Digital twinning for ports: from characterization to operations' modelling

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Abstract

Ports are actively pursuing greater operational efficiency to effectively handle the increasing global flow of goods, while striving to improve the energy efficiency of their operations to comply with new environmental regulations. As a result, innovation-leading ports have begun to recognize the potential of digital twins to overview, coordinate and optimize port processes, resulting in energy savings, and reductions of costs and of CO2 emissions. While digital twins have gained momentum in other domains such as smart manufacturing and aerospace, their adoption in ports has been comparatively slow. This can be explained, among other things, by the multi-stakeholder nature of the port and the high complexity of the often interconnected port processes. Thus, this thesis, grounded in the context of ports, discusses what constitutes a digital twin, proposes characteristics to assess the maturity of existing digital twins, and introduces and evaluates mathematical models to support a key port process, which can be used as components of a digital twin for the port. The thesis is composed of three papers:

Paper 1 is based on an extensive literature review, through which digital twins among different domains are studied in depth in order to transfer insights from these to the port domain. The resulting discussion of what constitutes a port’s digital twin and the requirements that a port’s digital twin must fulfil, together with a discussion of use cases of how port digital twins can contribute to energy savings, form the basis of Paper 1.

Paper 2 discusses how digital twins’ maturity can be assessed within six maturity levels and presents milestones for their implementation. Notably, Interoperability is identified as the highest maturity level, as the numerous stakeholders and their respective digital twins must work together to reach a coordinated system of systems performance. Using this assessment demonstrates that only a few innovation-leading ports have developed sophisticated digital twinning solutions so far.

Paper 3 is dedicated to coordinating container retrieval with stacking, combining two key port operations. Thus, it can present a key modeling component of a port digital twin, considering jointly the goals of reducing the energy demanding crane movements, as well as keeping schedules tight to avoid port congestion issues. This is directly reflecting the potentially conflicting perspectives of different stakeholders in the port context. The provided optimization model
and algorithm show that jointly addressing both problems may lead to a reduced efficiency of both individual objectives, but from a systems perspective, leads to a higher overall port efficiency.
Sammanfattning

Hamnar strävar aktivt efter ökad operativ effektivitet för att hantera den ökande globala varuflödet, samtidigt som de strävar efter att förbättra energieffektiviteten. Som ett resultat har ledande hamnar börjat se potentialen hos digitala tvillingar för att skapa överblick samt koordinera och optimera processer i hamnen. Målet med användningen av digitala tvillingar är energibesparingar samt minskning av kostnader och CO2-utsläpp. Medan digitala tvillingar har använts inom andra områden såsom tillverknings-, flyg- och rymdindustrin, har införandet i hamnar varit jämförelsevis långsamt. Detta kan förklaras, bland annat, av hamnens många olika involverade aktörer och den höga komplexiteten i de ofta sammanlänkade hamnprocesserna. Därför fokuserar denna avhandling, med utgångspunkt i hamnkontexten, vad som utgör en digital tvilling, presenterar egenskaper för olika mognadsnivåer hos befintliga digitala tvillingar, och introducerar samt utvärderar matematiska modeller som kan bli delkomponenter i en digital tvilling för hamnen. Avhandlingen består av tre artiklar:

Artikel 1 bygger på en omfattande litteraturöversikt, inom vilken digitala tvillingar för olika områden studeras ingående för att överföra insikter från dessa till hamndomen. Detta resulterar i en presentation av vad som utgör en hamns digitala tvilling och de krav som en hamns digitala tvilling måste uppfylla, tillsammans med en diskussion om möjliga sett på vilka hur hamnens digitala tvillingar kan bidra till energibesparingar.


Artikel 3 fokuserar på koordinering av containerupphämtning koordinerat med staplings effektivitet, två viktiga hamnaktiviteter. Därför representerar dessa en viktig modelleringsskymning i en hamns digitala tvilling, med beaktande av målen att minska de energikrävande kranrörelse, samt behovet av att hålla planerade tider för att undvika trängsel och väntan. Detta speglar direkt de potentiellt konfliktfyllda perspektiven hos olika intressenter i hamnkontexten. Den utvecklade
optimeringsmodellen och algoritmen visar att gemensam hantering av båda dessa problemen kan leda till en minskad effektivitet för de respektive individuella målen, men en ökad effektivitet från ett systemperspektiv för hamnen som helhet.
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Norrköping, 2024
Robert Klar
List of Papers

The present thesis “Digital twinning for ports: from characterization to operations’ modelling” consists of a kappa, which introduces the research topic, presents the relevant background and methodology, and provides a summary of three papers that form the core of this thesis, which are presented below along with the authors’ contributions.

  The authors contributed as follows:
  **R. Klar**: Conceptualization, Literature review, Visualization, Writing - original draft, Writing - review & editing. **A. Fredriksson**: Conceptualization, Research design, Supervision, Writing - review & editing. **V. Angelakis**: Conceptualization, Supervision, Writing - review & editing, Project administration.

  The authors contributed as follows:
  **R. Klar**: Conceptualization, Literature review, Visualization, Writing - original draft, Writing - review & editing. **N. Arvidsson**: Conceptualization, Supervision, Writing - review & editing. **V. Angelakis**: Conceptualization, Supervision, Writing - review & editing, Project administration.

- R. Klar, A. Andersson, A. Fredriksson and V. Angelakis, "Container relocation and retrieval tradeoffs minimizing schedule deviations and relocations”, currently under journal review.
  The authors contributed as follows:
  **R. Klar**: Conceptualization, Methodology, Simulation, Visualization, Writing - original draft, Writing - review & editing. **A. Andersson**: Methodology, Supervision, Writing - review & editing. **A. Fredriksson**: Policy implications, Supervision, Writing - review & editing. **V. Angelakis**: Conceptualization, Methodology, Supervision, Writing - review & editing, Project administration.
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Chapter 1

Introduction

Ports are under increasing pressure to improve the efficiency of their operations to cope with growing international freight volumes, while complying with new environmental regulations to reduce energy consumption [1]. Ports also need to optimize their use of resources and equipment as the growth of their surrounding cities limits their ability to expand. Ports, especially those transforming into smart ports, are therefore investing in innovative technologies and data-driven solutions to improve the efficiency of their operations [2].

As part of this transformation, leading ports have also discovered the value of digital twins in increasing efficiency and reducing costs, and have begun to develop sophisticated digital twinning solutions [3]. Originally developed to enable intelligent manufacturing, digital twins have attracted enormous attention in various domains due to their ability to mirror, optimize and ultimately (autonomously) remotely control the processes of a system [4].

However, ports differ significantly from traditional digital twin applications due to the complexity of their often interlinked processes and the large number of different actors involved due to their nature as multi-stakeholder environments [5]. In addition, there is a reluctance among ports to change traditional processes, which is compounded by differing views among port stakeholders on the benefits and capabilities of digital twins in the port context and how they should be implemented [6].
Chapter 1. Introduction

1.1 Objectives and research questions

The objective of this thesis is to contribute to the adoption of digital twins in the port context by conceptualizing digital twins in the port context, providing an assessment of how mature existing port digital twin solutions are, and providing key digital twin modeling components. More specifically, this thesis aims to answer the following Research Questions (RQs):

1 **RQ-1**: What are the key characteristics of cross-domain digital twinning solutions, and to what extent can they be transferred to the port?

2 **RQ-2**: How mature are existing digital twinning solutions in ports and how can their maturity be evaluated?

3 **RQ-3**: How can digital twin components be designed that could facilitate the effectiveness of multimodal transportation using ports to reduce the carbon footprint of cargo?

1.2 Scope

This thesis focuses on digital twins in the context of ports. The work herein revolves around assessing characteristics and requirements for implementation, characterizing the maturity of digital twins and evaluating deployed twins in major ports, and finally introducing a cross-stakeholder optimization model in which coordinating container retrieval with stacking can be seen as a key module that could be integrated into port digital twins.

1.3 Structure

This thesis begins with an overview of ports in Chapter 2 by outlining their core characteristics and requirements, emphasizing the multi-stakeholder nature of ports and the high degree of interdependency of port processes. Chapter 3 gives an overview of digital twins and outlines how digital twins can be used, implemented, and evaluated in the port context. It also provides an overview of key port operations that should be included as major modeling components of a port digital twin. Chapter 4 provides an overview of the tools used in
the three papers included in this thesis and discusses how they were applied in the corresponding papers. In Chapter 5, the aforementioned papers are presented and the most important results are summarized. In addition, relevant papers not included in the thesis are briefly presented. The thesis concludes with Chapter 6, which provides a summary and conclusion and gives a brief outlook on future research activities planned after this thesis.
Chapter 2

Ports

Ports, play a key role in global trade as they are the central hubs of many transportation chains, connect different modes of transport, and host business activities linked to the handling of ships and cargo in a port [7]. As the volume of global trade continues to grow, their role in the global transport system is becoming increasingly important, with 90% of world trade passing through ports on its way from origin to destination [8]. Due to the steady growth of maritime transport and the resulting increase in harmful CO2 emissions, which account for approximately 3% of the world’s annual CO2 emissions [9], ports are under increasing pressure to improve their profitability, environmental friendliness, energy performance and efficiency as part of global sustainability efforts [10]. Accordingly, ports, which occupy a strategic position in the supply chain as a driver of sustainability, are called upon to contribute to the overall sustainability of the maritime industry [11].

2.1 Ports as a multi-stakeholder environment

Ports are complex environments consisting of multiple stakeholders and inter-organizational port processes. In such complex environments, it becomes increasingly important to further improve coordination and the overall transparency of port processes to increase efficiency, safety and sustainability throughout the port ecosystem [12]. This requires a
Chapter 2. Ports

A high level of standardization and data exchange between port actors and stakeholders to increase cooperation, develop best practice standards, reduce negative externalities, and assist in developing more scientific tools for port performance analysis [13]. According to Ha et al. in [14], there are three groups of port stakeholders: terminal operators, port users, and port administrators, which can be described as follows:

- **Terminal operators**: they hold a right to operate and provide container handling services to port users based on concession or lease agreements in the port area.

- **Port users**: they are not only purchasers of port services but also influence the delivery of services in the container transport logistics chain. They include shipping lines, ship and cargo agents, logistics service providers, and freight forwarders, and road hauliers, etc.

- **Port administrators**: they enforce the operation of port systems (i.e. standard, regulations, etc.) within the port area. They are mostly public bodies such as port authorities.

Figure 2.1 provides an overview of the port, including its main operational processes and the corresponding actors involved. A port consists of one or more terminals that address the needs of different types of cargo. This thesis focuses on container terminals, which are characterized by their footprint, including quays, yard areas, equipment such as cranes, and other support facilities [1]. The six major port problems, with a focus on container rehandling and storage operations, can be divided into the four main parts of a port. At the seaside, the initial challenge is the allocation of berths, followed by the assignment of quay cranes. Containers are unloaded from vessels using quay cranes, stacked by destination in the storage yard, and rearranged once more information about their retrieval is available. They are then retrieved in a specific sequence defined by the truck retrieval order, in which blocked containers must be relocated first. Gate congestion is a significant issue on the hinterland side. It is important to note that these problems are interconnected and involve multiple actors with varying goals. The conflict between saving energy at the storage yard and maintaining tight schedules for trucks is evident in the container relocation and port congestion problems.
2.1. Ports as a multi-stakeholder environment

Figure 2.1: Overview of key port operations and the actors involved
Chapter 2. Ports

2.2  Ports seek to improve operational efficiency

Ports can contribute to maritime sustainability in various ways. Key factors that contribute to the sustainability of seaports (and maritime transport in general) are the use of renewable resources, electrification, energy-aware scheduling of equipment, the use of smart and innovative technologies, and the establishment of rules and regulations for the greening of seaports and to set initiatives for ships to adopt sustainable practices, i.e. slow steaming [15], [16].

It is important to note that optimizing a single or a series of port operations can lead to energy efficiency gains, time savings, and cost savings when implemented as part of the port’s overall strategy [17]. The operational efficiency of a port thus depends on how efficiently the available resources are managed. Therefore, there is a positive correlation between the reduction of operating times (e.g. ship handling times, container transport times in the yard) and operational efficiency in ports [18].

2.3  The need for sophisticated technical solutions

In the era of digital technology and the rise of Industry 4.0, more and more ports are striving to implement the idea of a data-driven smart port, which aims to leverage various integrated information sources and real-time analytics to improve the efficiency, flexibility, collaboration and safety of port processes [12].

The adoption of smart port planning is critical for ports seeking sophisticated and innovative technological solutions, as it aims to reduce cargo handling times, optimize asset and labor utilization, and significantly improve overall port operational efficiency. The key benefit lies in the seamless exchange of information between port operators, shippers and port authorities, allowing for joint decision-making [2]. One of the most sought-after technologies in the smart port is the “digital twin”, as it can help the port industry to better leverage digitalization and enter a new era of digital twin-driven management, allowing smart ports to develop far-reaching optimizations and more efficient port processes [3].
Chapter 3

Digital Twins

**Digital Twins**, considered the cornerstone of Industry 4.0, involve the twinning of physical assets or processes, a step in the digitization process that has evolved over the past two decades along with supporting technologies [19]. Digital twins are thus seen as paving the way for the realization of the various promises of Industry 4.0 [20], including improved monitoring and diagnostics of multifunctional systems, improved self-awareness and maintenance capability of systems, and real-time knowledge-based decision making [21].

### 3.1 Digital twin characteristics

The Digital Twin Consortium ¹ defines the digital twin as a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity [22]. The concept of digital twins involves the use of real-time connectivity, mapping, analysis, and interaction to depict, emulate, forecast, optimize, and control physical systems [23].

Digital twins (DTs) are constructed for various purposes, including the design, development, analysis, simulation, and operation of non-digital systems. They can be used to comprehend, monitor, and optimize various aspects of complex systems in fields such as design-space exploration during the design phase and enhancing performance

¹The Digital Twin Consortium brings together industry, government, and academia to promote consistency in the vocabulary, architecture, security, and interoperability of digital twin technology. See https://www.digitaltwinconsortium.org/
Digital twins are valuable tools in various domains as they provide insights into the behavior of complex systems, leading to better understanding, control, and optimization [25]. To achieve these capabilities, digital twins offer extensive visualization, modeling, interaction, synchronization, and self-learning features [26]. The components of a digital twin are often summarized as a system of physical entities, virtual models, physical-digital connections, data, and services [27], [26]. Efforts are being made in DT-powered industries to develop key technologies that contribute to three main capabilities: mirroring, shadowing, and threading [26]. The term mirroring refers to the ability to create a virtual representation, while shadowing refers to the ability to synchronize the physical entity with its virtual counterpart. Threading corresponds to the ability to connect different operation stages and DT instances [28].

Digital twins differ from a digital model by the use of real-time data and thus automatic information flow, where the digital twin interacts with the actual system in a bi-directional manner, as opposed to the digital shadow, where the automatic information flow is one-way from the actual system to its corresponding digital twin [4].

With reference to Paper 1, a port digital twin in the context of this thesis is defined as follows: “A digital twin of a port is a grouping of models and algorithmic components that jointly describe the complex interplay of port processes and operations allowing the characterization, estimation, and prediction of the most efficient operations at the process level, but also for the port as a whole. Through inputs from real-time sensors and experience from historical data, a user can identify patterns that led to inefficiencies in the past, get a complete view of current operating conditions, and predict future conditions by simulating what-if scenarios. Moreover, the algorithmic components of the port DT may allow it to act autonomously at any time, while providing full transparency, enabling the port to become a self-adapting system” [29].

### 3.2 Implementation of Digital Twins

Implementing a DT for a complex system such as a port requires an extraordinary investment of time, capital and knowledge. Core technologies for implementing digital twins include visualization and operation technologies, analysis technologies, multidimensional model-
3.3 Digital twins in the port context

Digital twins are also recognized in the port context and thus innovation-leading ports, such as the ports of Rotterdam and Singapore, have started launching efforts to provide a complete and up-to-date overview of port activities via digital twinning [31].

More precisely, Erwin Rademaker, Program Manager, Port of Rotterdam Authority, states that a port DT would provide “an accurate, current picture of what is going on in the port—everything from the weather to how many ships are sailing about, their speed, and where they are headed. Simulations would be run digitally to improve efficiency and save money in the real port. We anticipate being able to pinpoint the best times for ships to berth and offload or take on cargo, because the digital twin simulations will give them the optimal water depths and berth vacancies, among other variables” [31].

Zhou Chenhao of the National University of Singapore, who is currently developing maritime digital twin systems to assist port operators in decision making, has a similar view, arguing that as the scale and complexity of container port operations grow, more sophisticated and
accurate methods are needed to derive precise planning for the next generation port [32]. Chenhao further states that “with the ability to simulate the port as an complete system with different combinations of layout, equipment, and technologies and so forth, it enables the objective comparison of various options during the port design and transformation process ... With real-time operational data, it enables collective analysis scenarios on any look-ahead and what-if scenarios and serve as a basis for information sharing and coordinated decision making, this leading to operational improvements and productivity gains” [32].

3.3.1 Required models of a port digital twin

Figure 3.2 provides an outline of a digital twin in the context of the port and includes its main components. It presents a cycle starting from data collection (in real time), storage, subsequent pre-processing and analysis of the data using machine learning and other models to gain insights from the data. These insights are then used to enable intelligent decision making, both for specific port operations and for the port as a whole. It thus encompasses the main DT characteristics presented in section 3.1, including mirroring, modelling, interaction and synchronisation. The decision support tools enable to solve the main operational problems of the port as shown in Figure 2.1 on the basis of data driven decision making. A potential model for the container relocation problem is presented in Paper 3. An extended maturity model for complex systems, emphasising the interoperability aspects of whole DT systems, as required in the supply chain context, is presented in Paper 2.

3.4 Digital twins’ maturity

Originating in smart manufacturing [27], the concept of digital twins is expanding to entire cities [33], supply chains [34], and dynamic systems such as ports [35]. This expansion results in varying complexities, requirements, and architectures across application domains, making a universal characterization and definition of DTs increasingly challenging [36]. With a growing number of solutions and vendors promising efficiency gains through DT implementation, there is a need for guidelines to assess maturity. These guidelines are critical
3.4. Digital twins’ maturity

Figure 3.2: Required models of a port digital twin
for adopting organizations to assess and compare the maturity of existing and future digital twinning implementations. This lack of a consistent definition thus increases the risk of skepticism and rejection, potentially hindering the adoption of the technology [37].

A digital twin maturity model aims to provide an assessment tool to understand the level at which digital twin implementations and their functionalities belong, and thus can aspire to develop or improve their processes, practices and performance, and establish a roadmap for continuous development/improvement. It can also help focus technical discussions on relevant issues at the same level and identify issues at different levels [38].

Existing DT maturity models include the Institution of Engineering and Technology’s (IET) DT maturity model for the build environment [39] or Singh’s DT maturity model for smart manufacturing [40].

3.4.1 Maturity of existing port digital twinning solutions

Assessing the maturity of smart ports has received significant attention in recent literature [41], [42]. A mature smart port is characterized by high levels of operational efficiency, synchronized intermodality, security, and sustainability [41]. To achieve the highest level of smart port maturity, the port terminal must have, among other things, a high-fidelity digital twin [42]. Its use enables data-driven decision making and real-time monitoring. However, these papers do not consider the maturity of digital twins in the port context. This is despite the fact that digital twins, although seen as cornerstones of smart ports, are still constrained by varying understandings, implementations, and functional scopes [43].

Therefore, there is a need for concrete guidelines to assist ports in evaluating the quality of future DT solutions and in benchmarking and comparing existing DT solutions. To address this gap, further research conducted to complement the three core papers of this thesis highlights early successes of existing port DT solutions in areas such as visualization, real-time data acquisition, and modeling and simulation; these achievements are predominantly observed in innovation-leading ports. Furthermore, there remains untapped potential for networked process optimization, which ideally can be carried out autonomously and with full transparency in the future [44]. The application of maturity levels to the port domain are also discussed in Paper 3.
Chapter 4

Tools and Methods

The main methodology applied in this thesis is a combination of literature review and applied modelling of port processes for increased operational efficiency.

4.1 Tools

The tools used to conduct the papers included in this thesis are:

- **Literature review**
  The purpose of a literature review is to summarize and evaluate the state of knowledge or practice on a particular subject. A literature review is thus a synthesis that requires an analysis of the body of work as a whole [45]. From this review of past and present work, it is possible to identify areas where further research would be beneficial [46]. Denney and Tewksbury state in paper [47] that a literature review serves three main purposes: (1) sharing related study results with the reader, (2) relating the study to the ongoing literature dialog about the topic, and (3) providing a framework for establishing the study’s importance. Literature reviews generally take two main forms. The first is a literature review or background section found in journal articles, while the second form is a stand-alone review that serves as original research. The former synthesizes the existing literature and identifies the gaps addressed by the empirical study, while the latter provides an overview, if not detailed knowledge, of
the area in question, with references to key primary sources [48].

Two of the most popular methods in the field of literature review are descriptive reviews and systematic reviews [49]. Descriptive reviews evaluate existing studies in a research area to assess support for existing propositions, theories, methods, or findings. They focus on identifying patterns or trends within the literature [50]. In contrast, systematic reviews use a comprehensive plan and predefined search strategy to minimize bias and provide a more thorough and structured examination of the existing research landscape [51].

- **Integer Programming**
  Integer Programming (IP) is a subset of Linear Programming (LP) that uses implicit algebraic constraints, including linear equations and inequalities on integer-valued variables, to define the feasible set of alternatives. The objective functions in IP are linear and are designed to either minimize or maximize over this feasible set, providing criteria for optimality [52]. In many IP models, a subset or all variables are restricted to the two values 0 and 1. If all variables in an IP model can only take binary values, the resulting model is called a binary linear program. This is a common situation for problems where the values 1 and 0 have a boolean interpretation and the variables represent yes/no decisions [53]. As in other areas of mathematics, models involving integers are much harder to solve than models involving only real numbers [54].

- **Simulation**
  Simulation modeling serves as a tool that supports the planning, design and evaluation of dynamic systems. It is used to evaluate strategies for system transformation and change and provides a robust framework for testing and refining different scenarios. A model plays the role of a substitute for the system it represents, and its purpose is to replace the system in experimental studies [55]. The two prerequisites are that there is a system that has been identified for investigation and, secondly, that there is a problem associated with the identified system that needs to be solved [56]. Simulations are typically based on synthetic data, which attempts to preserve the overall properties and characteristics of the original data without revealing information about the actual individual data samples [57].
4.2 Methodology

An overview of the applied methodology for the three papers included in this thesis is presented in Figure 4.1. In the following paragraphs, the application of the tools presented above for the included journal articles will be presented in greater detail.

- Literature review
  Comprehensive reviews are conducted to gain an understanding of state-of-the-art digital twinning of ports and other related complex systems, such as cities and supply chains. Relevant literature for this thesis are: port processes and port characteristics, energy efficiency of port operations, digital twins, mathematical formulation of port operations, i.e. the container relocation problem. The literature review process for each paper is presented in greater detail below.

  Paper 1 is based on a descriptive review, as the aim of this paper is to show, based on a comprehensive literature review of DT practices and DT characteristics of ports and in functionally and characteristically related areas, that significant benefits in terms of operational efficiency and energy savings can be achieved by using digital twins in the port context. It is therefore not a systematic review, as literature was systematically evaluated from the outset with the aim of verifying (or refuting) the statement that DTs in ports can contribute to efficiency gains, and...
accordingly synthesizing new findings, challenges, and research gaps.

**Paper 2** applies a systematic review to systematically search, evaluate, and synthesize research evidence to determine best practices for evaluating digital twin maturity and facilitating interoperability among digital twins. In addition, the maturity of ports, cities, and supply chains is assessed based on a systematic review of their digital twinning progress.

**Paper 3** applies a literature review in the form of a background section to identify research gaps and align the research conducted in this paper with previous related research. It also elaborates on key previous findings, concepts, and contributions that form the basis of the current problem to be solved.

- **Integer Programming**
  **Paper 3** leverages a binary linear program to derive a mathematical formulation to jointly optimize the minimization of crane movements and truck schedule deviations. Each decision variable in this formulation represents a state where a container is either still in the bay, relocated (from and to), or retrieved. Given a set of realistic assumptions and the characteristics of the problem, several sets and parameters are defined that reflect certain port processes and container storage characteristics. Using these parameters, a set of 14 constraints is created to bound the solution space of this problem.

- **Simulation**
  **Paper 3** applies simulation to mimic the port operational process of retrieving all containers in a bay, given a predefined sequence based on the order of retrieval by truck. The system for investigation is thus the terminal container storage yard and the problem associated with it is termed the container relocation problem. The bay layout of the container terminal is mirrored based on a literature review of what an average terminal bay configuration looks like. For each configuration, 100 different test samples are created, reflecting different container storage configurations. The subsequent comparison and evaluation of these 100 different container storage configurations provides a realistic reflection that covers most cases in reality.
Chapter 5

Contributions

This thesis examines the potential of digital twins to improve operational efficiency in ports. For this purpose, three relevant journal papers and three relevant non-included papers have been written since the start of this thesis in October 2021. The corresponding studies employ literature reviews, simulations, and integer programming to characterize digital twins in the port context, assess their maturity, and demonstrate a potential modeling component that jointly optimizes key port problems. The papers included in this thesis highlight the significant potential of digital twins to improve port operational efficiency, but also the associated challenges of multi-stakeholder collaboration and the resulting need for standardization and interoperability. The main contributions are:

- **Port digital twin characterization, requirements and challenges for implementation and operation:** This thesis provides a comprehensive analysis of the definitions and characteristics of DTs, resulting in a discussion of its core characteristics, enablers, and potential usage in the port domain. Secondly, it reviews the major port processes and characteristics, leading to the identification of three core requirements. Finally, it proposes operational strategies on how a port DT can contribute to energy savings.

- **Port digital twin maturity assessment:** This thesis provides guidelines that help to assess the maturity of digital twins in the port context, but also of other complex systems such
as cities and supply chains, based on selected maturity levels. Building upon the multistakeholder environment of the port, the interoperability of DT systems is particularly emphasized.

- **Multi-objective optimization of key port processes:** The thesis presents a mathematical formulation and a heuristic for jointly minimizing (1) crane movements during container relocation and retrieval, and (2) truck schedule deviations. This joint optimization significantly improves port efficiency and can be considered a core module of a digital twin of the port.

### 5.1 Publications included in the thesis

Two published journal papers and a journal paper submission are included into this thesis. These papers can be summarized as follows:


In this paper, we critically assess the potential of digital twins to increase the efficiency of port operations. To achieve this, we first identify the characteristics of ports, such as multimodal transportation and multi-stakeholder environments, and the multiple, often interconnected processes, followed by a detailed characterization of digital twins in ports and related domains. In particular, based on the definitions of digital twins and the respective objectives of these applications, the components, the functional spectrum and the temporal span of digital twins are determined. The characterization of both digital twins and ports leads to the identification of three main requirements: (real-time) situational awareness, data-driven decision making, and facilitation of multi-stakeholder governance and collaboration. We then present a number of best practices for digital twins from smart cities and supply chains, and discuss how digital twins for ports can benefit from these experiences from these two related domains. Applications of existing digital twins include real-time traffic monitoring and control, urban heat island visualization and measurement, and estimation of potential countermeasures. Based on the findings of these two related domains and examples of applications from different
ports, concrete practices are proposed on how ports can contribute to energy savings through better coordination, equipment and facility utilization, scheduling, and intelligent lighting systems. Finally, we discuss the challenges of implementing digital twins in the port context and discuss possible solutions. These challenges include reluctance to share data, reluctance to change operations, complexity constraints, and security issues. This paper thus addresses research question 1.


In our second paper, we provide guidelines in the form of six maturity levels for assessing the quality of existing and emerging digital twinning solutions for complex systems such as ports. To achieve this, we provide a comprehensive review of existing, often highly domain-specific, digital twinning maturity frameworks, resulting in the identification of six concrete maturity levels that can be used to assess and compare existing and emerging digital twin solutions for ports and other complex systems. We then use these maturity levels to discuss how mature existing digital twins are in the port, city, and supply chain context and how they can be further improved. The assessment of application examples in these three domains indicates that existing digital twins have the potential for real-time situational awareness and process-level optimization. However, there is limited interaction between the digital twin and its system, and automation remains at a low level. As all three application systems are characterized by the multi-stakeholder context and a large number of interconnected processes, we place particular emphasis on interoperability to enable seamless joint optimization of the port and other related systems using data and digital twins from all port actors and port customers. Finally, we discuss the challenges and potential solutions to interoperability in the context of joint decision making between different digital twins. We further illustrate the need of joint decision in the supply chain context, whose flows of both freight and information passes through cities and ports. These challenges include standardization, data sovereignty, and lack of trust. Potential solutions include the use of data spaces and trust frameworks. This paper thus addresses research question 2.
Chapter 5. Contributions

Paper III: The Container Relocation Problem under Consideration of Truck Appointment Scheduling, co-authored with A. Andersson, A. Fredriksson, and V. Angelakis. Currently under journal review.

In our third paper, we highlight the importance of joint optimization of different port processes by linking two important port challenges and demonstrating that their joint optimization provides higher value than treating each problem in isolation. The first challenge, known as the Block Relocation Problem (BRP), aims to minimize the number of relocation moves required when relocating blocked containers in the process of emptying the bay in the container yard. Containers are often not stacked in the order of retrieval, which requires time-consuming and energy-intensive relocations. The second challenge is to maintain tight schedules, which is often hindered by congestion and truck rescheduling to avoid unnecessary relocation movements, as in the context of the first problem. To compute the best case for solving both isolated and combined problems, the problem is formulated as a multi-objective integer programming model, where the different problems are weighted differently. The results indicate that optimizing both problems jointly results in a higher benefit with only a slight decrease in the objective value of a single problem, while significantly improving the other problem. However, since the BRP is known to be NP-hard, we also provide a greedy heuristic to compute the joint optimization more efficiently in a timely manner. The comparison between the optimal values obtained from the optimization model and the results from our heuristics reveal a slight decrease in performance (in terms of relocations and schedule deviations), while significantly increasing runtime. The joint optimization model presented here could be an integral part of a digital twin. This paper thus addresses research question 3.
5.2 Publications not included in the thesis


Abstract: Ports are striving for innovative technological solutions to cope with the increasing growth in demand of goods transport, while at the same time improving their environmental footprint. An emerging technology that has the potential to substantially increase the effectiveness of the multifaceted and interconnected port processes is that of digital twins. Recognizing the potential of twinning assets and processes, innovation-leading ports have already started working on it. However, since there is no clear consensus on what a digital twin of a complex system comprises and how it should be designed, deployed digital twin solutions for ports, as in multiple other domains, often differ significantly. We address this issue by initially identifying three core aspect underpinning digital twins of complex systems, grounding our work on the domain of ports, and outlining five successive maturity levels based on these aspects’ instantiation. These identified aspects and the derived maturity levels are then used to examine real-world cases by critically evaluating existing digital twinning solutions in the port of Singapore, the Mawan port of Shanghai, and that of Rotterdam. Our work on maturity levels and core twinning aspects can provide a guideline for designing and benchmarking digital twinning solutions, applicable in any domain where a digital twin can be used. For ports, the capacity for innovation via twinning is highly contextual, with the key affecting factors being the availability of financial and technical resources.


Abstract: Ports, often located on the outskirts of (smart) cities, are striving for innovative technological solutions to attain efficiency gains to cope with raising trade volumes and energy savings towards improving their environmental footprint. With two-thirds of the world’s major ports located in urban areas, these efforts do not take place
in isolation, but in intersection with the multi-layered processes of the smart city. In this context, digital twinning can be a technology with the potential to significantly increase the efficiency of the multi-layered and interconnected ports and smart cities processes. While digital twins for the complex systems of the smart cities have gained momentum in recent years, digital twinning of ports is often narrowed to address only specific port assets. The aim of this article is to investigate how smart city digital twins tackle complex processes and how ports can draw from this experience. We discuss potential interfaces between a port digital twin and a city digital twin. It becomes evident that both these domains of application of digital twinning are complex systems having overlaps and functional interconnections. The paper presents how the port’s digital twin can contribute to threat detection, energy savings, cost reductions, performance gains, and improved stakeholder cooperation, based on insights from the city digital twin. Finally, the three overlap points maintenance of shared infrastructure, intelligent joint approaches to avoid congestion, and energy are identified as intersection points.


**Abstract:** Originally developed for enabling smart manufacturing, applications of digital twins now extend to ports, smart cities and supply chains. However, the wide range of applications results in a lack of uniform understanding of what constitutes a digital twin and how to implement it. Recent research therefore underlines the importance of standardization and interoperability as key prerequisites for building effective DT systems for complex applications. This poster thus provides an overview of the efforts of standardization bodies that foster the interoperability of digital twins.


**Abstract:** Policymakers must find efficient public transport solutions to promote sustainability and provide efficient urban mobility in the course of urban growth. A growing number of research papers are applying Geographically Weighted Regression (GWR) to model the
relationship between public transport demand and its influential factors. However, few studies have considered the rapid development of journey inference from ticket transaction data. Similarly, the potential of GWR to analyze spatio-temporal changes that reflect changes in transportation supply and thus provide a measure for evaluating the local success of transport supply changes has yet to be exploited. In this paper, we use inferred journeys from smart card inferences as the dependent variable and analyze how public transport demand responds to a set of explanatory variables, emphasizing transport supply. Consequently, GWR and its successor Multiscale Geographically Weighted Regression (MGWR) are applied to analyze the spatially varying impact of transport supply changes for seven consecutive time frames between autumn 2017 and spring 2020, allowing conclusions about local changes in transport demand, as well as the benchmarking of transport supply changes. The (M)GWR framework’s predictive power is evaluated by training the model with past transport supply data and testing the model with data from the following consecutive years. The conducted analyses reveal that the (M)GWR model, using inferred journeys and transport supply data, can retrospectively predict the impact of transport supply changes on travel behavior and thus provides conclusions about the success of transport policies.
Chapter 6

Concluding remarks and future research

The purpose of this thesis is to explore the potential of digital twins to improve the operational efficiency of port operations, thereby contributing to maritime decarbonisation. To this end, two in-depth literature reviews were performed to characterize digital twins in the port context (RQ-1) and to discuss the extent to which existing digital twins in the port sector have been developed and matured (RQ-2). In addition, minimizing schedule deviations and unnecessary container relocation movements, two key problems in the port that are critical to container retrieval and relocation, were jointly modeled (RQ-3). Such a joint optimization model is a key modeling component of a digital twin, which aims to approach efficiency gains not primarily at the process level, but at the system level.

From a port perspective, this thesis provides an overview of the potential, challenges, and practical use cases of how digital twins lead to overall port efficiency (Paper 1 and Paper 2). In this way, it contributes to the perception by ports of the value of investment in digital twins and thus to the spread of digital twin applications in ports. Particular emphasis is placed on the potential for joint optimization through which digital twins can contribute to sustainable port operations, among other measures such as electrification. In addition, a well-understood port problem, the BRP, is used to demonstrate how an application of the digital twin for joint optimization can be implemented by linking it to another core problem, i.e., maintaining
Chapter 6. Concluding remarks and future research

schedule reliability, as in Paper 3. This linking of the two problems in Paper 3 showcases the potential for jointly optimizing port operations to increase efficiency at the port level.

From a digital twin development perspective, this thesis outlines the characteristics and requirements of ports that differ significantly from traditional applications such as manufacturing or aerospace. The analysis and comparison of how port-related problems are addressed in other related domains, such as traffic in smart cities or risks in supply chains, and thus how digital twins in the port context can benefit from their experiences, enables a faster adoption of digital twins in the port context (Paper 1). Moreover, this thesis provides concrete guidelines on how digital twins could be implemented for complex systems such as ports, and provides a way to benchmark port digital twins based on the application of maturity levels (Paper 2).

Future research continuing the work of this thesis aims to provide further modeling and simulation components of a port digital twin. An example of such a model is predicting the most appropriate time for a maintenance period based on operational data from the crane monitoring system and data based on schedules and trucks approaching the port. In this way, there would be a trade-off between port utilization and the degree of need based on crane parameters. A limitation of this joint optimization model and others, such as the one proposed in this thesis to jointly minimize schedule deviations and crane movements, is the lack of data sharing. Although data sharing is inevitable for joint optimization, there is a redundancy to share data among the different port actors due to the fear of losing competitive advantages and many other reasons discussed in detail in Paper 1 and Paper 2.
Bibliography


Bibliography


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Bibliography


Bibliography


Abbreviations

DTs  Digital twins

RQs  Research Questions

IP   Integer Programming

LP   Linear Programming

BRP  Block Relocation Problem

GWR  Geographically Weighted Regression

MGWR Multiscale Geographically Weighted Regression
Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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Digital twinning for ports: from characterization to operations’ modelling

Robert Klar