters such as vessel types, handling requirements, and berth availability are taken into account (Bierwirth and Meisel 2015). Another important aspect of managing seaport terminals is the allocation of quay cranes to handle ships, as is discussed, e.g., by Yang et al. (2023). Researchers are working to develop advanced algorithms that optimize the allocation of quay cranes based on factors such as vessel size, cargo volume, and berth availability. By streamlining the use of quay cranes, terminals can significantly increase productivity and reduce vessel turnaround times. Related to this, container storage is an important area of research in seaport terminal management. Effective allocation of storage space within the terminal area is critical to reducing retrieval times, avoiding congestion, and maximizing space utilization (Chen and Lu 2012).

All of these issues are tangential to digital twins and are addressed in many of the subsequently analyzed scientific papers. Knowledge of these challenges in seaports and container terminals serves to follow the literature analysis and exploration of practical use cases. The research on digital twins in the context of ports and terminals in particular will be examined in the next section. The literature review will also examine the extent to which the contemplated strict definition of a digital twin has been followed by research and industry in the area of seaports.

## 3 Literature review

After defining digital twins in the field of seaports, a set of keywords was established as search terms for the literature search. The keywords were selected based on a sample of important works in the field and have been improved after the initial searches were completed. The search was conducted using Scopus, Web of Science, IEEE Xplore and included the first 50 Google Scholar results. Afterwards, the papers were filtered and additions were made, either manually or through conducted forward and backward searches. In general, the search was limited to recent papers (2000–2022) as the term digital twins has not been used in the past. In addition, only works in English were considered.[3] The process of searching can be summarized using the flowchart shown in Fig. 3.

The literature review resulted in a set of 141 papers. Although different structured and semi-structured approaches to find all related literature were carefully applied, the completeness of the selected literature cannot be fully assured.[4] Nonetheless, the literature analyzed should provide a solid overview of the research domain and support the subsequent conclusions.

After conducting the literature review, the papers were grouped according to the scientific methods and technologies used. In addition, the degree of understanding of the digital twin in the individual papers was analyzed. The result is a comprehensive overview of the entire research area of digital twins in seaports and terminals, which is visualized in Table 2. Due to the table's extensive length it is placed in Appendix A. The table is organized into four general sections, starting with the reference and a brief summary of the research scope of each paper on the left. After that, the methods used and the technologies are classified. These are selected based on the respective discussion of technologies or methods in the obtained papers. The third section lists the functions of each digital twin mentioned in the paper. Each of these sections either contains a (·) indicating usage or they contain a (−), indicating that the methods are mentioned as example only. A blank cell indicates that nothing related to the column is mentioned or included in the analyzed paper. The fourth and right part of Table 2 shows the classification of the digital twins based on the strict definition discussed in Sect. 2.

It can be shown that less than a quarter of all analyzed papers propose a strict digital twin (labeled "Twin" in Table 2). As a result of the research, it is shown that the majority of works presents the digital twin as digital shadow, support system or defines a digital twin in the broader sense. More than a quarter of all analyzed papers do not contain a digital twin, shadow or support system in general, but rather discuss specific parts or methods of one. On the one hand, this could indicate the need for a clear definition and further research. On the other hand, this has been expected as research is often rather theoretical in nature and practical implementations and automatic data flows back to the physical systems cannot always be realized. This approach advocates for an exploratory research of the field of digital twins in container terminals and seaports, where a variety of research methodologies, approaches and general principles are employed in the mentioned literature with the aim of gaining a deeper understanding of the subject matter. Not only are established technologies and their practical applications evaluated, but the potential for future

[3] To document this process and make the exclusions as transparent as possible, all search results and exemplary queries, separated by individual sources and keywords, are available as RIS files at: https://github.com/Newgefarmer/digital_twins.

[4] For a comprehensive discussion of structured literature reviews, which allows for better classification of the findings presented in this paper, see Pahl and Voß (2022).

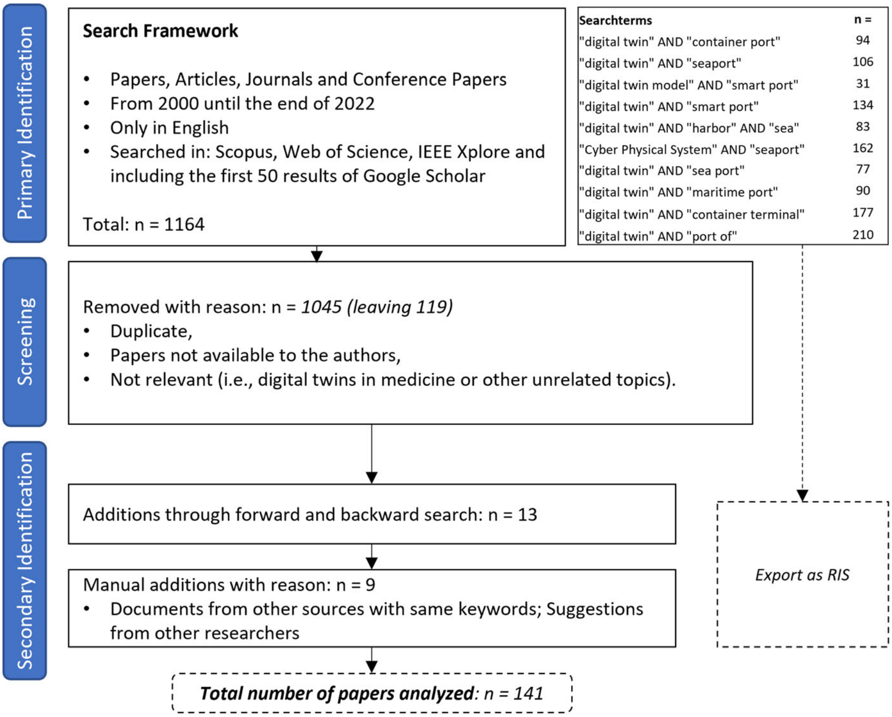


**Fig. 3** Search framework of the structured literature analysis

research and innovation is also taken into account. Both the practical and theoretical facets of the field are identified as areas that would benefit from further inquiry and investigation.

## 3.1 Scientific research by methods

The identified papers mainly use three different methodologies in developing and discussing digital twins in seaports. However, not all works use only one research methodology. An important part of digital twins is their implementation. A detailed literature analysis is conducted on the methods applied for decision support, especially with respect to mathematical optimization, ML and simulation. The aim is to explore the different research methods in the context of digital twins for seaports and container terminals. Afterwards the implementations and used technologies are explored.

### 3.1.1 Optimization methods and machine learning

Twenty-four papers contain elements of modeling and heuristic methods of varying complexity and depth, excluding the papers describing ML-based approaches (marked with a dot in column four of Table 2). The largest research area related to digital twins in this respect is the automated yard including AGVs. Gao et al. (2022b) describe an optimization approach for an automated storage yard in a container terminal supported by (near) real-time data of a digital twin. This is successfully accomplished by developing scheduling models for the AGVs, the automated stacking cranes (ASCs) and the storage area with the main objective being the minimization of the makespan for all container-related tasks. In addition, a case study shows that waiting times for ASCs can be shortened by applying the optimization while reducing the number of ASCs used. In particular, the prediction of the required number of ASCs plays an important role for the overall process optimization approach.[5] A similar optimization approach towards reducing the AGVs' transport times, but also optimizing the path finding of the AGVs, is described in Li et al. (2021d). This could be advanced further by implementing the trajectory predictions improving on scenarios with missing data based on local neural networks (Ni et al. 2021). All of these papers are using the model of the digital twin for simulation purposes to verify that optimization results are applicable in a more complex environment. They should be considered separately from simulations, which do not rely on a digital twin because the granularity is greater and real data from operations is included.

Making sure that the digital twin actually fits to the implemented models is a challenge worth considering. Li et al. (2021c) compare random forest, AdaBoost and XGBoost algorithms at the Shanghai Yangshan container terminals for a more precise data set and parameters to train the digital twin's simulation model using ML. The result is an improved prediction of which vehicles to deploy next. The mathematical models used in Shanghai (China), in combination with optimized AGV and quay crane scheduling, lead to higher efficiency in loading and unloading and improve overall operational time.

A different use of mathematical modeling is the performance and environmental evaluation developed by Sadri et al. (2021). Several criteria are used to calculate technical efficiency, in addition to port productivity. This evaluation is based on several criteria that include environmental friendliness as well as energy consumption, defined intelligence of the infrastructure and more. This result of the nonlinear programming problem facilitates the comparison of different ports. The model has been tested by evaluating several Iranian ports and shows that these still have a long way to apply the digital twin for improving decision support and ecology. This is due to the fact, for instance, that the actors are scattered and do not cooperate yet. The digital twin is used as a data source in this evaluation.

Another application of the digital twin in the context of mathematical modeling is risk assessment. Gunes et al. (2021) examine cybersecurity risks associated with the digital twin in the context of seaports, with various key performance indicators (KPIs) included in a target function that makes the level of risk calculable for a given digital twin implementation. Lennon et al. (2012) are more concerned with risks arising from general port operations and describe the digital twin as a tool for detecting potential threats which can be included as input data in the mathematical

[5] The interested reader is referred to, e.g., Cai et al. (2014) and Zehendner et al. (2015) for further works discussing the allocation of ASCs.

modeling, making it more precise in reflecting the current situation. In this context, Szpytko and Duarte (2019) have implemented an advanced model, reducing risks from gantry crane inefficiencies. The integrated maintenance decision-making model uses a sequential Monte Carlo Markov chain simulation model for risk assessment. A particle swarm optimization approach improves various maintenance schedules, providing a new way to simulate different scenarios and conditions with (near) real-time integration of problem cases. Although the presented model is very advanced, the digital twin described in this case is solely regarding the combination of simulation and (near) real-time updates and, therefore, rather constitutes a digital shadow. This is confirmed by a later published work, in which the digital shadow serves only as a decision support tool (Szpytko and Duarte 2021). Nonetheless, these papers play an important role in advancing maintenance planning by considering random factors. They can be considered prototypes and provide an important basis for digital twin implementations according to the strict definition given in Sect. 2.

In modeling and optimization, methods are developed to find optimal solutions for given problems. In the field of ML, these methods play an important role in estimating model parameters and minimizing error functions. Therefore, mathematical optimization represents an important foundation for the now discussed field of ML, especially for the complex domain of digital twins.[6] Li and He (2020) discuss a deep learning-based prediction for liner berthing times. This is realized using a deep neural network in TensorFlow. Resulting are predictions for Chinese liner shipping berthing times with an estimate for the number of arriving ships in a given time frame being described as good enough for decision making. Similar work focusing on terminal handling systems and logistics hubs, but also predicting liner berthing times as well as quay crane performance, is conducted in Li and He (2021). While not discussed in detail, predictions can become an important part of a digital twin, especially for emulating future scenarios and predicting all kinds of processes related to the seaport sector.

Li and He (2021) propose a combination of automated logistics and deep learning to address the non-linearity, coupling, and complexity of container terminal handling systems. They present a deep learning model for predicting liner berthing times, which is described as the central factor of terminal logistics service and carbon efficiency conditions. Yao et al. (2021a) review the concept, development history, and technical characteristics of digital twins and propose their application in the field of port construction and operation to digitize and integrate management, particularly in the areas of infrastructure and model construction. Gültekin et al. (2022) show how vehicles themselves can also incorporate ML by using pre-trained ML models to monitor operational status. Automated vehicles capable of detecting anomalies while underway, can help reduce the need for data communications and improve functionality when connectivity is not available, which can be a problem within the vast areas of modern seaports.

Although ML is certainly not the only tool for creating a digital twin, it can be very useful for optimization approaches either related to operational processes, to

[6] ML is often enabled by big data, which is described in Sect. 3.2, but since modeling is an essential part of a strict digital twin, it is considered separately at this point.

improve data quality (Doleski et al. 2022) or to ensure data integrity, e.g., by detecting sensor failures (Jakovlev et al. 2021). Particularly in the context of digital twins with (near) real-time data and generally large collections of data from sensors across the port, ML can support automated decision making and help extract useful information and insights from these otherwise too large data sets (Schislyaeva 2021). For this reason, application programming interfaces (APIs) providing predictions such as weather or tidal levels are integrated into the considered digital twins (Koroleva et al. 2019). Further predictions, albeit the least of them being provided through dedicated APIs, include vessel- and road traffic (Schislyaeva 2021), travel times[7] and failures of vehicles or equipment.[8]

Nearly all of the above cited papers describe predictions done using ML. Especially when using a model, being the main component of any digital twin, predictions are important to gain insights for future scenarios. Additional insights can also be generated with simulations which can be used to validate optimization results created with the digital twin. The relationship between simulation and optimization methods can be described as a procedural approach where the potential outcomes and impact of different decisions for a specific system or process are predicted by using simulation techniques and then (optimal) solutions are determined by utilizing optimization methods. This approach allows decision makers to evaluate the outcomes of potential decisions without actually making any changes, thus identifying the best possible solutions while taking into account given constraints and objectives. This points toward the need for interdisciplinary research in simulation-based optimization.

### 3.1.2 Simulation

Simulations can be used to gain new insights from data that were not previously available by showing the evolution of a model over time. Examples include emulating cranes to identify potential problems from operations that have not yet taken place or simulating different ways to optimize terminal operating system strategies without having to interrupt operations (Schütt 2020). Since emulations and simulations are often combined and can provide insights together, a distinction between the two can be helpful. Mi and Liu (2022a) define emulation as the analysis of simulations of system behavior that have not yet occurred. They further define simulation as the creation of a simulation model that can describe the structure or behavior of the system and has logical or quantitative relationships based on the properties of all elements of the system and their relationships. In the following sections, only simulation will be referred to, which may, however, include emulation.

Agostinelli et al. (2022a) and Damiani et al. (2019) use simulations in the context of energy and sustainability. For the Port of Anzio in Italy, a combination of Autodesk's simulation engine and the Green Building Studio is used to simulate

[7] The interested reader is referred to, e.g., Heilig and Voß (2017); Ni et al. (2021); Pavlić Skender et al. (2020); Pita Costa et al. (2021).

[8] The interested reader is referred to, e.g., Gao et al. (2022b); Mallah et al. (2020); Tesse et al. (2021); Uusitalo et al. (2021).

power generation and optimize consumption. The proposed optimized use of the implemented photovoltaic systems will potentially reduce total greenhouse gas (GHG) emissions by approximately 15 % and minimize electricity costs (Agostinelli et al. 2022a). Damiani et al. (2019) have similar goals, but achieved these with a different approach of simulating energy consumption with a port operations simulation. Powersim Studio is used to implement a simulation of the cranes, the arriving ships as well as the container depot. Trains and trucks with all necessary loading and unloading operations are modeled and included in the simulation. In combination with an energy price forecasting model, a decision support tool is provided to show the impact of different operating strategies on predicted energy bills. In both papers, a model of certain parts of the respective ports is developed and discussed as a digital twin, although in neither of the two papers an automatic data flow from the twin back to the physical system is implemented. Hence, it can be assumed that in both cases digital shadows are developed, even if a future development towards digital twins is possible. The same is true for Segovia et al. (2022) who propose a potential one-third reduction in GHG emissions focusing on seaport buildings and simulating these in MATLAB based on a digital shadow.

MATLAB is also used by Zhou et al. (2022b) utilizing IoT data and different models for simulation with the goal of monitoring and controlling a rail-mounted gantry crane. A strict digital twin is realized that provides insights into crane operation and allows new control algorithms for the crane to be tested virtually without interrupting operation. The focus on connectivity and positioning when using simulations is also addressed in the contributions of Ali-Tolppa and Kajo (2020); Balaji and Chaudhry (2018) and Uusitalo et al. (2021), focusing on data provided by global navigation satellite systems (GNSS). For validation, the NS2 simulator is used by Balaji and Chaudhry (2018) to prove that their localization algorithm based on triangulation is less error-prone in a container terminal. The 5G network, validated at the Kalmar test yard in Tampere (Finland), is developed using a multi-cell simulation of Uusitalo et al. (2021). The simulation focuses on optimal connectivity within the container terminal, similar to the consideration of 5G connectivity throughout the Port of Hamburg (Germany) in Ali-Tolppa and Kajo (2020). Both are able to use simulations of real-world environments to demonstrate low latency, adequate data throughput and cell coverage of their implementations. When connecting cranes and AGVs with 5G, these high capacities and data throughput rates are required for a digital twin as is demonstrated by Du et al. (2022).

A strict digital twin is only applied in the paper of Ali-Tolppa and Kajo (2020), in comparison to the other papers focusing on 5G. In this context, the Hamburg Port Testbed is used as digital twin providing the simulation basis. Using the simulation, the physical 5G towers are optimized in their beam configuration and transmission power, which indicates a practical use case and shows how a simulation-based optimization can be realized, adapting a fully automatic data flow. A similar approach is chosen by Zhou et al. (2018) discussing the integration of simulation and optimization methods based on a literature review. The result is a framework similar to the different levels of digital twins described in Fig. 1, with the highest integration level being the automatic data flow between the domains of simulation and optimization in (near) real time. In their later paper, Zhou et al. (2021) apply these results in improving port resilience regarding potential power supply disruptions. Optimal computing budget allocation (OCBA) is applied as a simulation-based optimization algorithm resulting in an optimal equipment configuration for lowering the impact of potential disruptions. Since this is a more tactical-related planning problem, no (near) real-time integration is realized. The same is true for the $O^2$ DES.NET framework described in Li et al. (2020). However, the reason for not applying the optimization approach in operations is rather that the computation times are not fast enough. Li et al. (2020) also use OCBA as a simulation algorithm and optimize a variety of problems on an event-driven basis. This includes comparing port designs in general, AGV routing, yard planning, AGV transponder positioning, land and sea traffic simulation and the simulation of warehouses. The system can be further customized by using PortML, a modeling language for modifying port properties. This can be done either through a graphical interface or by modifying XML code. Results of the comprehensive approach have not been described, yet the paper can be a guideline for a comprehensive integration of a digital twin in combination with simulation-based optimization for nearly all parts of a container terminal, especially because of the customizability using PortML. Although components of digital twins and simulations are applied directly in the cases described, other ways of integration can be used. Battilani et al. (2022) describe a business process re-engineering approach and link it to digitalization, through the "creation of a constellation of digital twins [...] driven by simulation aiming to simplify and optimize the information process supply chain." The paper develops a discrete event simulation using AnyLogic that suggests a reduction in resource saturation in the context of the respective simulated port equipment and processes by up to 20 %. Krüger et al. (2021) use the same approach, but with a different discrete event simulation software called Enterprise Dynamics. Several tracks, gantry cranes, reach stackers and a quay for barges with the underlying processes are simulated, but not using a digital twin or real data. The authors show that a simulation can be created automatically using a static layout, similar to PortML. They also demonstrate the performance that can be achieved with this method. Some authors further describe simulations for specific parts of container terminals or regarding specific use cases, but more specifically in combination with digital twins. Examples include synchromodality (Giusti et al. 2019), roll-on and roll-off (RoRo) processes in ports (Pacheco Bolaño and Troncoso-Palacio 2021) and automated terminal planning (Yao et al. 2021b), but the processes of combining simulations with digital twins have already been described in the other analyzed papers.

Most of the above literature concludes that future integration of digital twins can further advance simulation models and improve overall systems, although a strict integration of the digital twin is currently not considered in respective papers. Research on digital twins has shown promising results in terms of simulation-based optimization. The implementation of these results in (near) real-time scenarios has yet to be widely adopted. One important aspect of digital twin research is the comparison of different simulation tools and algorithms, as well as the development of more accurate simulations and plans through the use of optimization approaches that consider factors such as data granularity and timeliness. This can lead to more informed and data-driven decisions not only for operational decision making, but also at the tactical and strategic levels. In summary, there is still a lot of potential in the research areas of simulation and optimization methods.

### 3.1.3 Implementation and application

The broadest area within the identified literature discusses the implementation or application of digital twins as well as parts of it (marked with a dot in column 3 of Table 2). Although it is strictly speaking not a scientific research area, it shows the applied concepts and is, therefore, part of this exploratory research. From papers applying 5G as an enabling technology to assessing various impacts of digital twins, there is a wide variety of works. It should be noted that the following is an overview of most, but not all, of the work on applied digital twins, listed in Table 2.

Agostinelli et al. (2022a) and Cumo (2021) both apply digital twins and IoT in the context of maintenance and energy management, respectively. In the former, the solar and wind energy potential of the Port of Anzio (Italy) is analyzed based on data collected over the last 40 years. Energy consumption for lighting and power supply to parts of the port is planned to be improved as a result of the forecasts for energy generation. The results suggest lower GHG emissions due to a smarter use of renewable energy. Since the energy production data has already been collected, maintenance can also be improved. For example, a decrease in energy production under the same conditions could indicate the need to clean the solar panels. The approach of Cumo (2021) is similar and shows comparable results for the Ventotene Island Port (Italy) with greater focus on Building Information Modeling (BIM). In both papers, important parts of the port infrastructure are modeled in 3D and partially connected to data from IoT devices to enable transparency and more precise control. However, both papers only consider a digital shadow, since no automatic data flow back to the real system is implemented. This is in contrast to the literature dealing with the implementation of simulation-based digital twins. Gao et al. (2022b) focus on the automated yard and present special benefits of a digital twin application with respect to the simulation-based optimization. The application is divided into the control of machinery, display interfaces, programmable controllers and transmission lines. These are combined as "control and execution modules." Hereby, it is shown how an implementation can be facilitated with the digital twin bridging the gap between the optimization results and actual operations in the terminal. Meanwhile, Hofmann and Branding (2019) also apply a simulation model with a dispatching algorithm based on the concept of starvation avoidance. The digital twin is used to evaluate different results of the dispatching algorithm in combination with (near) real time data from IoT devices. However, no automated application of the optimization results is performed.

There is a paucity of literature on the topics discussed, especially when compared to literature dealing with a more general application of digital twins in the supply chain. Based on Busse et al. (2021), who present a framework for a universal digital supply chain twin, a commonly used perspective regarding the digital twin is its function as part of a general data space to connect a variety of actors. This can either be as part of a PCS, as part of a national single window (NSW), or regarding a general (industrial or maritime) data space. A PCS is generally described as an interorganizational system supporting the exchange of port-related information and documents needed to efficiently manage port operations and procedures (Heilig and Voß 2017; Simoni et al. 2022). Data in the PCS can be incorporated into the digital twin and its model and vice versa. The integration of a digital twin is proposed to support collaboration among stakeholders with technical standards and a similar objective, as these are necessary for the implementation of the digital twin. It makes it easier for users to utilize business-related information collected through the platform. The same holds true for the NSW, which can provide a more standardized access for even more users not included in the PCS, e.g., governments (Rødseth and Berre 2018). The Data Space (DS) as described in various forms[9] is even more generalized as the PCS or NSW. It can contain all data mentioned above and data beyond that. Examples include automatic identification system (AIS) data provided by the port authority (Sarabia-Jacome et al. 2020) or information for the tracking and monitoring of containers throughout the supply chain (Rajput and Singh 2018). Therefore, the DS either supports the digital twin by providing even more data as input to each model or by sharing the twin itself within the DS. This would not be possible with a PCS or NSW, as these are used more as data hubs for interorganizational processes.

Frequently mentioned problems concern data management and access rights control as well as finding the right management organization to which all stakeholders can entrust their data. None of the articles discuss standards, although it can be assumed that this must be a challenge for implementation. The results of implementing such a general DS are beneficial, as the example of the Port of Valencia (Spain) indicates. Sarabia-Jacome et al. (2019) indicate an improvement in interoperability and describe the generation of new port-wide KPIs that indicate the operational and overall efficiency of the seaport. Therefore, this supports better decision making regarding the included stakeholders of the DS. In most papers that mention a PCS, NSW or DS, only digital shadows are described or no other digital twin levels are discussed. Although the literature referenced in this section shows how the underlying technologies of digital twins are used, none of the papers describe an inclusion of the digital twin or how it could be made available to other stakeholders. It can, therefore, be concluded that further exploration is needed in this area. It is likely to be of interest, e.g., to make the simulation components of the digital twin available to other players in the seaport. This can be used, for instance, to simulate the estimated time of arrival of a truck at a container terminal based on traffic models provided by a port authority. The control of components via the digital twin of a container terminal, e.g., by third parties performing maintenance work, could also be analyzed.

A more generalized view on digital twin implementations and applications in the context of smart ports and in Industry 4.0 is considered in many of the analyzed papers. Dalaklis et al. (2021) describe a smart port as an integration of intelligent traffic flow, information systems and digital infrastructures. They conduct a literature review and identify digital technologies used in ports around the world. As one of

[9] The interested reader is referred to, e.g., Osório et al. (2019); Rajput and Singh (2018); Rødseth and Berre (2018); Sarabia-Jacome et al. (2019, 2020) and Schislyaeva (2021)

these technologies, the digital twin is characterized as a simulation of the port's characteristics, changing several variables and testing them quickly and effectively. The results of the literature review are compared with a case study at the Port of Gothenburg, Sweden. The case study shows that from the use of sensors to monitor emissions caused by onboard power generation to automatic gates for trucks, the overall performance of the port is suggested to improve. However, it is clear from the overview of used technologies that the definition of a smart port is very vague and can encompass a wide range of technologies and levels of digitalization. Wang et al. (2021) focuses more on the combined application of the various technologies mentioning the digital twin not only as part of some port's smart projects, but as a way of combining the technologies making up a smart port. This is done by developing a framework that divides the focus of managing the smart port processes into the physical-, data-, model-, service- and application layers. Results include recommendations for standardization and a suggested focus on platform building. Furthermore, using the digital twin as a connecting construct is suggested. Especially the concept of having the digital twin as a connection, representing all states and allowing to simulate different situations at the port, can be found in Pang et al. (2021) and Pita Costa et al. (2021), albeit to varying degrees.

Adding to these learnings with the focus on application and implementation of digital twins, Ibrion et al. (2019) discuss the possible risks of digital twins in the maritime domain. This is done in the context of learning from risks regarding the implementation of digital twins in aviation by focusing on problematic use cases. Results of this analysis include problems concerning sensor reliability and data quality, showing the importance of correct measurements, the risk of making decisions on the basis of wrong measurements and the importance of better or correct modeling, simulation and verification. Other risks considered by Ilin et al. (2022) include hacking or data manipulation, albeit with a greater focus on blockchain-based systems, showing that despite the existing risks, the potentials of digitalization are outweighed. This conclusion is also evident from the analysis of the North Sea Route as a whole, whose most important development step is suggested to be digitization according to Ilin et al. (2022). Interestingly, few authors discuss the risk associated with digital twins in global ports. There is a need to transfer research on digital twin risk to other areas. Besides Ilin et al. (2022), many other authors show a similar general need for digitalization and digital transformation, with the digital twin being a vital part of it.[10] In addition, in most cases, the described digital twins have a (near) real-time connectivity and a strong focus on visualization. The digitalization efforts, including the implementation of digital twins, are also included in the future development, e.g., for the Turkish Seaports (Özkanli and DeniZhan 2020) or the Port of Hamburg (Tesse et al. 2021). Altogether, most papers show a considerable need for implementing and applying digital twins in the seaport domain, albeit most often in the more general context of digital transformation as also discussed by Yang et al. (2023). Sanchez-Gonzalez et al. (2022) describe "quick-win applications" and include container tracking, virtual reality (VR) applications for maintenance or

[10] The interested reader is referred to, e.g., Heilig et al. (2017a); Koroleva et al. (2019); Min (2022); Pavlić Skender et al. (2020); Sanchez-Gonzalez et al. (2022); Wattanakul et al. (2022).

training, route optimization via ML as well as multiple applications of data analytics, especially concerning energy usage and emissions. All of these can be part of a digital twin application and contribute to the possible benefits for global seaports. Since they are the enabling part of digital twins these technologies get discussed further in the next section.

### 3.2 Research and use of digital twin enabling technologies

Digital twins can incorporate a variety of technologies. Especially for the realization of strict digital twins in modern seaports, it has to be discussed which technologies can be of use in which respect. Therefore, the next section analyzes the different possibilities of applicable technologies, starting with the acquisition of data, the different possibilities of usage and visualization and ending with the storage and processing of the data. As the various areas covered would provide sufficient depth in their own right, the next section only considers an overview and the impact of the technologies on the digital twin. Moreover, the ambition is not to provide a complete list of all potentially useful technologies, but rather those that are most common.

#### 3.2.1 Sensors, actuators and connectivity

In general, mobile wireless connectivity is the first step in digitizing the port, as in most cases this needs to be established in order to receive data from infrastructure and moving objects, like vehicles, ships and cranes. To make this possible, different technologies can be used. WiFi is particularly interesting for terminals, while wireless communications and especially LTE and 5G are useful for all port stakeholders (Heilig and Voß 2017). In all cases, a high bandwidth network and low latencies are required to transmit the amounts of data needed to create a digital twin with higher accuracy.

Transfers are often made over cellular as a backup when connection quality is poor. For larger areas, WiFi might be less practical, showing the advantage of fast cellular connections like 5G. For automation and for control, e.g., through a video transmission, 5G brings the necessary bandwidth and stability (Agarwala and Guduru 2021). Also the control of ships or the collection of sensor data from ships will only be possible with fast wireless connections, as stated in the Hamburg 5G trial (Rost et al. 2018). The use cases described above can be extended to those in terminals where remote crane operations and remote inspections as well as automated trucks can be realized and controlled based on 5G networking (Sun 2021). All in all, it is mobile connectivity that enables (near) real-time integration of physical systems and their digital twins. Sensors and many IoT devices are connected in the same way. The position of vehicles determined by GNSS, which includes GPS, Beidou, Galileo, etc., can also be transmitted like this. Positioning as part of the possible sensors directly shows what distinguishes the port and even more the terminal environment compared to digital twins used in other industrial applications, since the positioning gives the context information for the digital twin. In addition to GNSS, other methods of position determination can be used. Examples include laser, lidar or beacon-based systems, as well as differential GPS, and many others that can be improved by triangulation or trilateration where required (Balaji and Chaudhry 2018).

Which other sensors can be deployed depends on the respective use cases and objectives. If tire pressures of vehicles (e.g., straddle carriers, reachstackers, rubber-tyred gantry cranes) are to be transmitted, pressure sensors and temperature sensors must be used. For the monitoring of buildings and infra-/superstructure (e.g., quay cranes), ultrasonic sensors, strain gauges or various other sensors are helpful (Yang et al. 2018). The selected sensor should be considered according to the resulting detection capacities, implementation costs and accuracy. At the end of the digital twin cycle, actuators can be used to automatically adopt decisions made by the digital twin. These can be applied for controlling specific elements such as locks or traffic lights (Rost et al. 2018). Actuators thus provide means of (near) real-time interaction with the physical world through the digital twin.

The connection and integration of the various collected information with the Internet consequently define the IoT (Min 2022). Depending on the number and capabilities of the sensors used, different levels of detail of the digital twin as well as automation can be realized. However, the data often needs to be aggregated and filtered before transferring it to the model of the physical object. In combination with data from the terminal operating system (TOS), the supervisory control and data acquisition (SCADA)[11], the equipment control systems (ECS) for automated equipment or integrating the enterprise resource planning (ERP) system and others, the information from, e.g., vehicles, cranes and ships can be visualized and used to create models and simulate the various physical systems.

Although different combinations of IoT-enabled devices need to be implemented depending on the purpose of the digital twin, there is no analysis in the literature of which systems and devices need to be implemented for which purpose of the digital twin. Comparisons of different implementations and combinations have not yet been conducted, indicating a potential future development in this particular area with respect to the start of digital twin integration.

### 3.2.2 Virtual reality, augmented reality and visualization

Visualizations are important as an interface between users and digital systems. Because the complexity of digital twins can be substantial, dashboards and other 2D visualizations can have problems displaying all layers of the twin. Therefore, 3D visualizations are included in many digital twin realizations. Although visualization is not a necessary part of implementing the digital twin, it can often be beneficial. For instance, 3D visualization can be helpful for truck- or vessel stowage planning, since all dimensions of the goods can be viewed (Aro et al. 2020). Generally, for the planning and monitoring of all operations, it can be a supporting tool that gives a better overview of the usually huge area that has to be managed in the port. For example, Wang et al. (2022) use these visualizations to show a machine room or container with (near) real-time data overlaid for temperature, pressure, and other IoT

[11] SCADA describes a computer system with which technical processes in automated production can be monitored and controlled.

data. The general complexity and size of ports is certainly the reason why different forms of 3D visualization can be found in almost all use cases of the digital twin discussed in the analyzed literature. In addition, the visualizations can serve as a method for interpreting the results of simulations performed with other systems.

VR systems are just another use of this type of visualization, although potentially even more intuitive for the user. The benefits resulting from an implementation will be especially high in the areas of maintenance and training (Sanchez-Gonzalez et al. 2022). AR technology, which creates another layer on top of physical objects, requires a different approach, as the recognition of the object or at least another layer than the previously mentioned visualization has to be implemented (Pavlić Skender et al. 2020). This could be a reason why the analyzed literature mentions the visualization but does not discuss its implementation. However, this can be more helpful, as the analysis of Tam and Jones (2019) shows, because the overlaid information can be presented in an even more user-friendly way without having to create a complete separate visualization of the physical object. An example is navigation of a ship, where waypoints and markers on the sea are overlaid. Another example is visual confirmation of correct alignment for the operator of a container gantry crane, enabling faster operation. Since there are no publications yet that analyze AR systems to support a digital twin of a container terminal, the potential impact has yet to be discussed, even if the combined application of AR and digital twins is already happening in industry (Ericsson 2020). Certainly, it would be helpful for staff monitoring port operations to look out of the window and see the overlaid KPIs of the equipment working on the terminal. But the size of most modern container terminals, or ports in general, exceeds the areas visible from one position, which could lead to the conclusion that AR systems are simply not capable of visualizing or supporting the entirety in a helpful way. These potentially very different outcomes of an AR-based implementation suggest a need for further exploration and thus point to potential areas of further development.

BIM is a completely different approach to not only visualizing but also modeling. Not only is an object (usually a building or infrastructure) digitized with a 3D model, but a variety of information can be included in the model. The Port of Anzio (Italy) uses this technique in combination with information from a geographic information system (GIS). Areas for the installation of solar panels can thus be identified and energy production modeled in combination with the geographical position of the solar panels (Agostinelli et al. 2022a). Combining GIS and BIM is encountered several times in the seaport sector, but mostly in relation to the integration of this data into the overall visualization or as a further basis for the digital twin.[12] Therefore, these data models can be a good starting point to make the construction of the digital twin more accessible, even if a model of the functions of the physical objects still needs to be created independently.

Although the various types of visualization are not absolutely necessary for a digital twin, they help to prepare resulting additional information in a comprehensible way. Therefore, and due to the intuitive operation, visualization options are an

[12] The interested reader is referred to, e.g., Cumo (2021); Yao et al. (2021a); Doleski et al. (2022); Wang et al. (2021).

important part of digital twin considerations, especially in the context of seaports and container terminals, with the typically large areas that need to be monitored.

#### 3.2.3 Big data and cloud computing

No matter what system has been discussed in the above sections, required data must be processed, transformed, analyzed and provided again. Therefore, it is to be expected that most of the work analyzed is related to data lakes, cloud computing or big data in one form or another. Heilig et al. (2020) describe cloud computing as well as big data technologies as a basis for scalable data mining. Data has existed in all phases of port development, but with the ever increasing amount of data generated by IoT devices and the processing it requires, the term big data has taken hold. While many technologies must be linked to enable big data, typically only the resulting insights are of interest, which has shaped the term big data analytics (Henríquez et al. 2022). Compared to the technical domain regarding cloud computing, the actual outcomes and impacts are more often discussed in the literature on digital twins in the context of seaports. Cloud computing makes data accessible from any device, including handhelds and the resulting computing power supports decision making, simulations and enables digital twins, much like big data or any other advanced data storage (Brunetti et al. 2020). In summary, the broad application of big data in almost all of the literature analyzed emphasizes the importance of data processing, transformation, analysis and provision for various systems. The main focus is on the insights gained, hence the term big data analytics. In addition, cloud computing plays a key role in advanced data storage and decision making in various areas of digital twins for seaports and container terminals.

## 4 Case studies of digital twins in the seaport context

In this section, digital twins in the context of seaports are considered both from the perspective of the selected literature and from a practical perspective. For the latter, interviews with 16 questions as a guideline were conducted with decision makers from container terminals and port authorities around the world as well as with researchers involved in practical projects. An unstructured interview style was chosen because it allows to represent the different levels of implementation and to take into account the exploratory nature of the areas studied. The aim is not to provide a complete list of all projects, but to provide an overview and look in particular at advanced digital twins in ports. In the following, an outline of practical projects is given, sorted by the digital twin implementation level. This is combined and put into perspective regarding the existing literature.

### 4.1 Digital twin use cases in seaports around the world

About one third of the literature contains a use case showcasing the functions of the digital twin studied. It varies whether these use cases refer to a real use case, if several use cases are analyzed or if a fictional use case is considered. In this section, the focus is on analyzing the various levels of digital twin implementation and their related implications. It is important to note that the term “level” is used appropriately, as only a portion of the selected papers discussing use cases propose a strict digital twin, while none outlines the implementation process. Furthermore, a comparison between theoretical work and practical projects or implementations is strived for. By comparing the two, the paper can provide a more complete picture of the state of digital twins in seaports and container terminals, and identify areas where additional research or development is needed. To further illustrate the feasibility, limitations, and real-world impact of the proposed solution, Table 1 is created, also using the information from the conducted interviews. It shows the global ports being analyzed as part of the exploratory analysis and their progress on the implementation of digital twins and parties involved in research as well as the development of the digital twin (PA = Port Authorities; INS = Institutions and Universities; CT = Container Terminal Operators; BBT = Break Bulk Terminal Operators). For each item in the last column, an interview was conducted in addition to the analyzed literature (two separate interviews in Hamburg).

Moreover, Table 1 shows how different the levels of digital twins in seaports across the world are. For example, the largest seaports in Asia, Europe and North America have implemented a strict digital twin. Smaller but still large ports and terminals are working on or planning the integration and small ports have only implemented digital shadows or are still working on basic digitization. In addition, almost all of the digital twins in seaports are described and developed by or in collaboration with a university or research institute. This could be due to the research character especially regarding the modeling of digital twins, but also due to the approach of a literature analysis. A broad range of use cases in different ports applying a variety of technologies and connecting different parts and processes exists.

As can be seen from Fig. 4, the range of applied technologies is broader in the practical domain. The majority of interviewed decision makers from the port domain named nine or more technologies which were or will soon be applied in their digital twin implementation. All incorporate IoT or sensor data and a system to process and analyze collected data, for which big data technologies are used. In addition, every digital twin implementation addressed in the interviews includes a 3D visualization, while this is an aspect not often considered in literature. Due to the similar shape of the technologies discussed and shown on the right side of Fig. 4, it can be assumed that the literature has a roughly similar view on the implementation of digital twins in the field of seaports and terminals. However, the generalized view of practical implementations is clear, in contrast to the more technology-specific view in the literature.

Functions incorporated into the digital twin implementation include simulation, business intelligence and monitoring at nearly all ports surveyed. These are frequently addressed in the literature, although less often in combination with the multitude of other functions. The only topic that occurs more frequently is advanced optimization methods. This more holistic view of practical implementations might result from the fact that half of the surveyed ports have implemented strict digital twins, based on the definition of Sect. 2. The other half have implemented at least a

**Table 1** Classification of digital twin use cases in the analyzed ports

| Port of | Mio. gross tons/year | Described parts | Parties included | Summary | Level of digital twin | Sources (excl. interview) | Interview |
|---|---|---|---|---|---|---|---|
| Antwerp-Bruges, Belgium | 289.3 | Infrastructure, Seaside | PA | Geographical digital twin with AIS, BIM, GIS, radar, power and weather data, traffic management and automated drones. Predictions are currently being implemented | Shadow (Twin in Future) | Pavlić Skender et al. (2020) | • |
| Anzio, Italy | n.a. | Infrastructure (Energy Systems) | INS | Evaluation of solar and wind potential with BIM and GIS data | Shadow | Agostinelli et al. (2022a) | |
| Barcelona, Spain | 67.7 | Terminal | INS | Adoption of Industry 4.0 technologies still limited. Improvement of overall port competitiveness as scope | – | Henríquez et al. (2022) | |
| Bremen, Germany | 59,7 | Terminal | BBT | Digital twin of a steel coil terminal with focus on positioning and automated booking in the TOS | Shadow | | • |
| Genoa, Italy | 51.4 | Terminal, Infrastructure | INS, PA, CT | Business process re-engineering with simulation-based validation. Energy management and forecasting | Shadow | Battilani et al. (2022), Damiani et al. (2019) | |
| Gothenburg, Sweden | 39.0 | Port Community | CT, PA, INS | Digitalization with a focus on the port community, describing features such as intelligent traffic flow and container- and vessel management | – | Dalaklis et al. (2021) | |
| Hamburg, Germany | 128.7 | Terminal, Infrastructure, Seaside | CT, PA, INS | Digital twin testbed of the port infrastructure including bridges, streets, traffic, etc. One container terminal is currently building a digital twin | Digital Twin | Ali-Tolppa and Kajo (2020), Harnischmacher et al. (2021), Özkanli and DeniZhan (2020), Pavlić Skender et al. (2020), Rost et al. (2018), Tesse et al. (2021) | • • |

**Table 1** continued

| Port of | Mio. gross tons/year | Described parts | Parties included | Summary | Level of digital twin | Sources (excl. interview) | Interview |
|---|---|---|---|---|---|---|---|
| Livorno, Italy | 29.6 | Terminal, Infrastructure, Seaside | PA, INS | Currently forecasting, monitoring and control tools implemented. Aim is to build a digital twin for ports, routes, environment, energy production and pollution | Shadow (Twin in Future) | Cavalli et al. (2021), Pagano et al. (2022) | • |
| Los Angeles + Long Beach, USA | 256.2 | Infrastructure, Seaside | INS | Implementation of a risk assessment tool and decision support system | – | Lennon et al. (2012), Pavlić Skender et al. (2020) | |
| Multiple, Thailand | n.a. | Seaside | INS | Adoption of Industry 4.0 technologies still limited, simulations of port capacity are already created for a future digital twin. The scope is the implementation of autonomous equipment | Shadow | Pavlić Skender et al. (2020), Wattanakul et al. (2022) | |
| Multiple, Turkey | n.a. | Terminal, Infrastructure | INS | Adoption of Industry 4.0 technologies only planned. Currently a guideline for future implementations of the technologies is being defined | – | Özkanli and DeniZhan (2020) | |
| Rotterdam, Netherlands | 468.7 | Terminal, Infrastructure, Seaside | INS, CT, PA | Digital twin of the complete container terminal processes and containers shipped with focus also on the port community | Digital Twin | Henríquez et al. (2022), Özkanli and DeniZhan (2020), Pavlić Skender et al. (2020), Simoni et al. (2022), Taylor et al. (2021) | |
| Shanghai (Application also at Dalian), China | 514.0 | Terminal | INS, CT | Digital twin of the complete container terminal processes | Digital Twin | Li et al. (2021c), Pavlić Skender et al. (2020), Yao et al. (2021a) | • |

**Table 1** continued

| Port of | Mio. gross tons/year | Described parts | Parties included | Summary | Level of digital twin | Sources (excl. interview) | Interview |
|---|---|---|---|---|---|---|---|
| Singapore, Singapore | 503.0 | Terminal | INS | Digital twin of the complete container terminal processes. Digital twin for planning of future and theoretical ports | Digital Twin | Li et al. (2020), Mi and Liu (2022a), Pavlić Skender et al. (2020) | • |
| Valencia, Spain | 81.0 | Terminal | INS, CT | Static model of the terminal for simulating and capacity planning. Goal is to simulate dynamically and automating optimization and implementing a seaport data space | Shadow (Twin in Future) | Sarabia-Jacome et al. (2020), Sarabia-Jacome et al. (2019) | • |
| Ventotene Island, Italy | n.a. | Infrastructure | INS | Future digital twin for facility management, predictive maintenance of infrastructure and for energy management | Shadow | Cumo (2021) | |
| Zhoushan, China | 744.0 | Terminal | INS | Digital twin of complete container terminal processes | Digital Twin | Sun (2021) | |

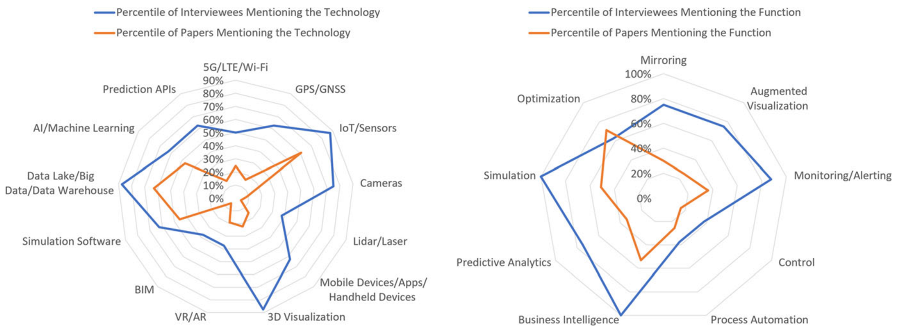


**Fig. 4** Comparison of technologies and functions by use in the analyzed papers and in the conducted interviews

digital shadow, with almost all of them planning to implement a strict digital twin in the future. In contrast, less than a quarter of the papers mention a strict digital twin, with nearly 40 % discussing digital shadows. Digital support systems or no digital systems specifically are mentioned in about 39 % of the literature, as can also be seen from the last column of Table 2. Further insights are considered in the next section, starting with a description of various practical implementations of digital twins.

## 4.2 Practical digital twin implementations

On the basis of the interviews and further research, the digital twin implementations of different ports in Germany, Belgium and China are described. The other seaports surveyed are compared with these, resulting in an overview of the practical implementation status.

*Weserport, steel coil terminal in Bremen*

The “Weserport” located in Bremen is used for handling steel coils and other break bulk or general cargo. Overall, it may be considered a small specialized port. The implementation of the digital twin focuses on precise positioning with a satellite-based system triangulated with position data from a base station installed directly on the terminal. This data, accurate to a maximum deviation of three centimeters in all directions, is combined with proximity sensors installed on all forklifts and can be used to detect if something is picked up and where the picked-up object is subsequently located (Fig. 5).

The result of this implementation is an automatic data sharing of all operations to the TOS and a live visualization of current operations. In addition, ML is used to predict transportation times and improve moves as well as the allocation of storage locations. Although a strict digital twin is not applied, there is already a (near) real time integration of data with a model-based approach for manual dispatching. A key benefit is the better use of resources described by port stakeholders. The implementation of automated processes based on the digital model in Bremen has resulted in several improvements in terms of reducing search orders for misplaced items and automatically recording and storing precise location data, which were previously completed manually. However, with the introduction of automated

**Fig. 5** Digital twin visualization at the Weserport (provided by OHB, systems provider based in Bremen)

processes and the ability to track the exact locations of goods, search orders for misplaced items have become rare.

The survey of the Port of Valencia (Spain) yields similar results in terms of process improvements, specifically at a container terminal. While the implementation of a digital twin at the terminal is still in its early stages, the steps that have been taken so far, such as creating a simulation model, integrating data from the TOS and other sources and using ship forecasting APIs and data collected in a data lake to inform capacity planning, have established a foundation for more advanced simulations. These simulations, which utilize visualization and prediction tools to enhance transparency and optimize vehicle movements, will be crucial to the development of a comprehensive digital twin at the Valencia container terminal. According to Sarabia-Jacome et al. (2019, 2020) these process improvements in efficiency and resource utilization would not be possible without the developments towards a digital twin. However, both implementations had hurdles to overcome, such as the lack of data standards for the integration of IoT devices or the connection of different databases, while finding the necessary acceptance for the implementation of the digital twin and its improvements.

*Port authority of the Port of Antwerp-Bruges, Belgium*

As one of the largest ports in Europe (Pavlić Skender et al. 2020), the Antwerp-Bruges Port Authority already has quite a large area to monitor, but since the merger of the ports, the Port Authority also needs to monitor the river section between the two ports, thus increasing the need for transparency. Everything already connected in the port environment is now connected to the digital twin, with the main goal of greater visibility. BIM data, vessel tracking and vessel information, AIS, radar and weather data, air quality data, shore power data, wind turbine information and data from IoT devices from safety buoys are all included and connected. Systems for visualization have been created based on this data, either with 3D visualization or in VR to display the geographic features along with the sensor data. The data is used for maritime traffic management and data analytics to enable proactive measures. For example, if a sensor detects higher than normal pollution, this is visualized in the VR environment and the operator has the option to send an autonomous drone to take further measurements. Simulations combined with wind data are then used to locate the source of the pollution and further actions can be taken.

Of course, the goal of increasing efficiency is different here than in the terminal, but data aggregation still offers major efficiency gains. Although models have already been implemented and their use is automated and in (near) real time, i.e., it is a strict digital twin, further elements, e.g., to increase resilience in the Port of Antwerp-Bruges, can still be integrated into the models of the digital twin. Just as in Bremen, the strict digital twin in Antwerp-Bruges has helped to transform previous manual processes. With the model of the twin, new insights can be gained and the simulation can, e.g., highlight potential problems based on the (near) real-time state of the port area. Additionally, the strict digital twin can assist with operational planning by providing a prediction of future situations based on current and past states using simulation.

Although the digital twins fulfill different objectives, the implementation criteria identified in Antwerp-Bruges are almost identical to those of the terminals described in the section concerning the Weserport, which also applies to the Port Authority in Hamburg. The identification of meaningful business cases, however, is described as a hurdle in the interview with the Hamburg Port Authority. The "Digital Twin Testbed", implemented by the port authority in Hamburg, includes traffic management and health data from structures such as bridges (Tesse et al. 2021). In Hamburg, the port authority has described that different digital twins are created depending on the integrated system. By connecting these twins, an overall picture or overview is created, similar to Antwerp-Bruges. Since traffic management models are already deployed in combination with "what-if" analyses and the results are utilized to automatically control traffic signs and traffic flows, the applications can be seen as a strict digital twin. However, further integration and development may lead to greater improvements resulting in a larger model of the entire port. To support the development of ever increasing model sizes, a process similar to federate learning in the domain of ML could be used. Federated digital twins could possibly be a faster way of creating advanced models. An indication of this would be the smaller digital twins, which are combined in Hamburg, so that more complex twins including their connections to each other are created with minor additional effort.

Other port authorities have not yet adopted digital twins. Although the port authorities in Los Angeles and Long Beach (USA) (Lennon et al. 2012), Livorno (Italy) (Cavalli et al. 2021), Genoa (Italy) (Battilani et al. 2022) and Gothenburg (Sweden) (Dalaklis et al. 2021) utilize certain parts of digital twin, like visualizations, simulations or optimization approaches, none have a strict digital twin implemented yet.

*Shanghai Maritime University, Ports of Shanghai and Dalian, China and beyond*

Currently, one of the most far-reaching digital twins for container terminals is applied in the Ports of Shanghai and Dalian. The digital twin is developed by the Shanghai Maritime University. The system can mirror the current operations in (near) real time, includes positioning of all vehicles and cranes, a multitude of optimization algorithms as well as alerting and visualization in 3D. Additional dashboards and heatmaps are implemented. What makes the system even more advanced is the representation of the full life cycle of container terminal operations represented in the digital twin. This means schedulers are able to go back in time, monitor the present in (near) real time or simulate future operations. For the automated terminal Yangshan Phase 4 in Shanghai, mainly (near) real-time data from the ECS (Equipment Control System) is used. However, sensor data typically used for maintenance is not included and could potentially improve the models. In comparison, Dalian container terminals do not yet include data from IoT devices, but otherwise the models are similar. The manual terminals at the Port of Dalian, operated with RTGs, do not yet utilize a strict digital twin.

The implementation of the digital twins in Shanghai and Dalian mainly consist of three layers: Model layer, data layer and rendering layer. The model layer mainly encapsulates the modeling algorithm, including the berth plan, crane schedules and more. The data layer uses a big data computing engine to process the data streams or batch data generated by the operation. The rendering layer encapsulates the 3D elements such as the port infrastructure and terminal superstructure and uses a Unity 3D game engine. It includes an overall model of the terminal in the background allowing automated optimization methods to be performed even with different simulations to compare the results of the simulation-based optimization (Ding et al. 2023). The same approach using Unity is described by Yang et al. (2023) for a container terminal in Qingdao (China), who discuss intuitive visualizations for container terminals and the benefits of high-fidelity models, while also looking at the challenges of such integrations. These, namely, are the integration of scheduling in such a approach as well as visualizations of different analysis, of scene loading- and unloading processes, prediction and, the adaption of acts' construction design.

All the advances described for the Ports of Dalian and Shanghai lead to a highly detailed visualization of the digital twin that can be accessed using a web browser. The sophisticated models can show effects on the whole terminal, adapting all processes and integrating all changes between model and physical objects or operation in (near) real time. Through all this, an extensive decision support system is realized. Therefore, the implementation can serve as an example for other similar implementations, particularly regarding the simulation used. Shanghai's strict digital twin is more than just a simulation with an optimization component, because it is a digital representation of a physical system, process or product. It includes not only a simulation of the system's behavior, but also a representation of its physical and functional properties. The digital twin is connected to the physical system via sensors and other data sources that continuously feed data into the digital twin model. In this way, the digital twin can map the real system in (near) real time and provide insights and predictions about its behavior, allowing container terminal processes to be redesigned and innovated.

The approach of the Shanghai Maritime University is similar to the implementations at the University in Singapore, although it is addressing strategic decision-making problems regarding the design of container terminals. Their digital twin implementation has been described in the interview with the Centre of Excellence in Modelling and Simulation for Next Generation Ports and uses different types of simulation-based optimizations for planning the future port in Singapore, optimizing the layout and overall throughput (Li et al. 2021b). Thereby, the entire port, with land and sea side on a broad level and details such as crane models, different routes and work steps of everything that can move in the terminal are simulated. Another feature of the Singapore implementation is the additional scope on vehicle charging for automated battery-powered vehicles in the terminal. Although using extensive simulation, a strict digital twin is not implemented due to the lack of (near) real-time data being included.

Similar to those two projects, the EUROGATE container terminal in the Port of Hamburg pursues the development of a strict digital twin for the visualization and simulation-based optimization of processes at the terminal (TÜV Rheinland 2021). The visualization of (near) real-time-IoT data from the terminal equipment, in particular the container gantry cranes and straddle carriers, as well as data analytics, should make optimization potentials visible. To address optimization potentials, procedures for straddle carrier dispatching and storage allocation are developed and integrated with a discrete-event simulation considering performance and environmental objectives. For the Container Terminal Hamburg (CTH), it will be possible to view past, present and future simulated operations, with the inclusion of maintenance data highlighting potential failures and allowing condition-based predictive maintenance. This will lead to the ability to be proactive in even more areas of operations. The manual operation of straddle carriers controlled by humans is supported, leading to even more complex models as the human component must be included. In addition to optimizing terminal equipment and networking through IoT, the implementation of a strict digital twin in Hamburg will lead to innovations in manual processes. For example, predictive APIs can be used to forecast weather conditions, ship arrivals and departure times, enabling more accurate planning and decision making. By providing ML-based predictions created with historic transportation times and other sources of information (like weather conditions), e.g., optimization approaches for vehicle routing can be fed with more realistic assumptions regarding travel times. The digital twin will also enable the linking of terminal superstructures and operational data, which will provide a deeper understanding of equipment and processes, making, e.g., the impact of maintenance measures more transparent.

### 4.3 Insights from the digital twin implementations

In more general terms, almost all projects and implemented digital twins have in common that optimization approaches not only support direct operations, but also aim to reduce GHG emissions in respective ports. Be it by minimizing the distance traveled by the vehicles, ensuring shore power connection or enforcing pollution regulations. In most of the port projects studied, not only one actor is working on the implementation of digital twins, but many. The port authorities and terminals implementing these systems are supported by various institutions and companies and often plan to integrate these systems. Therefore, standardization is key to facilitating secure data exchange in the form of future PCSs or DSs, which is a goal for future systems according to all parties interviewed. However, standardization is only a goal so far and is not currently the focus of implementations, which shows that there is still a need for research and development in this area, as implementation is not realized from the outset. Projects such as PortML or TIC4.0 can be seen as pioneers in this regard.

Other hurdles highlighted by interviewees were finding personnel with technical skills, including simulation component development and operational knowledge for the complex port or terminal processes. Furthermore, the methodology for developing a digital twin is not yet clear or even in place, as it is still very new and each digital twin is as different as the physical objects and processes. This means that the scope and size of the investments required to implement a digital twin are not entirely clear at the outset. The need to create an understanding of the novel digital twins and their technical implementation reinforces this problem. Decision makers may underestimate the financial outlay and technical requirements for creating the digital twin. The problem of finding good business cases for implementing a digital twin is similar.

Discussing these hurdles might give the impression that the implementation is not worthwhile, making it equally important to look at practical strategies for implementing digital twins. During the interviews, it was suggested that a selection of initial use cases should be made during the start of the implementation to address issues related to communications, protocols, data exchange and security levels that need to be properly addressed from the beginning. Additionally, optimization methods should be considered separately at the operational and strategic levels. Operationally, optimization approaches could be considered, e.g., in terms of increasing twin movements, strategically, general processes and strategies can be considered, which could lead to various deeper and long-term changes. The digital twin could further help with optimization approaches by showing the current state as well as suggesting changes and trying out different approaches before making medium- to long-term decisions. This improved information flow and better understandability was cited by all respondents as a strategic goal for implementing the respective digital twins. A general framework, if one exists at all, could be helpful for port decision makers in implementing and applying digital twins in seaports and terminal facilities, but specific working methods may also provide support. These topics are discussed further in the next section.

## 5 Discussion and future research agenda

The analysis aims to explore what the digital twin looks like in global ports. Literature in this regard is still scarce, but already shows the potential of the implementation and research domain, although the main focus varies depending on the particular scope as can be seen in Fig. 6, depicting a word cloud generated from all texts cited in Table 1.

The terms “system,” “data” and “port” are used most frequently in the literature analyzed, but the wide use of the terms “model,” “service,” “information” and “operation” also indicates the focus on developing digital twins in the seaport domain. However, the deep implementation of models of seaports and the (near) real

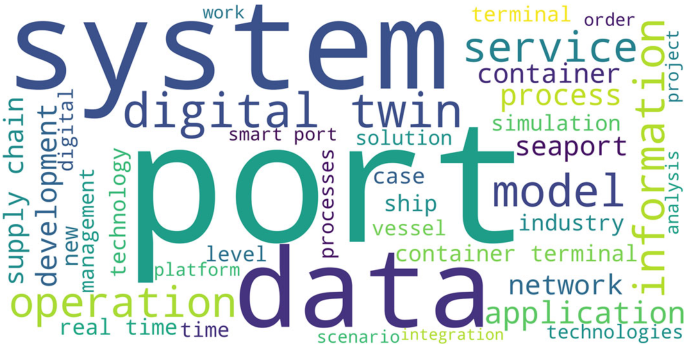


**Fig. 6** Word cloud of literature on digital twins in seaports

time integration of the results obtained by the digital twin is almost absent from the literature so far. This is due to the fact that most research is rather theoretical and practical implementations are rarely published. However, the collaboration between institutions and ports shows that interdisciplinary research is already making an important contribution towards this area. It is important to keep in mind that digital twins are primarily to be understood as an application area and that, e.g., modeling or optimization methods within the digital twin are tangible research areas. The use cases considered show how far some seaports have come with the implementation of strict digital twins, but this is mainly the case with the largest ports. In contrast, the implementation of strict digital twins in smaller ports has not been described in literature. In general, the location of the port has a great impact on how advanced the implemented system and digital twin are, as it can be assumed that smaller ports have fewer resources available for developments.

Since the field of research under consideration is quite new, especially in terms of implementation in seaports and terminals, there are still some areas that need to be explored. These areas include the actual benefits of implementing digital twins in seaports, which have yet to be quantified. Further, the development of a more general implementation framework needs to be explored, since currently all twins are very different and there is not a general guide for implementing such a system. This framework would describe the basic architecture needed based on the different goals of the implementation. Furthermore, once implementations are becoming broader, the sharing of digital twins and their models must be discussed as well as problems resulting from false models or decisions autonomously made on the basis of these. The implementation process itself is another area that should be examined more closely, as the way of working on such an implementation may involve workshops, the adoption of SCRUM or other project management methodologies such as the V-model, which are mentioned in the interviews. Determining a best possible approach, particularly in the port space or, comparing these approaches for implementing digital twins, may be an area for additional exploration.

The parties involved in the processes described are different, which demonstrates the importance of having an appropriate working angle. This is shown by the results of the interviews. A digital twin combines real processes, planning information and technological tools, which means that employees from operations, information technology (IT) and other departments have to work closely together. Especially in the interviews with European ports, unions and work councils were mentioned as important groups which need to be integrated and informed about any project with a certain size. This is because increased transparency can often lead to more surveillance opportunities for the employer, which must be avoided according to the respective applicable law. In addition, employees working in planning often fear that a digital twin with greater optimizing possibilities could lead to their jobs being eliminated. The same applies to the employees affected by the optimization approaches, since ideally resources can be better used, therefore, reducing the need for crane operators, e.g.. Although this may be the case in future, these worries have to be addressed to facilitate the most effective use of the digital twin by all parties and for the optimization results to actually be trusted by the respective employees.

The interviews showed that involving many parties and employee groups at an early stage and then focusing on the implementation of processes and their gradual implementation in the digital twin model can be a good starting point for any port or terminal that wants to implement a strict digital twin in the future. This should currently be true for almost all ports and terminals around the world. The technologies that are then used must be aligned with the goal of the digital twin and can be implemented one after the other. This also applies to the model of the digital twin and simulation or emulation, which can be developed to enable increasingly complex operations. In this way, a strict implementation of the digital twin can be done incrementally, lowering barriers to entry. Currently, many ports and terminals practice this, albeit perhaps unknowingly, as ports and terminals are already digitizing individual parts or implementing digital shadows that can become a strict digital twin in the future. With the increase in the number of implementations, research is becoming increasingly important to support the modeling and optimization approaches and, e.g., to develop new and faster simulation methods. In addition, research for applied technologies is getting more important, as the requirements for 5G networks, e.g., also increase with the complexity of the systems or processes to be interconnected. The small number of papers regarding research topics of digital twins in the special application areas of ports and container terminals is a research gap that needs to be closed.

## 6 Conclusion

This paper presents a comprehensive study of the research and practical applications of digital twins in the context of seaports and container terminals. Subsequently, the main findings in the areas of implementation, modeling, optimization approaches, ML, simulation and applied technologies were reviewed based on a literature review and compared to practical use cases. It can be subsumed that a strict digital twin, as defined in Sect. 2, must include four parts: the integration of components or processes with their data in (near) real time, modeling of the twinned system with no specific minimum complexity required, decision support or optimization functionality and automated application of the obtained decision back to the physical object or process being twinned. Creating an understanding of how a strict digital twin is defined, as well as how it is implemented in research and practice, are the main contributions of this work to the general body of knowledge focused on digital twins in seaports and terminal operations. In addition, the following learnings were identified.

The literature analyzed shows an inconsistent state of research in the field of digital twins in terminals and seaports. Some papers, ports or terminals are still working on or describing basic digitization, while others are already implementing strict digital twins or researching complex methods to support the development of digital twins. This currently still leads to the incorrect use of the term digital twin, defined as "strict" digital twin in Sect. 2. The incorrect usage of the term digital twin shows the need, besides other identified open research and development areas, for further advancements in the field. The reasons for the frequent misuse of the term lie mainly in the novelty of the research area. Other reasons include the development of a strict digital twin, which is often too extensive and research subsequently focuses on partial areas. However, these should not be confused with a complete twin. In addition, for certain research areas related to digital twins, such as the implementation of sensor technology, only the consideration of data acquisition is relevant, so although this subject area can be part of a strict digital twin, it does not have to be, e.g., should no communication back to the physical object take place.

With respect to the explored literature, it was noted that the largest area of research related to digital twins in the context of ports is the automated yard, specifically in regard to AGVs and ASCs. Additionally, one of the challenges identified in the literature is ensuring that the optimization approaches are aligned with the implementation and the use of ML techniques to enhance the accuracy of the digital twin's simulation model. Furthermore, different mathematical modeling techniques for enabling performance and environmental evaluations, risk assessments and for supporting maintenance decisions, were identified as ways to improve efficiency, reduce risks and increase decision support in ports.

After the literature review, the practical application of digital twins in seaports was studied through the analysis of use cases based on the conducted interviews with decision makers in the domain. The main goal of implementing digital twins at ports is to increase operational efficiency and reduce GHG emissions by minimizing travel and enforcing pollution regulations. Moreover, it was observed that while standardization is an objective for future systems, it is currently not a focal point in implementation. The functions and methodologies studied in the literature review were further discussed in the practical use cases, allowing for a deeper understanding of the challenges and opportunities of digital twin implementations in the context of seaports and container terminals.

Given the increasing complexity and size of port systems and terminal infrastructures, the digital twin can be a useful tool to increase transparency and improve performance while reducing complexity. New interfaces are, on top of that, more user-friendly and facilitate the operations of future workforces that are already growing up with interfaces similar to modern video games as implemented in today's most advanced terminals. However, this whole improvement and twinning cycle has a high degree of complexity. Therefore, it is proposed to split the different phases into different domains. For example, as already done for optimization problems in the container terminal, where the research is divided into optimization approaches supporting yard, berth, vessel planning, and more. However, a combination of these phases is also necessary for implementation and overarching research as well.

Based on the practical projects and literature analyzed, several areas for further research and exploration have been identified. One area for further research is the quantification of the benefits of implementing strict digital twins in seaports. This could include a more detailed analysis of the cost savings, improved efficiency, and increased safety that can be achieved through digital twinning in ports. Another area for further investigation is the development of a general implementation framework for strict digital twins in seaports. This could include more detailed guidance on how to implement digital twins in ports, including determining a best-practice approach. The literature also highlighted the potential of sharing digital twins and their models among different stakeholders in the port ecosystem. Further research in this area could include the examination of the best practices for sharing strict digital twins and models, and the impact it has on collaboration and coordination among different parties. Additionally, further research could be conducted on the examination of the implementation process, including the investigation of the relationship between complexity and the level of detail in digital twin implementations. This could include a more in-depth analysis of the challenges and best practices for implementing digital twins in ports. Another area for further research is the advancement of optimization and simulation methods with large and always changing data sets. This could include the development of new methods and tools that can handle (near) real-time monitoring and prediction of issues that may arise in ports. Overall, the application of the potential benefits of federated digital partnerships that enable faster and more comprehensive modeling could be further explored.

Finally, lessons learned from the literature review and the analysis of the use cases were discussed, highlighting the problems and opportunities of the implementation for all levels of digital twins. The need for further research in the field, specifically in terms of standardization and alignment of the models used for optimization approaches with the physical systems, was emphasized. With the increasing complexity and size of port systems and terminal infrastructures, the digital twin can be a valuable tool for increasing transparency, improving performance and reducing complexity. However, further advancements in the field are necessary to fully realize the potential of strict digital twins in ports and container terminals.

## Overview of the analyzed literature

See Table 2.

**Table 2** Overview and classification of the analyzed literature

| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Agarwala and Guduru (2021) | Overview of 5G being used in commercial shipping, being analyzed from design to actual operations | – | | | • | • | • | • |
| Agatić and Kolanović (2020) | Seaport service quality and how it improves the digitalization | | | | | | • | |
| Agostinelli et al. (2022a) | Optimizing maintenance and energy efficiency for renewables with the support of a digital twin for investigating and lowering GHG emissions | – | | • | | | • | • |
| Agostinelli et al. (2022b) | Renewable energy production systems in ports can improve sustainability and efficiency in urban development | – | • | – | | | • | |
| Ali-Tolppa and Kajo (2020) | ML and optimization approaches to prevent service degradation of dynamic 5G coverage | | | • | • | | • | |
| Aro et al. (2020) | Looking at the Baltic sea maritime industry and showing digital twins in the context of stowage and shipyards | • | | | | | | |
| Balaji and Chaudhry (2018) | Better localization in ports using trilateration method combined with wireless sensor network (WSN) and simulation of the proposed technique | | | • | | • | • | |
| Bao et al. (2022) | Asset management for decision making in industrial applications combined with an integrated digital twin frame | • | | | | | • | |
| Battilani et al. (2022) | Business process re-engineering with simulation-based validation | | | • | | | | |
| Boullauazan et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | – | | | | | | |
| Brunetti et al. (2020) | Looking at smart yards and giving a framework for simulation | | | • | | | | |

**Table 2** continued

| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Busse et al. (2021) | A framework for a digital twin for a complete supply chain | • | | | • | | • | |
| Cai et al. (2022) | Digital twin application from the aspects of port operation business model and the cooperation of members mechanism | • | | | | | | |
| Carvalho et al. (2020) | Propose a data and connectivity standard for easier communication and implementation of digital twins | • | | | | | | |
| Cavalli et al. (2021) | Port KPIs improving by use of 5G-cellular | • | | | • | | • | |
| Chuprina et al. (2022) | Learnings from the digitalization strategies of global seaports as support for governments and other authorities | | | | | | • | |
| Cumo (2021) | The digital twin at the Ventotene Island Port (Italy) for facility management, predictive maintenance of infrastructure and for energy management | • | | – | | | • | |
| Dalaklis et al. (2021) | Analysis of digital tools and technologies for future ports and giving an overview of ports around the world and the technologies already applied | • | | | • | • | • | |
| Damiani et al. (2019) | Energy purchasing optimization methods based on a port simulation and energy price forecasting | | | • | | | | |
| de la Peña Zarzuelo et al. (2020b) | Technologies and tools of Industry 4.0 in the port literature being analyzed | | | | | | • | |
| Doleski et al. (2022) | Energy system modeling for digital decarbonization in ports and logistic infrastructure | • | | | | | | |

**Table 2** continued

| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Douaioui et al. (2018) | Looking at the four industrial revolutions and showing the need for further research, training and development of technologies in Industry 4.0 | | | | • | | • | |
| Du et al. (2022) | 5G network simulation and evaluation based on a digital copy of a port | – | | • | • | | • | • |
| Fahim et al. (2021) | Track and trance as a basis for future ports and overall supply-chain cooperation | | | | | | | |
| Gao et al. (2022a) | Data governence specifically for IoT data | • | | | • | | • | |
| Gao et al. (2022c) | Performance advantage of digital twin-based Q-learning solutions over Dijkstra's algorithm for AGV path planning | | • | | | | | |
| Gao et al. (2022b) | Simulation-based optimization for an automated storage yard in a container terminal supported by (near) real-time data of a digital twin | • | • | – | | | • | |
| Gasparotti (2022) | Demonstrate the benefits of introducing digital technologies in the Romanian maritime sector | – | | | • | • | • | • |
| Gerlitz and Meyer (2021) | Decision-making tools are proposed to facilitate and strengthen the transition in small- and medium-sized ports toward environmental responsibility, social equity, and economic efficiency | – | | | | | • | |
| Giusti et al. (2019) | Success factors and enabling technologies of synchromodality | | | • | | | | |
| Golovianko et al. (2021) | Machine learning for image classification to replace human decision making | – | | | | | | • |

**Table 2** continued

| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| González-Ramírez et al. (2023) | Decision support for container terminal operations with disturbances and analysis of main disturbances to port operations | – | | – | | | | |
| Gunes et al. (2021) | Defining and managing cyber risks in ports regarding the inclusion of digital twins | | – | | | | • | |
| Guo (2021) | Digital twin for harbor hydraulic structures and concrete | | | – | | | • | |
| Gültekin et al. (2022) | Use of edge-based AI for autonomous vehicle fault detection and condition monitoring, reducing network requirements and shortening data transmission times | – | – | | • | | • | |
| Harnischmacher et al. (2021) | Supporting the power grid with AGV batteries and optimizing the dispatching based on the current grid power need | • | | | | • | | |
| Heikkilä et al. (2022) | Characterization of worldwide ports in the areas of automation, sustainability and collaboration. Showing the benefits of digital collaboration | • | | | • | | • | |
| Heilig et al. (2017a) | A game theoretic framework for digitalization in seaports | • | | | | | • | |
| Heilig et al. (2020) | Data mining application in the port domain. Concluding that this research domain is yet to be developed more broadly | | | | | | · | |
| Heilig and Voß (2017) | Overview of technologies used in smart ports and the drivers such as the PCS or the NSW | • | | | • | • | • | |
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| Höpfner et al. (2021) | Dynamic storage space monitoring based on (near) real-time lidar information | • | – | | | • | • | |
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| Li et al. (2021d) | Digital twinning supporting the AGV scheduling strategy | | • | – | | | • | |

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|---|---|---|---|---|---|---|---|---|
| Nwakanma et al. (2022) | Analysis of the prospects of introducing a digital twin in the Nigerian shipping industry | – | | | | | • | |
| Osório et al. (2019) | Showing an open integration architecture for IoT with multiple suppliers | • | | | • | | • | |
| Othman (2021) | Showing the correlation between Industry 4.0 application and seaport quality | • | | | | | • | |
| Özkanli and DeniZhan (2020) | Developing a roadmap for the Turkish seaports, which lack in digitalization | • | | | | | • | |
| Pacheco Bolaño and Troncoso-Palacio (2021) | Simulation of roll-on and -off unloading at a port for bottleneck analysis | | | • | | | | |
| Pagano et al. (2022) | Showing the benefits of standardization for digitalization in seaports. Concluding that only few seaports are state of the art in regard to digitalization | • | | | • | • | • | • |
| Pang et al. (2021) | Digital twin especially for production and product development in the maritime domain | • | | | | | • | |
| Paulauskas et al. (2021) | Showing a correlation between port size and digitalization level | | | | | • | • | |
| Pavlić Skender et al. (2020) | Technologies used in the some of the biggest seaports worldwide | • | | | • | • | • | • |
| de la Peña Zarzuelo et al. (2020a) | Describing simulation over the course of the digitalization in ports | | | • | | | • | |
| Pita Costa et al. (2021) | Learnings from developing smart ports and showing a rising need for sustainable digitalization in ports | • | | | | | • | |

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| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Portapas et al. (2021) | Analysis of autonomous ships for new transport routes and digital twins for their monitoring and evaluation | – | | | | • | · | |
| Pyykkö et al. (2020) | A simulation-based environment for cybersecurity training in the maritime domain | | | – | | • | | |
| Rajput and Singh (2018) | Cyber-physical systems (CPS) and their implications on supply chain management. Furthermore, discussing the implementation levels of CPS's | • | | | | | • | |
| Ramirez et al. (2022) | Network focused implementation of a basic digital twin using 5G | • | | | • | | • | |
| Rødseth and Berre (2018) | Describing the need for an industrial data space in the maritime domain to support the data exchange while using digital twins | • | | | | | • | |
| Ross et al. (2022) | Analysis of a conceptual implementation of a digital twin at a British dockyard with a focus on multi-objective optimization | • | | – | | | | |
| Rost et al. (2018) | A few 5G enabled applications being tested in Hamburg (Germany) | | • | • | | | • | |
| Sadri et al. (2021) | Port KPIs analyzing greenness and progressiveness of ports | | • | | | | | |
| Mohd Salleh et al. (2021) | Defining the state of Malaysian seaport readiness regarding Industry 4.0 | | | | | | | |
| Garrido Salsas et al. (2022) | General development perspective for the Port of Barcelona | – | | | | | | |
| Sanchez-Gonzalez et al. (2022) | Analyzing the most effective digitalization steps for maritime container handling companies | • | | | | | • | |

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| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Sarabia-Jacome et al. (2019) | Defining a seaport data space architecture and analyzing it. A standardized way of information and data sharing for interoperability is also shown | • | | | | | • | |
| Sarabia-Jacome et al. (2020) | Potential of improving the communication and communication cost by implementing a seaport data space, also partially including digital twins | • | | | | | | |
| Schislyaeva (2021) | Examining the elements of a digital twin in logistic hubs as part of infrastructure innovation | • | – | | | | • | |
| Segovia et al. (2022) | A feasibility study on emissions reductions and demand response in a seaport buildings | | | • | | | • | |
| Shcherbakov and Silkina (2021) | Supply chain management integration over multiple participants. Analyzing logistics platforms and ecosystems | | | | | | | |
| Shi et al. (2022) | Analysis of key objects and control mechanisms as a basis for future digital twins and terminal control models | – | | | | | | |
| Short et al. (2022) | Modeling of electric gantry cranes for regeneration capture | | • | – | | | • | |
| Simoni et al. (2022) | Comparing port community systems in literature and in Rotterdam and showing the potential benefits | • | | | | | • | |
| Pavlić Skender et al. (2020) | Overview of modern technologies in leading global seaports, showing that future developments will lead to greater automation | • | | | • | • | • | • |
| Song (2021) | Analysis of the supply chain in container shipping, showing how it can be improved through less fragmentation and further digitalization | • | | | | | • | |
| Sun (2021) | 5G powered applications for the smart port realization at the Mawan and Zhoushan port (China) | – | | – | • | • | • | • |

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| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Szpytko and Duarte (2019) | Modeling of gantry cranes and risk simulation for creating a decision support model for integrated maintenance | | • | – | | | | |
| Szpytko and Duarte (2021) | A framework for digital twins in crane maintenance and showing a decision support model | | • | | | | • | |
| Tam and Jones (2019) | Emerging technologies in the maritime domain and their cybersecurity risks | – | | | | | · | |
| Tardo et al. (2022) | Proposal for a prototyping framework for agile development of smart services in the port, based on a set of off-the-shelf and open-source technologies | • | | | • | • | • | |
| Taylor et al. (2020) | Digital twins being described regarding the general maritime application and usage | • | | | | | | |
| Taylor et al. (2021) | Differentiating simulation and modeling and digital twins. Defining the benefits of (near) real time data integration of digital twins | | | – | • | | • | |
| Tedeschi and Sciancalepore (2019) | Advantages and disadvantages of fog and edge computing with respect to security and research challenges | | | | | | • | |
| Tesse et al. (2021) | Digital twin projects being analyzed for creating a digital twin metamodel, which is then used as a layer in strategic management of IoT cloud architecture | • | | | | • | • | |
| Trichias et al. (2021) | The “Vital-5G” project is being described, implementing “NetApps” to showcase and support the creation of 5G-based solutions to monitor, automate and improve in different parts of port logistics | • | | | • | | • | |
| Triska et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | • | | | • | • | • | |

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| Reference | Research scope | Implementation and application methods | Modeling and heuristics methods | Simulation methods | 5G/ LTE/ Wi-Fi | GPS/ GNSS | IoT/ sensors | Cameras |
|---|---|---|---|---|---|---|---|---|
| Tubis and Poturaj (2022) | Identify risks in AGV operations based on a literature review. The results show a deficiency in the identification and assessment of risks | – | | | | • | • | • |
| Uusitalo et al. (2021) | Simulation of 5G network infra-structure to facilitate future port automation and the underlying technologies | | | • | • | • | • | • |
| Vakili et al. (2021) | Development of a framework for a shipyard with the main objective of energy saving | | • | | | | | |
| Ramos Velasco et al. (2022) | Transition suggestions for a fishing port, becoming less reliant on fishing | – | | | | | • | |
| Wang et al. (2022) | Ship engine system and cargo monitoring for process management using Maya and Unity 3D | | • | – | | | • | • |
| Wang et al. (2021) | Showing digital twins result in benefits for port management. Supporting decision making and improving resilience and performance | • | | | | | • | |
| Wattanakul et al. (2022) | Generating data with digital twins for ML regarding port capacity prediction under uncertainty | • | | • | | | | |
| Wu et al. (2021) | A digital twin of inland waterways based on 3D video fusion for improved efficiency of daily monitoring, evidence collection and emergency response | • | | | • | | • | • |
| Yang et al. (2022a) | Status monitoring and simulation to support container gantry cranes' transition to and decision on hydrogen power | | • | – | | | • | |
| Yang et al. (2022b) | A case study on the digital twin of Qingdao Port and illustration of the development process and function of the digital twin for typical terminals | • | | – | • | • | • | • |
| Yang et al. (2018) | Overview of underlying tech-nologies of IoT in smart ports and their challenges, e.g., comparing prices for data connectivity | • | | | • | • | • | • |

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|---|---|---|---|---|---|---|---|---|
| Yang et al. (2022a) | Overview of smart port development and future planning guidelines | • | | | | • | • | |
| Yao et al. (2021a) | Digital twins and smart port concepts should be combined. Digital twin can improve the ports substantially | | | • | | | | |
| Yao et al. (2021b) | Digital twin supported planning of automated smart ports | | | • | • | • | • | |
| Zaychenko et al. (2021) | Comparing Russian and global seaports regarding their digitalization level | | | | | | | |
| Yang et al. (2022b) | Requirements and design principles for the digital twin in the port from a technical perspective | • | | | • | • | • | • . |
| Zhao et al. (2022) | A digital twin for energy-efficient planning of multiple cranes and selection of the number of cranes is described | | • | – | | • | • | |
| Zhou et al. (2022a) | Review of current technology trends and relevant research topics related to the container terminals and examining the implications on how container terminals can achieve their strategic goals | • | | | | | • | • |
| Zhou et al. (2022b) | A system for monitoring the operational status of port cranes based on digital twins is presented | | – | • | • | | • | • |
| Zhou et al. (2018) | Simulation-based optimization for improving maritime systems | | | • | | | | |
| Zhou et al. (2021) | Digital twins and simulation for resilience improvement | | | • | | | | |

**Table 2** continued

| Citation | Research scope | Lidar/laser | Actuators | Apps/ handheld-/ mobile devices | 3D visualization | VR/AR | BIM | Simulation software |
|---|---|---|---|---|---|---|---|---|
| Agarwala and Guduru (2021) | Overview of 5G being used in commercial shipping, being analyzed from design to actual operations | | | • | | • | | |
| Agatić and Kolanović (2020) | Seaport service quality and how it improves the digitalization | | | | | • | | • |
| Agostinelli et al. (2022a) | Optimizing maintenance and energy efficiency for renewables with the support of a digital twin for investigating and lowering GHG emissions | | | | • | | • | • |
| Agostinelli et al. (2022b) | Renewable energy production systems in ports can improve sustainability and efficiency in urban development | | | | | | • | • |
| Ali-Tolppa and Kajo (2020) | ML and optimization approaches to prevent service degradation of dynamic 5G coverage | | | | • | | | • |
| Aro et al. (2020) | Looking at the Baltic sea maritime industry and showing digital twins in the context of stowage and shipyards | | | | • | • | | • |
| Balaji and Chaudhry (2018) | Better localization in ports using trilateration method combined with WSN and simulation of the proposed technique | | | | | | | |
| Bao et al. (2022) | Asset management for decision making in industrial applications combined with an integrated digital twin frame | | | | • | | | • |
| Battilani et al. (2022) | Business process re-engineering with simulation-based validation | | | | | | | • |
| Boullauazan et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | | | | | | | |
| Brunetti et al. (2020) | Looking at smart yards and giving a framework for simulation | | | | • | | | • |

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|---|---|---|---|---|---|---|---|---|
| Busse et al. (2021) | A framework for a digital twin for a complete supply chain | | | | | | | • |
| Cai et al. (2022) | Digital twin application from the aspects of port operation business model and the cooperation of members mechanism | | | | | | | |
| Carvalho et al. (2020) | Propose a data and connectivity standard for easier communication and implementation of digital twins | | | | | | | • |
| Cavalli et al. (2021) | Port KPIs improving by use of 5G-cellular | • | | • | • | • | | |
| Chuprina et al. (2022) | Learnings from the digitalization strategies of global seaports as support for governments and other authorities | | | | | | | |
| Cumo (2021) | The digital twin at the Ventotene Island Port (Italy) for facility management, predictive maintenance of infrastructure and for energy management | | | | • | | • | • |
| Dalaklis et al. (2021) | Analysis of digital tools and technologies for future ports and giving an overview of ports around the world and the technologies already applied | | | | | • | | • |
| Damiani et al. (2019) | Energy purchasing optimization methods based on a port simulation and energy price forecasting | | | | | | | • |
| de la Peña Zarzuelo et al. (2020b) | Technologies and tools of Industry 4.0 in the port literature being analyzed | | | | | • | | |
| Doleski et al. (2022) | Energy system modeling for digital decarbonization in ports and logistic infrastructure | | | | | | | |

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|---|---|---|---|---|---|---|---|---|
| Douaioui et al. (2018) | Looking at the four industrial revolutions and showing the need for further research, training and development of technologies in Industry 4.0 | | • | • | | • | | |
| Du et al. (2022) | 5G network simulation and evaluation based on a digital copy of a port | | | | • | | | • |
| Fahim et al. (2021) | Track and trance as a basis for future ports and overall supply-chain cooperation | | | | | | | |
| Gao et al. (2022a) | Data governence specifically for IoT data | | | | | | | |
| Gao et al. (2022c) | Performance advantage of digital twin-based Q-learning solutions over Dijkstra's algorithm for AGV path planning | | • | | | | | |
| Gao et al. (2022b) | Simulation-based optimization for an automated storage yard in a container terminal supported by (near) real time data of a digital twin | | | | | • | | • |
| Gasparotti (2022) | Demonstrate the benefits of introducing digital technologies in the Romanian maritime sector | | | | | | | • |
| Gerlitz and Meyer (2021) | Decision-making tools are proposed to facilitate and strengthen the transition in small- and medium-sized ports toward environmental responsibility, social equity, and economic efficiency | | | | | | | |
| Giusti et al. (2019) | Success factors and enabling technologies of synchromodality | | | | | | | • |
| Golovianko et al. (2021) | Machine learning for image classification to replace human decision making | | | | | | | |
| González-Ramírez et al. (2023) | Decision support for container terminal operations with disturbances and analysis of main disturbances to port operations | | | | | | | • |

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|---|---|---|---|---|---|---|---|---|
| Gunes et al. (2021) | Defining and managing cyber risks in ports regarding the inclusion of digital twins | | | | | | | |
| Guo (2021) | Digital twin for harbor hydraulic structures and concrete | | | | | | | • |
| Gültekin et al. (2022) | Use of edge-based AI for autonomous vehicle fault detection and condition monitoring, reducing network requirements and shortening data transmission times | | | | | | | |
| Harnischmacher et al. (2021) | Supporting the power grid with AGV batteries and optimizing the dispatching based on the current grid power need | | | | | | | • |
| Heikkilä et al. (2022) | Characterization of worldwide ports in the areas of automation, sustainability and collaboration. Showing the benefits of digital collaboration | | | | | | | |
| Heilig et al. (2017a) | A game theoretic framework for digitalization in seaports | | | • | | | | |
| Heilig et al. (2020) | Data mining application in the port domain. Concluding that this research domain is yet to be developed more broadly | | | | | | | |
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| Jost et al. (2022) | Leverage geospatial context provided by LiDAR technology and methods to create digital twins | • | | | • | | | • |
| Karaś (2022) | Literature review of smart ports, showing the importance of a standard smart port definition | | | | | | | |
| Klar et al. (2022) | Assessing the maturity of digital twins for ports and showing future digital twinning approaches | | | | | | | • |
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| Kutzler et al. (2021) | Using a digital twin of all information systems to improve IT-security | | | | | | | |

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| Li and He (2021) | A combination of automated logistics and deep learning for berth liner predictions and container terminal improvements | | | | | | | |
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| Li et al. (2020) | Multiple simulation modules combined with a digital twin for supporting the Singapore port being planned | | | | • | • | | • |
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| Makkawan and Muangpan (2021) | Indicators of port performance and digitalization level. Helping develop smart port performance | | | | | • | | |
| Mallah et al. (2020) | Combining supply chain optimizing methods and industrial control systems for decision making and disturbance reaction at an export bulk port | | | | | | | |
| Maydanova et al. (2022) | Balanced scorecard for implementing IT-architecture for digital twins | | | | | | | • |
| Medyakova et al. (2020) | Studying digitalization efforts increasing because of a global pandemic (Covid-19) | | | • | | | | |
| Meyer et al. (2021) | Sustainability and efficiency in small and medium sized ports in future development | | | | | | | |
| Mi and Liu (2022a) | Maintenance using monitoring in smart ports | | | | • | | | |
| Mi and Liu (2022b) | Overview of simulation for planning container ports. Differentiating between emulation and simulation | | | | • | | | • |
| Min (2022) | Technical port development guidelines, including integration of TOS, SCADA, ERP, sensors and many more | | • | | | | | |
| Morra et al. (2019) | Use of a digital twin for planning alternative rail-based transportation in combination with the port area | | | | • | | | • |
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| Tam and Jones (2019) | Emerging technologies in the maritime domain and their cybersecurity risks | | | | | • | | • |
| Tardo et al. (2022) | Proposal for a prototyping framework for agile development of smart services in the port, based on a set of off-the-shelf and open-source technologies | | | | • | | | • |
| Taylor et al. (2020) | Digital twins being described regarding the general maritime application and usage | | | | | | | |
| Taylor et al. (2021) | Differentiating simulation and modeling and digital twins. Defining the benefits of (near) real-time data integration of digital twins | | | | | | | • |
| Tedeschi and Sciancalepore (2019) | Advantages and disadvantages of fog and edge computing with respect to security and research challenges | | | | | | | |
| Tesse et al. (2021) | Digital twin projects being analyzed for creating a digital twin metamodel, which is then used as a layer in strategic management of IoT cloud architecture | | | | • | | | • |
| Trichias et al. (2021) | The “Vital-5G” project is being described, implementing “NetApps” to showcase and support the creation of 5G-based solutions to monitor, automate and improve in different parts of port logistics | | | | | | | |

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| Triska et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | | | | | | | • |
| Tubis and Poturaj (2022) | Identify risks in AGV operations based on a literature review. The results show a deficiency in the identification and assessment of risks | • | | | • | | | • |
| Uusitalo et al. (2021) | Simulation of 5G network infra-structure to facilitate future port automation and the underlying technologies | | | | | • | | • |
| Vakili et al. (2021) | Development of a framework for a shipyard with the main objective of energy saving | | | | | | | |
| Ramos Velasco et al. (2022) | Transition suggestions for a fishing port, becoming less reliant on fishing | | | | | | | • |
| Wang et al. (2022) | Ship engine system and cargo monitoring for process management using Maya and Unity 3D | | | | • | • | | • |
| Wang et al. (2021) | Showing digital twins result in benefits for port management. Supporting decision making and improving resilience and performance | • | | | • | | • | • |
| Wattanakul et al. (2022) | Generating data with digital twins for ML regarding port capacity prediction under uncertainty | | | | • | | | • |
| Wu et al. (2021) | A digital twin of inland waterways based on 3D video fusion for improved efficiency of daily monitoring, evidence collection and emergency response | | | | • | | • | • |
| Yang et al. (2022a) | Status monitoring and simulation to support container gantry cranes' transition to and decision on hydrogen power | | | | | | | • |
| Yang et al. (2022b) | A case study on the digital twin of Qingdao Port and illustration of the development process and function of the digital twin for typical terminals | • | | | • | | | • |

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|---|---|---|---|---|---|---|---|---|
| Yang et al. (2018) | Overview of underlying tech-nologies of IoT in smart ports and their challenges, e.g., comparing prices for data connectivity | • | | • | | | | |
| Yang et al. (2022a) | Overview of smart port development and future planning guidelines | | | | • | | • | • |
| Yao et al. (2021a) | Digital twins and smart port concepts should be combined. Digital twin can improve the ports substantially | | | | • | | • | • |
| Yao et al. (2021b) | Digital twin supported planning of automated smart ports | | | | • | | • | • |
| Zaychenko et al. (2021) | Comparing Russian and global seaports regarding their digitalization level | | | | | | | |
| Yang et al. (2022b) | Requirements and design principles for the digital twin in the port from a technical perspective | • | | | | | | |
| Zhao et al. (2022) | A digital twin for energy-efficient planning of multiple cranes and selection of the number of cranes is described | | | | | | | • |
| Zhou et al. (2022a) | Review of current technology trends and relevant research topics related to the container terminals and examining the implications on how container terminals can achieve their strategic goals | | | | | • | | • |
| Zhou et al. (2022b) | A system for monitoring the operational status of port cranes based on digital twins is presented | | • | | • | | | • |
| Zhou et al. (2018) | Simulation-based optimization for improving maritime systems | | | | | | | • |
| Zhou et al. (2021) | Digital twins and simulation for resilience improvement | | | | | | | • |

**Table 2** continued

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|---|---|---|---|---|---|---|---|---|
| Agarwala and Guduru (2021) | Overview of 5G being used in commercial shipping, being analyzed from design to actual operations | • | • | | • | • | • | • |
| Agatić and Kolanović (2020) | Seaport service quality and how it improves the digitalization | • | • | | | | | |
| Agostinelli et al. (2022a) | Optimizing maintenance and energy efficiency for renewables with the support of a digital twin for investigating and lowering GHG emissions | • | • | • | • | • | • | • |
| Agostinelli et al. (2022b) | Renewable energy production systems in ports can improve sustainability and efficiency in urban development | | | | | • | | |
| Ali-Tolppa and Kajo (2020) | ML and optimization approaches to prevent service degradation of dynamic 5G coverage | • | • | | | • | | |
| Aro et al. (2020) | Looking at the Baltic sea maritime industry and showing digital twins in the context of stowage and shipyards | | | | | | | |
| Balaji and Chaudhry (2018) | Better localization in ports using trilateration method combined with WSN and simulation of the proposed technique | | | | | | | |
| Bao et al. (2022) | Asset management for decision making in industrial applications combined with an integrated digital twin frame | • | • | • | • | • | • | • |
| Battilani et al. (2022) | Business process re-engineering with simulation-based validation | | | | | | | |
| Boullauazan et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | | | | | | | |
| Brunetti et al. (2020) | Looking at smart yards and giving a framework for simulation | | | | | | | |

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| Citation | Research scope | Data lake/ big data | ML | Predictive APIs | Mirroring function | Augmented visualization function | Monitoring/ alerting function | Control function |
|---|---|---|---|---|---|---|---|---|
| Busse et al. (2021) | A framework for a digital twin for a complete supply chain | • | • | | • | | • | |
| Cai et al. (2022) | Digital twin application from the aspects of port operation business model and the cooperation of members mechanism | | | | • | | | |
| Carvalho et al. (2020) | Propose a data and connectivity standard for easier communication and implementation of digital twins | | | | | | | |
| Cavalli et al. (2021) | Port KPIs improving by use of 5G-cellular | | • | | • | • | | |
| Chuprina et al. (2022) | Learnings from the digitalization strategies of global seaports as support for governments and other authorities | • | | | | | | |
| Cumo (2021) | The digital twin at the Ventotene Island Port (Italy) for facility management, predictive maintenance of infrastructure and for energy management | • | • | | • | | • | |
| Dalaklis et al. (2021) | Analysis of digital tools and technologies for future ports and giving an overview of ports around the world and the technologies already applied | • | • | | | • | • | |
| Damiani et al. (2019) | Energy purchasing optimization methods based on a port simulation and energy price forecasting | • | | • | | | | |
| de la Peña Zarzuelo et al. (2020b) | Technologies and tools of Industry 4.0 in the port literature being analyzed | | • | | | | | |
| Doleski et al. (2022) | Energy system modeling for digital decarbonization in ports and logistic infrastructure | | | | | | | |

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| Citation | Research scope | Data lake/ big data | ML | Predictive APIs | Mirroring function | Augmented visualization function | Monitoring/ alerting function | Control function |
|---|---|---|---|---|---|---|---|---|
| Douaioui et al. (2018) | Looking at the four industrial revolutions and showing the need for further research, training and development of technologies in Industry 4.0 | • | | | | | | • |
| Du et al. (2022) | 5G network simulation and evaluation based on a digital copy of a port | | | | • | | | |
| Fahim et al. (2021) | Track and trance as a basis for future ports and overall supply-chain cooperation | | | | | | • | |
| Gao et al. (2022a) | Data governence specifically for IoT data | • | | | | | | |
| Gao et al. (2022c) | Performance advantage of digital twin-based Q-learning solutions over Dijkstra's algorithm for AGV path planning | | • | | | | | |
| Gao et al. (2022b) | Simulation-based optimization for an automated storage yard in a container terminal supported by (near) real-time data of a digital twin | • | • | • | • | | | |
| Gasparotti (2022) | Demonstrate the benefits of introducing digital technologies in the Romanian maritime sector | • | • | | | | | |
| Gerlitz and Meyer (2021) | Decision-making tools are proposed to facilitate and strengthen the transition in small- and medium-sized ports toward environmental responsibility, social equity, and economic efficiency | • | | | | | | |
| Giusti et al. (2019) | Success factors and enabling technologies of synchromodality | | | | | | | |
| Golovianko et al. (2021) | Machine learning for image classification to replace human decision making | | • | | | | | • |
| González-Ramírez et al. (2023) | Decision support for container terminal operations with disturbances and analysis of main disturbances to port operations | | | | | | • | |

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|---|---|---|---|---|---|---|---|---|
| Gunes et al. (2021) | Defining and managing cyber risks in ports regarding the inclusion of digital twins | | | | | | • | • |
| Guo (2021) | Digital twin for harbor hydraulic structures and concrete | | • | | | | • | |
| Gültekin et al. (2022) | Use of edge-based AI for autonomous vehicle fault detection and condition monitoring, reducing network requirements and shortening data transmission times | | • | | | • | • | • |
| Harnischmacher et al. (2021) | Supporting the power grid with AGV batteries and optimizing the dispatching based on the current grid power need | | • | | • | | | |
| Heikkilä et al. (2022) | Characterization of worldwide ports in the areas of automation, sustainability and collaboration. Showing the benefits of digital collaboration | • | • | • | | | • | • |
| Heilig et al. (2017a) | A game theoretic framework for digitalization in seaports | • | • | | | | | |
| Heilig et al. (2020) | Data mining application in the port domain. Concluding that this research domain is yet to be developed more broadly | • | | | | | | |
| Heilig and Voß (2017) | Overview of technologies used in smart ports and the drivers such as the PCS or the NSW | • | | • | | • | • | |
| Henríquez et al. (2022) | Explaining the relationship between the adoption of Industry 4.0 technologies and the seaports' business model | • | • | | | | • | |
| Hofmann and Branding (2019) | Simulation-based digital twin in python | • | | | | | | |
| Höpfner et al. (2021) | Dynamic storage space monitoring based on (near) real-time lidar information | | | | | • | • | |

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|---|---|---|---|---|---|---|---|---|
| Ibrion et al. (2019) | Comparing aviation and maritime digital twins and showing the risks of digital twins and possible failures | | | | • | • | • | |
| Ichimura et al. (2022) | It is discussed that all carriers are focused on digitalization | | • | | | | | |
| Ilin et al. (2022) | Target architecture for the digitalization of the North Sea | | | | • | | • | |
| Inkinen et al. (2021) | Future prospects and scenarios as well as technological drivers in Finnish seaports | • | • | | | | | |
| Jakovlev et al. (2021) | A framework for increasing port safety and security using a digital twin | • | • | | | • | • | |
| Krüger et al. (2021) | Linking a static planning tool and a simulation for terminal operations including layout planning | | | | | | | |
| Jedermann and Lang (2022) | Showing low effort modeling and prediction methods for potential digital twins from a data perspective | • | | | • | | • | |
| Jeevan et al. (2021) | It is discussed that Industry 4.0 needs investment, the right leadership and can result in greater competitiveness | • | • | | | | | |
| Jost et al. (2022) | Leverage geospatial context provided by LiDAR technology and methods to create digital twins | | • | | • | • | • | • |
| Karaś (2022) | Literature review of smart ports, showing the importance of a standard smart port definition | • | | • | | | | |
| Klar et al. (2022) | Assessing the maturity of digital twins for ports and showing future digital twinning approaches | • | | | • | • | • | • |
| Koroleva et al. (2019) | Comparing the digitalization of global and Russian ports | | • | • | • | | | |
| Kutzler et al. (2021) | Using a digital twin of all information systems to improve IT-security | • | | | • | | • | |

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|---|---|---|---|---|---|---|---|---|
| Lennon et al. (2012) | Showing the advancements of the risk assessment tool and decision support system at the Port of Los Angeles/Long Beach/Long Beach (USA) | • | | | | | | |
| Li et al. (2022) | Modeling and reduction of energy consumption of container terminals considering, e.g., route optimization and integration of an economic benefit analysis | • | | | | | | |
| Li and He (2020) | Time predictions for berthing in container terminals using (DNN) | | • | | | | | |
| Li and He (2021) | A combination of automated logistics and deep learning for berth liner predictions and container terminal improvements | • | • | | | | | |
| Li et al. (2021a) | Calculating and improving seaport operation performance with artificial neural networks | • | • | | | | | |
| Li and Song (2020) | Discussing automated logistics in general and showing the importance based on general principles of computation for the future port including digital twins | | | | | | | |
| Li et al. (2021b) | Analysis of the combination of ML, optimization and simulation methods in general in combination with digital twins | • | • | | | | | |
| Li et al. (2020) | Multiple simulation modules combined with a digital twin for supporting the Singapore port being planned | | • | | • | • | | |
| Li et al. (2021c) | A digital twin supported terminal operation with higher efficiencies and application in AGV scheduling | • | • | | • | | • | • |
| Li et al. (2021d) | Digital twinning supporting the AGV scheduling strategy | • | • | | | | | |

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| Lind et al. (2018) | Digitalization as an urgent need for optimizing communication between port actors. Amazon/Alibaba and others increasingly demanding digital services in the maritime transport domain | • | • | | | | | |
| Makkawan and Muangpan (2021) | Indicators of port performance and digitalization level. Helping develop smart port performance | • | • | | | | | • |
| Mallah et al. (2020) | Combining supply chain optimizing methods and industrial control systems for decision making and disturbance reaction at an export bulk port | • | | • | | | • | |
| Maydanova et al. (2022) | Balanced scorecard for implementing IT-architecture for digital twins | | • | | • | | | |
| Medyakova et al. (2020) | Studying digitalization efforts increasing because of a global pandemic (Covid-19) | | • | | • | • | • | |
| Meyer et al. (2021) | Sustainability and efficiency in small and medium sized ports in future development | | | | | | | |
| Mi and Liu (2022a) | Maintenance using monitoring in smart ports | • | • | | | | • | |
| Mi and Liu (2022b) | Overview of simulation for planning container ports. Differentiating between emulation and simulation | | | | | | | |
| Min (2022) | Technical port development guidelines, including integration of TOS, SCADA, ERP, Sensors and many more | • | • | | • | • | • | |
| Morra et al. (2019) | Use of a digital twin for planning alternative rail-based transportation in combination with the port area | | | | • | | | |
| Ni et al. (2021) | AGV route and path planning based on local neural networks improving on scenarios with missing data | | • | • | | | | • |

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**Table 2** continued

| Citation | Research scope | Data lake/ big data | ML | Predictive APIs | Mirroring function | Augmented visualization function | Monitoring/ alerting function | Control function |
|---|---|---|---|---|---|---|---|---|
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| Tubis and Poturaj (2022) | Identify risks in AGV operations based on a literature review. The results show a deficiency in the identification and assessment of risks | | • | | • | • | | • |
| Uusitalo et al. (2021) | Simulation of 5G network infra-structure to facilitate future port automation and the underlying technologies | • | • | • | • | • | | • |
| Vakili et al. (2021) | Development of a framework for a shipyard with the main objective of energy saving | | | | | | | |
| Ramos Velasco et al. (2022) | Transition suggestions for a fishing port, becoming less reliant on fishing | • | | | | | | |
| Wang et al. (2022) | Ship engine system and cargo monitoring for process management using Maya and Unity 3D | • | • | • | • | • | • | • . |
| Wang et al. (2021) | Showing digital twins result in benefits for port management. Supporting decision making and improving resilience and performance | • | | | • | • | • | |
| Wattanakul et al. (2022) | Generating data with digital twins for ML regarding port capacity prediction under uncertainty | | | | | | | |
| Wu et al. (2021) | A digital twin of inland waterways based on 3D video fusion for improved efficiency of daily monitoring, evidence collection and emergency response | • | | | • | • | • | |
| Yang et al. (2022a) | Status monitoring and simulation to support container gantry cranes' transition to and decision on hydrogen power | | | | • | | | |
| Yang et al. (2022b) | A case study on the digital twin of Qingdao Port and illustration of the development process and function of the digital twin for typical terminals | • | • | • | • | • | • | • |

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| Citation | Research scope | Data lake/ big data | ML | Predictive APIs | Mirroring function | Augmented visualization function | Monitoring/ alerting function | Control function |
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| Yang et al. (2022a) | Overview of smart port development and future planning guidelines | • | | | • | • | • | • |
| Yao et al. (2021a) | Digital twins and smart port concepts should be combined. Digital twin can improve the ports substantially | | | | • | | | |
| Yao et al. (2021b) | Digital twin supported planning of automated smart ports | • | • | | | • | | |
| Zaychenko et al. (2021) | Comparing Russian and global seaports regarding their digitalization level | | | | | | | |
| Yang et al. (2022b) | Requirements and design principles for the digital twin in the port from a technical perspective | • | | | | | | |
| Zhao et al. (2022) | A digital twin for energy-efficient planning of multiple cranes and selection of the number of cranes is described | | | | • | | | |
| Zhou et al. (2022a) | Review of current technology trends and relevant research topics related to the container terminals and examining the implications on how container terminals can achieve their strategic goals | • | | | • | | | |
| Zhou et al. (2022b) | A system for monitoring the operational status of port cranes based on digital twins is presented | • | | | • | • | • | |
| Zhou et al. (2018) | Simulation-based optimization for improving maritime systems | • | | | | | | |
| Zhou et al. (2021) | Digital twins and simulation for resilience improvement | | | | | | | |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Agarwala and Guduru (2021) | Overview of 5G being used in commercial shipping, being analyzed from design to actual operations | | | • | • | | Shadow |
| Agatić and Kolanović (2020) | Seaport service quality and how it improves the digitalization | | • | • | • | • | Shadow |
| Agostinelli et al. (2022a) | Optimizing maintenance and energy efficiency for renewables with the support of a digital twin for investigating and lowering GHG emissions | | • | • | • | • | Shadow |
| Agostinelli et al. (2022b) | Renewable energy production systems in ports can improve sustainability and efficiency in urban development | | • | | • | | Shadow |
| Ali-Tolppa and Kajo (2020) | ML and optimization approaches to prevent service degradation of dynamic 5G coverage | | • | | • | • | Shadow |
| Aro et al. (2020) | Looking at the Baltic sea maritime industry and showing digital twins in the context of stowage and shipyards | | | | • | • | Shadow |
| Balaji and Chaudhry (2018) | Better localization in ports using trilateration method combined with WSN and simulation of the proposed technique | | | | | | Digital Support System |
| Bao et al. (2022) | Asset management for decision making in industrial applications combined with an integrated digital twin frame | • | • | • | • | • | Twin |
| Battilani et al. (2022) | Business process re-engineering with simulation-based validation | | • | | | • | Shadow |
| Boullauazan et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | | | | | | n.a |
| Brunetti et al. (2020) | Looking at smart yards and giving a framework for simulation | | | | • | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Busse et al. (2021) | A framework for a digital twin for a complete supply chain | | • | | • | • | Shadow |
| Cai et al. (2022) | Digital twin application from the aspects of port operation business model and the cooperation of members mechanism | | • | | | • | Shadow |
| Carvalho et al. (2020) | Propose a data and connectivity standard for easier communication and implementation of digital twins | | | | | | Shadow |
| Cavalli et al. (2021) | Port KPIs improving by use of 5G-cellular | | | | | • | Shadow |
| Chuprina et al. (2022) | Learnings from the digitalization strategies of global seaports as support for governments and other authorities | | | | | | n.a |
| Cumo (2021) | The digital twin at the Ventotene Island Port (Italy) for facility management, predictive maintenance of infrastructure and for energy management | | • | • | • | • | Shadow |
| Dalaklis et al. (2021) | Analysis of digital tools and technologies for future ports and giving an overview of ports around the world and the technologies already applied | • | • | | • | · | Shadow |
| Damiani et al. (2019) | Energy purchasing optimization methods based on a port simulation and energy price forecasting | • | • | • | • | • | Shadow |
| de la Peña Zarzuelo et al. (2020b) | Technologies and tools of Industry 4.0 in the port literature being analyzed | | | | | | n.a |
| Doleski et al. (2022) | Energy system modeling for digital decarbonization in ports and logistic infrastructure | | | | • | • | Shadow |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Douaioui et al. (2018) | Looking at the four industrial revolutions and showing the need for further research, training and development of technologies in Industry 4.0 | • | | | | | Twin |
| Du et al. (2022) | 5G network simulation and evaluation based on a digital copy of a port | | | | • | | Digital Support System |
| Fahim et al. (2021) | Track and trance as a basis for future ports and overall supply-chain cooperation | • | • | | | • | Twin |
| Gao et al. (2022a) | Data governence specifically for IoT data | | | | | | Shadow |
| Gao et al. (2022c) | Performance advantage of digital twin-based Q-learning solutions over Dijkstra's algorithm for AGV path planning | • | | | | • | Twin |
| Gao et al. (2022b) | Simulation-based optimization for an automated storage yard in a container terminal supported by (near) real-time data of a digital twin | • | • | • | • | • | Twin |
| Gasparotti (2022) | Demonstrate the benefits of introducing digital technologies in the Romanian maritime sector | | | | | | n.a |
| Gerlitz and Meyer (2021) | Decision-making tools are proposed to facilitate and strengthen the transition in small- and medium-sized ports toward environmental responsibility, social equity, and economic efficiency | | | | | | n.a |
| Giusti et al. (2019) | Success factors and enabling technologies of synchromodality | | | | • | | Shadow |
| Golovianko et al. (2021) | Machine learning for image classification to replace human decision making | • | | | | • | Twin |
| González-Ramírez et al. (2023) | Decision support for container terminal operations with disturbances and analysis of main disturbances to port operations | | | | • | • | n.a |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Gunes et al. (2021) | Defining and managing cyber risks in ports regarding the inclusion of digital twins | | | | | | Shadow |
| Guo (2021) | Digital twin for harbor hydraulic structures and concrete | | • | • | • | | Shadow |
| Gültekin et al. (2022) | Use of edge-based AI for autonomous vehicle fault detection and condition monitoring, reducing network requirements and shortening data transmission times | • | | • | | | Twin |
| Harnischmacher et al. (2021) | Supporting the power grid with AGV batteries and optimizing the dispatching based on the current grid power need | • | | • | • | • | Twin |
| Heikkilä et al. (2022) | Characterization of worldwide ports in the areas of automation, sustainability and collaboration. Showing the benefits of digital collaboration | • | • | | | • | n.a |
| Heilig et al. (2017a) | A game theoretic framework for digitalization in seaports | | | | | • | n.a |
| Heilig et al. (2020) | Data mining application in the port domain. Concluding that this research domain is yet to be developed more broadly | | • | | | • | Twin |
| Heilig and Voß (2017) | Overview of technologies used in smart ports and the drivers such as the PCS or the NSW | | · | | | | n.a |
| Henríquez et al. (2022) | Explaining the relationship between the adoption of Industry 4.0 technologies and the seaports' business model | • | | • | | | Shadow |
| Hofmann and Branding (2019) | Simulation-based digital twin in python | | | • | • | • | Twin |
| Höpfner et al. (2021) | Dynamic storage space monitoring based on (near) real-time lidar information | • | • | | • | • | Shadow |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Ibrion et al. (2019) | Comparing aviation and maritime digital twins and showing the risks of digital twins and possible failures | | • | • | • | • | Shadow |
| Ichimura et al. (2022) | It is discussed that all carriers are focused on digitalization | | | | • | • | Shadow |
| Ilin et al. (2022) | Target architecture for the digitalization of the North Sea | | • | | | | Twin |
| Inkinen et al. (2021) | Future prospects and scenarios as well as technological drivers in Finnish seaports | | • | | | • | n.a |
| Jakovlev et al. (2021) | A framework for increasing port safety and security using a digital twin | | • | | | • | Shadow |
| Krüger et al. (2021) | Linking a static planning tool and a simulation for terminal operations including layout planning | | | | • | • | n.a |
| Jedermann and Lang (2022) | Showing low effort modeling and prediction methods for potential digital twins from a data perspective | | | • | • | • | Shadow |
| Jeevan et al. (2021) | It is discussed that Industry 4.0 needs investment, the right leadership and can result in greater competitiveness | | • | | • | • | Shadow |
| Jost et al. (2022) | Leverage geospatial context provided by LiDAR technology and methods to create digital twins | • | • | • | • | • | Twin |
| Karaś (2022) | Literature review of smart ports, showing the importance of a standard smart port definition | | | | | | n.a |
| Klar et al. (2022) | Assessing the maturity of digital twins for ports and showing future digital twinning approaches | • | • | • | • | • | Twin |
| Koroleva et al. (2019) | Comparing the digitalization of global and Russian ports | | | | | • | Digital Support System |
| Kutzler et al. (2021) | Using a digital twin of all information systems to improve IT-security | | • | | • | • | Shadow |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Lennon et al. (2012) | Showing the advancements of the risk assessment tool and decision support system at the Port of Los Angeles/Long Beach (USA) | | • | | • | • | n.a |
| Li et al. (2022) | Modeling and reduction of energy consumption of container terminals considering, e.g., route optimization and integration of an economic benefit analysis | | | | | • | n.a |
| Li and He (2020) | Time predictions for berthing in container terminals using (DNN) | | | • | | | n.a |
| Li and He (2021) | A combination of automated logistics and deep learning for berth liner predictions and container terminal improvements | | | • | • | • | Shadow/Twin |
| Li et al. (2021a) | Calculating and improving seaport operation performance with artificial neural networks | | • | • | | • | Shadow |
| Li and Song (2020) | Discussing automated logistics in general and showing the importance based on general principles of computation for the future port including digital twins | • | • | | | • | n.a |
| Li et al. (2021b) | Analysis of the combination of ML, optimization and simulation methods in general in combination with digital twins | | • | | • | • | Shadow |
| Li et al. (2020) | Multiple simulation modules combined with a digital twin for supporting the Singapore port being planned | | • | • | • | • | Twin |
| Li et al. (2021c) | A digital twin supported terminal operation with higher efficiencies and application in AGV scheduling | • | • | | • | • | Shadow |
| Li et al. (2021d) | Digital twinning supporting the AGV scheduling strategy | • | • | • | • | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Lind et al. (2018) | Digitalization as an urgent need for optimizing communication between port actors. Amazon/Alibaba and others increasingly demanding digital services in the maritime transport domain | | | | | | n.a |
| Makkawan and Muangpan (2021) | Indicators of port performance and digitalization level. Helping develop smart port performance | • | | | | | n.a |
| Mallah et al. (2020) | Combining supply chain optimizing methods and industrial control systems for decision making and disturbance reaction at an export bulk port | | • | • | | • | Digital Support System |
| Maydanova et al. (2022) | Balanced scorecard for implementing IT-architecture for digital twins | | | | • | • | Shadow |
| Medyakova et al. (2020) | Studying digitalization efforts increasing because of a global pandemic (covid-19) | • | | • | • | | Shadow/Twin |
| Meyer et al. (2021) | Sustainability and efficiency in small and medium sized ports in future development | | | | | • | n.a |
| Mi and Liu (2022a) | Maintenance using monitoring in smart ports | | • | | | | Digital Support System |
| Mi and Liu (2022b) | Overview of simulation for planning container ports. Differentiating between emulation and simulation | | | • | • | • | Shadow |
| Min (2022) | Technical port development guidelines, including integration of TOS, SCADA, ERP, Sensors and many more | • | • | | | • | Twin |
| Morra et al. (2019) | Use of a digital twin for planning alternative rail-based transportation in combination with the port area | | | | • | | Digital Support System |
| Ni et al. (2021) | AGV route and path planning based on local neural networks improving on scenarios with missing data | • | | • | • | • | n.a |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Nwakanma et al. (2022) | Analysis of the prospects of introducing a digital twin in the Nigerian shipping industry | | | · | | | Shadow |
| Osório et al. (2019) | Showing an open integration architecture for IoT with multiple suppliers | • | • | | | | Shadow |
| Othman (2021) | Showing the correlation between Industry 4.0 application and seaport quality | | • | | | | n.a |
| Özkanli and DeniZhan (2020) | Developing a roadmap for the Turkish seaports, which lack in digitalization | | | | | • | Digital Support System |
| Pacheco Bolaño and Troncoso-Palacio (2021) | Simulation of role-on and -off unloading at a port for bottleneck analysis | | • | | • | • | Shadow |
| Pagano et al. (2022) | Showing the benefits of standardization for digitalization in seaports. Concluding that only few seaports are state of the art in regard to digitalization | | • | | | • | n.a |
| Pang et al. (2021) | Digital twin especially for production and product development in the maritime domain | | • | | • | • | Twin |
| Paulauskas et al. (2021) | Showing a correlation between port size and digitalization level | | • | | | • | n.a |
| Pavlić Skender et al. (2020) | Technologies used in the some of the biggest seaports worldwide | | • | • | | • | Digital Support System/Shadow |
| de la Peña Zarzuelo et al. (2020a) | Describing simulation over the course of the digitalization in ports | | • | • | • | • | Shadow |
| Pita Costa et al. (2021) | Learnings from developing smart ports and showing a rising need for sustainable digitalization in ports | | • | • | | • | Shadow |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Portapas et al. (2021) | Analysis of autonomous ships for new transport routes and digital twins for their monitoring and evaluation | • | • | • | | • | Twin |
| Pyykkö et al. (2020) | A simulation-based environment for cybersecurity training in the maritime domain | | | | | | Digital Support System |
| Rajput and Singh (2018) | Cyber physical systems (CPS) and their implications on supply chain management. Furthermore, discussing the implementation levels of CPS's | | • | • | | • | Twin |
| Ramirez et al. (2022) | Network focused implementation of a basic digital twin using 5G | | | | • | • | Twin |
| Rødseth and Berre (2018) | Describing the need for an industrial data space in the maritime domain to support the data exchange while using digital twins | | • | • | • | • | Shadow |
| Ross et al. (2022) | Analysis of a conceptual implementation of a digital twin at a British dockyard with a focus on multi-objective optimization | | • | | • | • | Digital Support System |
| Rost et al. (2018) | A few 5G enabled applications being tested in Hamburg (Germany) | | • | | | | Twin |
| Sadri et al. (2021) | Port KPIs analyzing greenness and progressiveness of ports | | • | | | | n.a |
| Mohd Salleh et al. (2021) | Defining the state of Malaysian seaport readiness regarding Industry 4.0 | | | | | • | n.a |
| Garrido Salsas et al. (2022) | General development perspective for the Port of Barcelona | | | | | | n.a |
| Sanchez-Gonzalez et al. (2022) | Analyzing the most effective digitalization steps for maritime container handling companies | • | | • | | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Sarabia-Jacome et al. (2019) | Defining a seaport data space architecture and analyzing it. A standardized way of information and data sharing for interoperability is also shown | | • | | | | n.a |
| Sarabia-Jacome et al. (2020) | Potential of improving the communication and communication cost by implementing a seaport data space, also partially including digital twins | | | | | • | n.a |
| Schislyaeva (2021) | Examining the elements of a digital twin in logistic hubs as part of infrastructure innovation | • | • | • | • | • | Shadow |
| Segovia et al. (2022) | A feasibility study on emissions reductions and demand response in a seaport buildings | | • | • | • | | Shadow |
| Shcherbakov and Silkina (2021) | Supply chain management integration over multiple participants. Analyzing logistics platforms and ecosystems | | | | | | n.a |
| Shi et al. (2022) | Analysis of key objects and control mechanisms as a basis for future digital twins and terminal control models | | | | | | n.a |
| Short et al. (2022) | Modeling of electric gantry cranes for regeneration capture | | • | | • | • | Shadow |
| Simoni et al. (2022) | Comparing port community systems in literature and in Rotterdam and showing the potential benefits | | | | | · | Shadow |
| Pavlić Skender et al. (2020) | Overview of modern technologies in leading global seaports, showing that future developments will lead to greater automation | • | | • | • | • | Shadow |
| Song (2021) | Analysis of the supply chain in container shipping, showing how it can be improved through less fragmentation and further digitalization | • | • | • | | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Sun (2021) | 5G powered applications for the smart port realization at the Mawan and Zhoushan port (China) | • | | | • | • | Twin |
| Szpytko and Duarte (2019) | Modeling of gantry cranes and risk simulation for creating a decision support model for integrated maintenance | | • | | • | • | Digital Support System/Shadow |
| Szpytko and Duarte (2021) | A framework for digital twins in crane maintenance and showing a decision support model | • | • | • | • | • | Digital Support System |
| Tam and Jones (2019) | Emerging technologies in the maritime domain and their cybersecurity risks | • | | | • | | Digital Support System |
| Tardo et al. (2022) | Proposal for a prototyping framework for agile development of smart services in the port, based on a set of off-the-shelf and open-source technologies | | • | | | • | Twin |
| Taylor et al. (2020) | Digital twins being described regarding the general maritime application and usage | | | | | | Shadow |
| Taylor et al. (2021) | Differentiating simulation and modeling and digital twins. Defining the benefits of (near) real-time -data integration of digital twins | • | • | | • | • | Shadow |
| Tedeschi and Sciancalepore (2019) | Advantages and disadvantages of fog and edge computing with respect to security and research challenges | • | • | • | | • | Shadow |
| Tesse et al. (2021) | Digital twin projects being analyzed for creating a digital twin metamodel, which is then used as a layer in strategic management of IoT cloud architecture | • | • | • | • | • | Shadow/Twin |
| Trichias et al. (2021) | The “Vital-5G” project is being described, implementing “NetApps” to showcase and support the creation of 5G-based solutions to monitor, automate and improve in different parts of port logistics | • | | • | • | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Triska et al. (2022) | Maturity model for smart ports with recommendations for a digitalization strategy | | | | | | n.a |
| Tubis and Poturaj (2022) | Identify risks in AGV operations based on a literature review. The results show a deficiency in the identification and assessment of risks | • | | • | | • | Twin |
| Uusitalo et al. (2021) | Simulation of 5G network infra-structure to facilitate future port automation and the underlying technologies | | | • | • | | Shadow |
| Vakili et al. (2021) | Development of a framework for a shipyard with the main objective of energy saving | | | | | | n.a |
| Ramos Velasco et al. (2022) | Transition suggestions for a fishing port, becoming less reliant on fishing | | | | | | n.a |
| Wang et al. (2022) | Ship engine system and cargo monitoring for process management using Maya and Unity 3D | | • | • | • | • | Shadow |
| Wang et al. (2021) | Showing digital twins result in benefits for port management. Supporting decision making and improving resilience and performance | | • | | • | • | Shadow |
| Wattanakul et al. (2022) | Generating data with digital twins for ML regarding port capacity prediction under uncertainty | | | • | • | • | Digital Support System |
| Wu et al. (2021) | A digital twin of inland waterways based on 3D video fusion for improved efficiency of daily monitoring, evidence collection and emergency response | | • | | • | | Shadow |
| Yang et al. (2022a) | Status monitoring and simulation to support container gantry cranes' transition to and decision on hydrogen power | | • | • | • | | Shadow |
| Yang et al. (2022b) | A case study on the digital twin of Qingdao Port and illustration of the development process and function of the digital twin for typical terminals | • | • | • | • | • | Twin |

**Table 2** continued

| Citation | Research scope | Process automation function | Business intelligence function | Predictive analytics function | Simulation function | Optimization function | Understanding of digital twin |
|---|---|---|---|---|---|---|---|
| Yang et al. (2018) | Overview of underlying tech-nologies of IoT in smart ports and their challenges, e.g., comparing prices for data connectivity | | | | | | n.a |
| Yang et al. (2022a) | Overview of smart port development and future planning guidelines | | • | | • | • | Twin |
| Yao et al. (2021a) | Digital twins and smart port concepts should be combined. Digital twin can improve the ports substantially | | • | • | • | • | Twin |
| Yao et al. (2021b) | Digital twin supported planning of automated smart ports | • | • | | • | • | Digital Support System |
| Zaychenko et al. (2021) | Comparing Russian and global seaports regarding their digitalization level | | | | | • | n.a |
| Yang et al. (2022b) | Requirements and design principles for the digital twin in the port from a technical perspective | | | | | | n.a |
| Zhao et al. (2022) | A digital twin for energy-efficient planning of multiple cranes and selection of the number of cranes is described | | • | • | • | • | Twin |
| Zhou et al. (2022a) | Review of current technology trends and relevant research topics related to the container terminals and examining the implications on how container terminals can achieve their strategic goals | • | • | • | • | • | Shadow |
| Zhou et al. (2022b) | A system for monitoring the operational status of port cranes based on digital twins is presented | • | • | • | • | • | Twin |
| Zhou et al. (2018) | Simulation-based optimization for improving maritime systems | | | | • | • | Shadow |
| Zhou et al. (2021) | Digital twins and simulation for resilience improvement | | • | | • | • | Shadow |

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## Declarations

**Conflict of interest** The authors declare that there are no potential conflicts of interest. All participants have declared their consent to the publication of the information from the interviews.



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**Julian Neugebauer** is a researcher at the Institute of Information Systems at the University of Hamburg and works in a consulting capacity for various companies with a focus on digitalization and digital twins. He holds a B.Eng. degree in Transportation and Logistics and an M.Sc. degree in Logistics, Management and Engineering from Bremerhaven University of Applied Sciences, where he also worked as a project manager on researching blockchain and its application for the Bill of Lading as well as developing emissions calculations for blockchain applications and logistics transports. In his role as a researcher, he is a speaker at various scientific and business conferences, with his current research focusing on machine learning applications enabled by digital twins. He has published scientific articles in these areas. In addition, Julian is an avid pilot and has experience working with major international logistics companies.

**Leonard Heilig** is co-founder and CTO of driveMybox, and holds a position as project leader and lecturer at the Institute of Information Systems, University of Hamburg (Germany). He received a B.Sc. degree in information systems from the University of Münster (Germany) and an M.Sc. and a doctoral degree in information systems from the University of Hamburg (Germany). In his role as CTO at driveMybox, he leads the technical development of their logistics platform, optimization, AI, and cloud infrastructure. He has published more than 50 scientific articles and books in the areas of maritime logistics, operations research, and cloud computing. He has also worked as a consultant for several international logistics projects, and served as the guest editor for several peer-reviewed journals, and provides guest lectures at various universities worldwide.

**Stefan Voß** is professor and director of the Institute of Information Systems at the University of Hamburg. Previous positions include full professor and head of the department of Business Administration, Information Systems and Information Management at the University of Technology Braunschweig (Germany) from 1995 up to 2002. From 2020 to 2022 he served as dean of the Hamburg Business School (School of Business Administration). He holds degrees in Mathematics (diploma) and Economics from the University of Hamburg and a Ph.D. and the habilitation from the University of Technology Darmstadt. His current research interests are in quantitative / information systems approaches to supply chain management and logistics including public mass transit and telecommunications. He is author and co-author of several books and several hundred papers in various journals and compilations. In the German Handelsblatt ranking he is continuously within the top 20 professors in business administration within the German speaking countries. The most recent Wirtschaftswoche rankings list him among the top 10. Stefan Voß serves on the editorial board of some journals including being Editor of Public Transport. He is frequently organizing workshops and conferences. Furthermore, he is consulting with several companies.