Scaling digital twins

A roadmap to address operational planning uncertainties of container terminals

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by

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Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in Construction Management and Engineering
at the Delft University of Technology.

September 2022

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Preface

As I write this preface as the final part of my thesis, a special time is coming to an end. In just over seven years, I have experienced many unique and interesting events and met many kind and wonderful people. I would like to thank many, many people for this wonderful time in Delft; so thank you to all who are reading this! However, this is the preface to my final thesis, so let me talk about the last phase of my student career.

With a bachelor's degree in Marine Technology and a master's degree in Construction Management and Engineering, I was looking for a topic that would combine my master's expertise with my interests in the maritime industry. Fortunately, Deloitte and my supervisor Bram gave me the freedom to search for the perfect topic. After several interesting coffee chats and Microsoft Teams calls, I met Mark who had the right topic in mind for me. The introduction to digital twins of container terminals was the start of my last academic research at TU Delft.

First, I would like to thank all my supervisors for their contribution to my work. Bram gave me the freedom to find a topic that matched my interests and supported me with critical questions throughout the graduation period. He also introduced me to a great team at Deloitte and provided helpful feedback on how to visualize my story. I would like to thank Mark for his support and expertise on digital twins and the container terminal industry. He not only introduced me to an interesting project, but also to some interviewees. Of course, I also would like to thank my TU Delft supervisors. Paul gave me the freedom to find a research method that suited my strengths rather than sticking to a traditional way of doing research. Also, his critical but very sharp questions helped me find the right direction. Finally, Sander gave me many tips during my work and always had time to answer my questions.

Without the contribution of all the interviewees, my thesis would not contain so many interesting insights from the industry. These insights have transformed an academic research into a thesis that is of direct benefit to container terminals and other interested organizations. Therefore, I would like to thank all of you for your time and effort in helping me write my thesis.

And most of all, I would like to thank all of my friends, family and colleagues who have supported me during this time. Whether it was over coffee to ask how things were going, reviewing my work, helping me design my roadmap, or just distracting me, it made a difference and made completing my thesis less difficult than expected. Let us all stay in touch to see what the future holds for us, but hopefully in real life and not through a digital twin!

Mick van der Velden
Delft, September 2022

Summary

Container terminals are critical infrastructure for the economy, and the need to digitalize them is felt in an industry where port automation is gaining momentum [7]. One solution is to combine digital integration and process automation with a digital twin. This is an ideal tool to identify weaknesses and opportunities in the operations of a container terminal [48]. However, digital twins are often developed for a single terminal with unique characteristics, which means that the tool cannot be easily scaled to other sites. To optimize operations at multiple container terminals, it is necessary to explore how the twin can be scaled. Such a strategy for scaling digital twins at container terminals cannot be found in literature. Therefore, this research aims to fill this gap by developing a criteria-based roadmap.

First, the problem statement and research objective were transformed into a main research question and four related sub-questions. The main research question is: 'How can container terminals address uncertainties in operational planning by scaling digital twins?' The question can be divided into three parts, namely, the context of the research and two research concepts. Each part has one or two sub-questions leading up to answering the main question. An overview of the questions is shown in Figure 1.

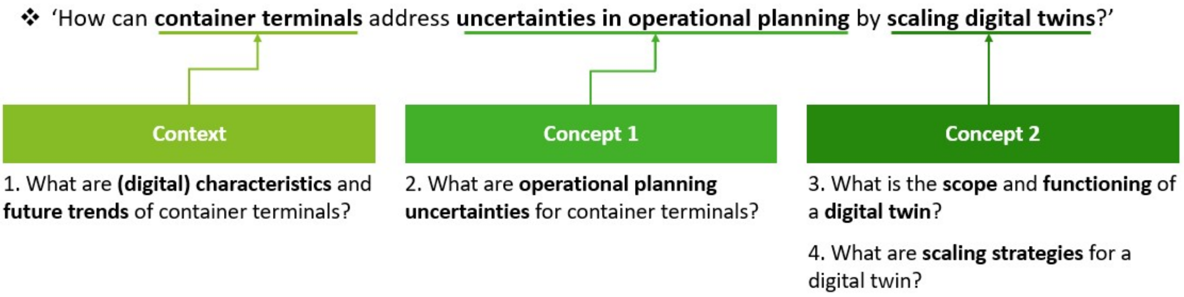

Figure 1: The main research question can be divided into the context and two research concepts, including four sub-questions.

The research started with a review of the literature to gain theoretical knowledge. The second step was to complement this knowledge with practical insights gained during the interviews. In step three, all insights were analyzed and combined to form the criteria for the roadmap, which led to the design of the roadmap in step four. Then, this design was discussed with industry experts to validate the findings. Based on their feedback, the roadmap was improved, the results were discussed, and the (academic) relevance was determined to draw a conclusion. A flowchart of the research steps is shown in Figure 2.

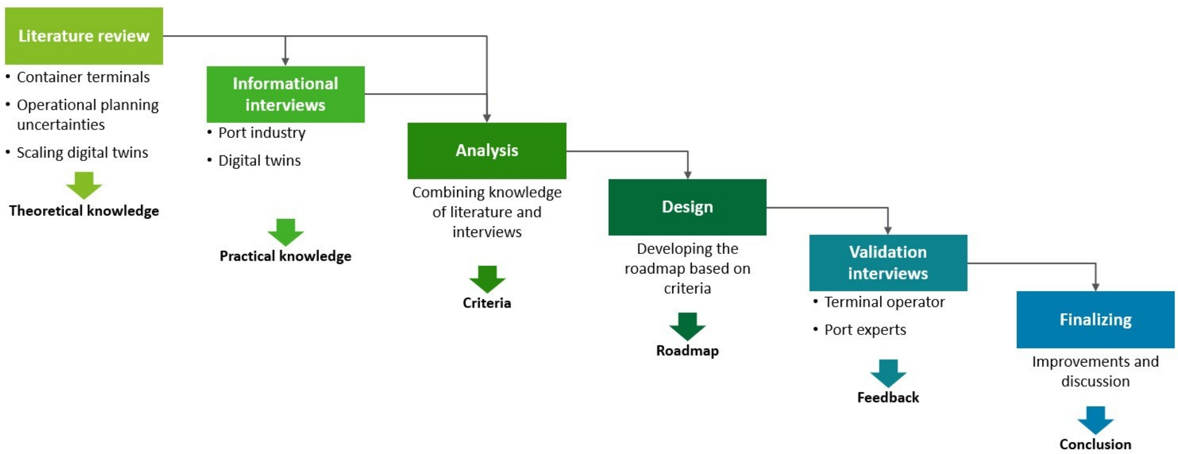

Figure 2: A flowchart of the research steps that are taken for this thesis.

Theoretical background

Ports have experienced a wave of digitization and automation initiatives in the last three to five years. This is primarily due to the pressure on efficiency caused by the professionalization and scale expansion of container shipping and logistics [60]. Digital twins and AI could inspire new products (just-in-time call platforms) and business strategies (new pricing tools). However, the pace of digital transformation in the maritime industry is still slow [9]. Industry-specific characteristics, such as high asset costs, high development costs, aging workforce and strict regulations, negatively impact the ability to digitize effectively. Also, due to the traditional set-up of the organizations, conventional players often lack the skills and agile processes for successful digital adoption.

The operational planning of a container terminal is complex, as it depends on many external variables, such as the arrival of vessels, trains, trucks, and the efficiency of (un)loading containers. In addition to weather-related delays or delays experienced during previous port visits, changes in the number of containers, traffic jams and mechanical failures also have an impact [25]. Uncertain vessel arrivals have the greatest impact on yard operations due to the tight and complex schedule, leading to congestion and transshipment. Knowing the possible deviation from the scheduled arrival time in advance is important for planners to more efficiently allocate the manpower, equipment and spatial resources required to perform handling operations. This means that planners must be supported at each stage with tools that are capable of supporting the decision-making process. Having all information available could reduce operating costs, maximize terminal efficiency, and thus competitiveness [42]. Therefore, reducing operational planning uncertainties by making smart decisions that are supported by digital tools is important for improving terminal operations.

A solution for making smart decisions can be found in a digital twin. It is a dynamic digital representation of a physical object or a system. The added value of the model lies in 'automatic data collection, conceptual development, dynamic analysis, problem diagnosis and optimization for smart design, operation, control, and maintenance' [41]. The first step of determining the modelled process and configuration of the digital twin must be done carefully. The scope is important, as it determines the physical entity that will be modelled and thus establishes the boundary between the physical system and its surrounding environment [59]. The balance between the appropriate level of detail and minimizing complexity is an important result of the scope. More detail results in higher quality of the simulations, but makes the model more complex and costly to develop.

After the development, it is important to determine a scaling strategy to increase the use of the twin. In the context of container terminals, scaling out can be seen as widening the scope of the digital twin, or including more use cases. Scaling up means including more terminals or ports in the digital twin, while the simulated processes and goal remain equal. The support and willingness of senior management, together with sufficient resources, are critical throughout the scaling project [27]. Organizational factors, such as culture, agility, structure, and alignment between departments, become important later in the process when scaling starts to affect other organizational units. Furthermore, organizations need to ensure the right skills for users of the digital tool to adopt it in the operations as they scale. Lastly, many challenges related to the integration of operational systems and existing ICT infrastructure occur when companies try to scale up their pilot projects. Three main strategies for scaling-up are: proof-of-value, treating and managing data as a key asset, and a top-down and bottom-up approach.

Designing the roadmap

Since the roadmap describes the scaling of digital twins for container terminals, several assumptions were made. First, the business case for developing and scaling digital twins is determined to be viable and approved by the organization. A Proof of Concept proved positive results for the operation, and a digital twin is determined to be the right tool. The organization has executed a problem analysis and drafted a hypothesis that the digital twin can improve its operation or solve the problem. The roadmap of this report is intended for the senior management of global container terminals that have influence on the (digital) strategy of the company. The roadmap is meant for organizations that have multiple container terminals, since this scaling strategy focuses on scaling up to multiple locations instead of scaling out to several processes on the same terminal. The digital twin is intended for the planners of a container terminal (users). Planners are involved as a subject matter expert for different terminals to advise on the unique challenges of operations.

After a detailed review of the literature and conducting interviews, the main findings were combined into design criteria for the roadmap. The criteria were established for different purposes and were used to review the roadmap afterwards. A distinction was made between four criteria:

- Criteria for the **digital twin**
- Criteria for **developing** the digital twin
- Criteria for **using** the digital twin
- Criteria for **scaling the use** of the digital twin

The design of the roadmap template began after the criteria for the roadmap were established. The three phases for the timeline are shown as three columns in the roadmap, and the three themes are represented by rows. The phases are 'developing the digital twin', 'using the digital twin' and 'scaling the use of the digital twin'. Most used in transformation projects is the People, Process and Technology (PPT) framework [45], so people (key actors), process (operations and strategy) and technology (data, hardware and software) are the three themes. The key actors of the roadmap are the users (planners of the terminal), developers (software engineers) and product owners (management).

When the roadmap template was designed and all criteria were established, the roadmap design started. The logical steps of the roadmap were identified for each of the three phases. These steps were complemented and validated to see if important information or focus points were missing. For each step, it was determined which themes (people, process and technology) were applicable. Sometimes, roadmap steps overlap multiple phases when it was relevant for two or three phases. After the design of the first version, several interviews were conducted with experts from the container terminal industry were conducted to validate the roadmap. Based on their feedback, the roadmap was improved by adding information or clarifying the roadmap steps. Also, six stages were added to the final phase to emphasize the scaling phase. Each stage describes an essential element for scaling up and it is important to understand these to establish successful scaling procedures. The final version of the roadmap is presented in Appendix C.

At the end of the research, the roadmap was verified by comparing the final version and the criteria. All established criteria are mentioned in the roadmap, except for the possibility of incorporating external disruptions into the digital twin. Therefore, the roadmap is verified and complies with the requirements. An overview of the verification is presented in Table 5.1. The roadmap was validated during two interviews and, in general, the interviewees were positive about the design and its content. Especially during the second interview, the value of the roadmap for container terminals was recognised. It was pointed out that a description of the Proof of Concept phase was missing, but if a roadmap exists for this phase or the terminal has experience with it, the roadmap of this research is a good starting point for a scaling project. The interviewees confirmed that important actions, steps and phases are mentioned that guide the product owner during the various phases.

Conclusion

To answer the main research question, the answers of the four sub-questions mentioned in Figure 1 are combined into the designed roadmap of Appendix C. In conclusion, the roadmap developed in this study is useful for container terminals looking to scale up digital twins. It provides insight into the steps required to develop, use, and ultimately deploy digital twins on a larger scale. Especially for terminals that have no experience with such projects, it serves as a starting point to define the strategy and free up resources within the organization. Because the roadmap was developed at a strategic level, not all steps are very detailed, so an organization will need to do further research to determine its strategy. However, the roadmap does cover important aspects of scaling projects and what actions are needed. Each organization can determine for itself which steps are familiar with internal knowledge and which steps require more attention. Therefore, this roadmap serves as a solid starting point for senior management looking to scale digital twin solutions.

Contents

Nomenclature

Abbreviation	Definition
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIoT	Artificial Intelligence of Things
AIS	Automatic Identification System
API	Application Programming Interface
BIM	Building Information Modelling
CIO	Chief Information Officer
CLPH	Container Lifts Per Hour
CPS	Cyber-Physical Systems
CT	Container Terminal
DT	Digital Twin
ETA	Estimated Time of Arrival
GC	Gantry Crane
GRC	Governance, Risk management and Compliance
ICT	Information and Communications Technology
IMO	International Maritime Organization
IoT	Internet of Things
IP	Intellectual Property
IT	Information Technology
JIT	Just-In-Time
MPH	Moves Per Hour
MVP	Minimum Viable Product
NDA	Non-Disclosure Agreement
PoC	Proof of Concept
PPT	People, Process and Technology
QC	Quay Crane
RMGC	Rail-Mounted Gantry Cranes
RtD	Research through Design
RTGC	Rubber-Tired Gantry Cranes
SC	Straddle Carrier
SLA	Service-Level Agreement
STS	Ship-To-Shore
TEU	Twenty-foot Equivalent Unit
TOS	Terminal Operating System
UI	User Interface

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1 Introduction

1.1. Background information

Port infrastructures have an important indirect impact on economic growth. Therefore, national economies consider ports as essential business environments operating in a highly competitive market and worth attracting investments in digitalization and infrastructure [40]. Container terminals are a special area within a port where cargo stored in standardized containers is transported from sea to land and vice versa. It is an environment where incremental improvements mean significant cost savings and performance improvements [48]. Container terminals and ports are therefore critical infrastructure for maintaining competitiveness and supporting economic growth.

The need to keep developing is being realized in the industry, where port automation is gaining momentum [7]. Shipping companies seem interested in using digital technologies to increase cost efficiency by optimizing operations and the logistics chain [20]. Both current operations and future needs can be managed through digital models, provided that the sector works together to standardize digital data streams. Tijan et al. [58] highlighted several drivers of digitization for ports, including reducing wait times and effectively complying with regulatory requirements to protect the environment. The difficulties associated with the uncertainty of vessel arrivals and the complexity of planning processes mean that planners must be supported by tools that facilitate the decision-making process. Knowing in advance the potential deviation from the planned arrival time is important to more efficiently allocate the manpower, equipment, and spatial resources needed for transshipment [42]. Unreliability of schedules causes inconvenience for shipping companies and the entire supply chain. Therefore, more reliable information from digital tools on arrival times could reduce operating costs, maximize terminal efficiency, and thus increase competitiveness. Besides providing reliable information, digital integration could improve port operations by automating paperwork and procedures. Container shipping involves many different parties and paperwork, which often hinders accurate planning, causes congestion in ports, creates additional work such as rescheduling, and creates distrust among stakeholders [55].

A solution for digital integration and process automation could be found in the form of a digital twin [48]. Similarly to other concepts of digitalization, the digital twin has gained increasing interest in both academia and industry in recent years [59]. A digital twin is a dynamic digital representation of a system or process that describes its properties as a set of equations [29]. According to Pan and Zhang [41], the added value of the model lies in 'automated data collection, conceptual development, dynamic analysis, problem diagnosis and optimization for intelligent design, operation, control, and maintenance'. A digital twin is an ideal way to identify weaknesses and opportunities in the operation of a terminal. Twins are already being used to test and redesign container stacking and the potential profitability of installing new facilities [48]. Driven by multiple streams of real-time and historical data, it is also an operational planning tool to coordinate and synchronize port operations [30], and is the most rigorous approach for decision-making [29]. It could be an essential foundation for virtual arrival processes and green steaming [61]. The digital twin can test various scenarios to speed up loading and unloading and ways to accommodate more vessels. Thus, digital twins are a promising development in the port industry.

1.2. Problem statement

Currently, some port organizations are developing a digital twin to simulate the processes of a container terminal. It provides access to numerous potential advantages and often, the goal is to reduce uncertainties in the operational planning for arriving container vessels. The operational planning of a container terminal is a complex context, as it depends on many external variables, such as the arrival of vessels, trains, and trucks, and the efficiency of (un)loading containers [6]. Ku et al. [25] mentioned uncertain vessel arrivals as the biggest impact on yard operations due to the tight and complex schedule, leading to congestion and transshipment. In addition to weather-related delays or delays experienced during previous port visits, changes in the number of containers, traffic jams or mechanical failures also have an impact. By simulating different scenarios with the digital twin, the impact on planning can be investigated to allow better decision-making. Varying the number of cranes and trucks to (un)load the vessel result in different turnaround times, which influences the overall terminal planning. If the vessels know their arrival time further in advance, they are able to adjust their sailing speed. As ships currently travel at higher speeds to avoid missing their slots, they often have to wait if they arrive too early. By optimizing the schedule, the vessels could travel at slower speeds, ultimately resulting in lower fuel costs and fewer emissions.

The initial results are promising, however, digital twins are often developed for a single container terminal with unique characteristics, which means that the simulation tool cannot be easily scaled to other sites. Terminals operate with different processes and have different tasks in the logistics chain. In addition, some terminals are better suited for digital twins than others and may require less effort to customize the tool. Digital twin analytics is based on historical and real-time digital data [29], so input, output, and underlying digital processes are important to consider. To optimize operations at multiple container terminals, it is necessary to investigate how the promising digital twin can be scaled to other terminals. As independent innovation processes seem to be less effective in achieving success [1], a clear strategy or approach for scaling digital twins at container terminals is necessary. Scaling digital innovations is defined as “the industrialization of digital solutions whereby, following the proof-of-concept and the pilot experiments, these technologies are rolled out into industrial practices on a large scale” [27]. However, such a strategy for scaling digital twins at container terminals cannot be found in the literature, so this research aims to fill this gap.

1.3. Research objective

When the functioning of a digital twin and the properties of container terminals and operational planning uncertainties are understood, a roadmap based on criteria can be developed to scale digital twins in container terminals. The goal of this research is to develop a roadmap that provides information on the use of digital twins in container terminals and that can be used for future digitalization projects. An overview of the research sub-problems is shown in Figure 1.1.

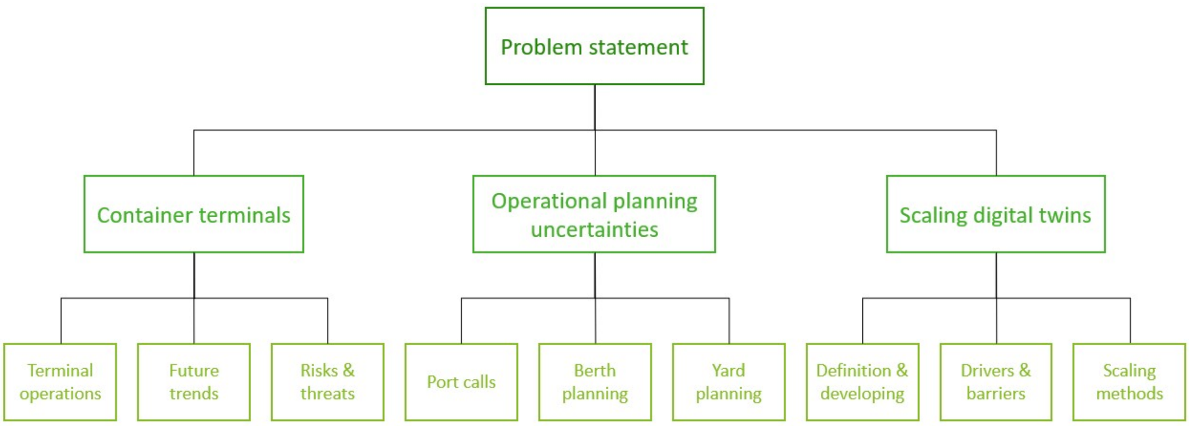


Figure 1.1: The defined problem statement of the thesis with a subdivision of topics.

The problem statement and research objective are transformed into a main research question and related sub-questions. The main research question is: ‘How can container terminals address uncertainties in operational planning by scaling digital twins?’ The question can be divided into three parts, namely, the context of the research and two research concepts. Each part has one or two sub-questions leading up to answering the main question. An overview is shown in Figure 1.2.

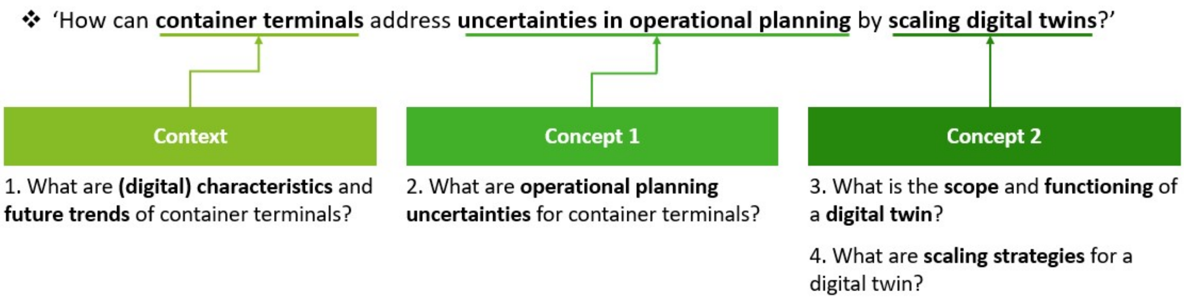


Figure 1.2: The main research question can be divided into the context and two research concepts, including four sub-questions.

The four sub-questions that are building up to answering the research question are:

1. What are (digital) characteristics and future trends of container terminals?
2. What are operational planning uncertainties for container terminals?
3. What is the scope and functioning of a digital twin?
4. What are scaling strategies for a digital twin?

The first sub-question has the goal of becoming acquainted with the port industry and container terminals. Since this will be the context of the research, it is necessary to understand the dynamics of the sector with its trends, and become familiar with the terminology and activities.

The second sub-question will dive into the problems that terminals face during daily operations. The uncertainties of operational planning have a large impact on the terminal activities, because it is a complex interplay of cranes, trucks, trains and other vessels that are all depending on each other.

The functioning of a digital twin will be investigated with the third sub-question, which will dive into the technical part of the research. The input, output, and scope of a digital twin will be investigated, as well as the development process.

The last sub-question has the goal of investigating how digital twins can be scaled and which strategies are most appropriate. Factors that influence the process, and the drivers and barriers are important to consider.

1.4. Research scope

It is important to clearly define the scope of the research on beforehand. It aligns the goals and expectations of the author and readers, but also minimizes the chance on scope creep. The scope of the research in this report remains at a strategic level. The level of detail of the roadmap steps mainly provide guidelines for further research and enable prioritization of the organization’s resources. The focus of the roadmap is on the technological aspects and less on the organizational aspects of scaling digital twins. The financial side of projects is completely kept out, as this information is often classified and difficult to collect. A more detailed roadmap is a recommendation for further research, since a lot depends on the unique characteristics of a container terminal. Therefore, the scope of the digital twin only focuses on internal processes of the container terminal as well, and excludes external parties, such as pilots, trucks and trains. These external parties bring many additional challenges and require a more custom approach for every location. Lastly, the target audience of the roadmap is the senior management of global container terminals that have influence on the (digital) strategy of the company (product owners). The research is conducted with the goal of collecting and providing information for this audience.

1.5. Structure of the report

This report has the following structure:

1. **Introduction:** This chapter presents an introduction to the topic and the problem statement of the research. The research questions and scope are also discussed.
2. **Research methodology:** The research method based on Research through Design is presented. The research steps, data collection and analysis are described, as well as the concept of a roadmap.
3. **Literature review & interviews:** A literature review of the current body of knowledge is described. First, the port industry and container terminals are reviewed, together with the uncertainties of operational planning. In the following, the chapter describes the concept of digital twins and how to develop such a digital tool. Hereafter, the focus points and strategies for scaling digital twins are presented. The chapter concludes with several interviews to complement theoretical knowledge with practical insights.
4. **Designing the roadmap:** After reviewing the current body of knowledge, this chapter describes the design of the roadmap. The criteria for designing the roadmap will be collected, and the framework of the roadmap is designed. The roadmap itself is designed and validated by professionals. Based on this feedback, various improvements have been applied to the roadmap.
5. **Discussion:** The final criteria and the roadmap are discussed in this chapter. The results are related to the body of knowledge and limitations of the research are described.
6. **Conclusion & recommendations:** The main content of the study is described, including the problem, how it is addressed, the final design and the results. Furthermore, recommendations are described for future research and for the company.

2

Research methodology

The research methodology is described in this chapter. First, the used method of Research through Design (RtD) is explained in Section 2.1, as this is slightly different than conducting a more traditional academic research. The outline of the research with corresponding steps is described in Section 2.2 and the method to collect data follows in Section 2.3. Data analysis is treated in Section 2.4 and the chapter concludes with Section 2.5 that provides information on designing a roadmap.

2.1. Research through Design

The Research through Design (RtD) method is used to create the roadmap of this report. RtD is an approach for conducting research that employs the methods, practices, and processes of design with the aim of generating new knowledge. RtD draws on the strength of design as a reflective practice [65]. The desire to make improvements to a design or prototype can motivate and guide the learner [56]. RtD is a systematic and reflective process and requires detailed documentation of the decisions to capture knowledge. The roadmap of this research plays a central role in the knowledge generation process [65]. Despite the fact that RtD is a systematic approach, Stappers and Giaccardi [56] state that there is no clearly defined method by which RtD is performed. However, documentation and reflection are essential to capture and translate design knowledge into academic knowledge [3]. Rodríguez Ramírez [47] defined a model with four steps based and forms the basis for this thesis:

1. Performing a literature review to come up with a set of criteria for the roadmap. The review will focus on container terminals and its future (digital) trends, operational planning uncertainties, digital twins and scaling strategies. The criteria will provide guidance for the roadmap.
2. Based on the knowledge gathered during the literature review, a set of questions is established for interviews with practitioners. The aim is to discover new potential research areas that help answer the research question. New or improved criteria are created according to the results.
3. Step three involves designing the roadmap that aims to meet the developed criteria. This stage involves iterations based on feedback collected during validation interviews and is systematically evaluated according to criteria and literature.
4. The criteria developed during the investigation are used to evaluate the final roadmap and elaborate how the roadmap met or did not meet the criteria. The criteria can then be used to describe the design and its explicit contribution to knowledge.

Using the Research through Design (RtD) method brings the advantage of being able to stay flexible and reflective. During the design of the criteria and the roadmap, it can be decided to do more research on a topic or decide that certain criteria are no longer relevant based on the feedback of professionals. It is a repeated process that seeks to improve the previous design or prototype. However, decisions made during the process must be carefully documented to contribute to the knowledge gap and communicate tacit knowledge. The final design of the roadmap does not include all the lessons learned during the process, as some decisions to leave out certain criteria can be just as interesting.

2.2. Research steps

A flowchart of the phases of this thesis is shown in Figure 2.1. The research begins with a review of the literature to gain theoretical knowledge on the topics of the problem statement shown in Figure 1.1. The second step is to complement this knowledge with practical insights gained during informational interviews. The interview questions are drafted to obtain experience from practitioners. In step three, all insights are analyzed and combined into the criteria for the roadmap and lead to the design of the roadmap in step four. This design is then discussed with subject matter experts to validate the findings. Based on their feedback, the roadmap is improved, the results are discussed and the (academic) relevance is determined to draw a conclusion. By reviewing the criteria and documenting all decisions and design steps, the (tacit) knowledge gained during the research will be available to others.

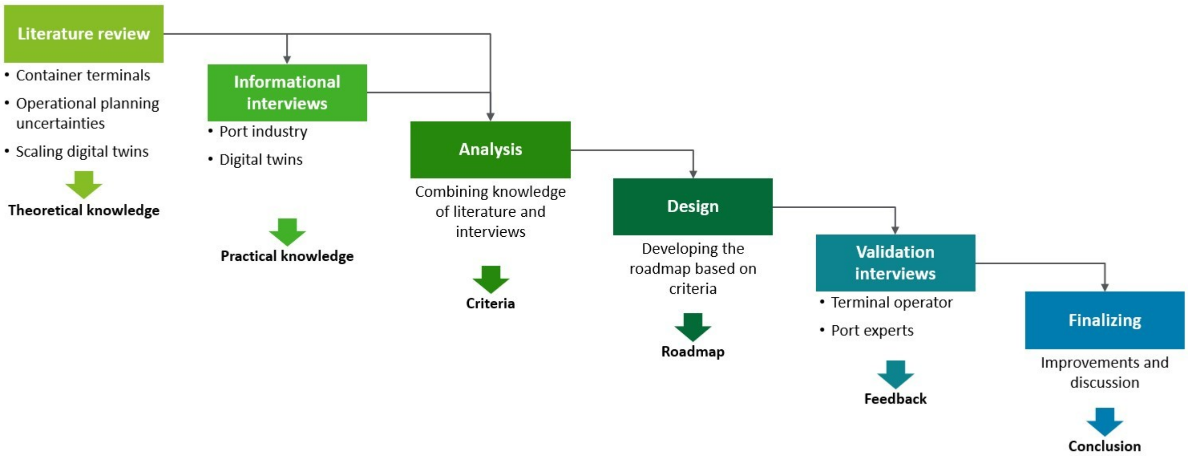


Figure 2.1: A flowchart of the research steps that are taken for this thesis.

2.3. Data collection

In this section, the requirements for the necessary data, the location of the data (sources) and a plan for analyzing the data are described. The goal of the literature review is described and hereafter, the method for conducting interviews will be discussed.

2.3.1. Literature review

First, the context of the research should become familiar. A review of the literature on container terminals and future trends is necessary to investigate the (digital) characteristics of the industry. Risks and threats, as well as digitalization, will be reviewed to understand the market conditions of the sector. Information about operational planning uncertainties will also be gathered during the literature study. The goal is to understand the problems that arise from these uncertainties and to determine how a digital twin can improve or solve these problems. In addition, information on digital twins will be collected to gain an understanding of digital twins and its possibilities. More detailed information on the desired scope for container terminals will be collected by conducting interviews. The goal is to understand the developed digital twin and to determine what input and output must be changed for the implementation at other container terminals. Also, lessons learned from other digital twin projects can be used to optimize the criteria for the roadmap. Scaling strategies for digital innovations will be investigated and reviewed for the applicability for digital twins.

2.3.2. Interviews

Interviews are a qualitative research technique and are based on the collection of data using questions. There are various types of interview, which are frequently distinguished by their degree of structure. In structured interviews, questions are asked in a prearranged sequence and all questions are the same for interviewees. Unstructured interviews have no fixed questions and order set in advance, but based on the participant's prior responses, the interview can proceed more intuitively. Semi-structured interviews fall somewhere between structured and unstructured interviews [15].

For this research, two rounds of interviews will be conducted. The purpose of the first interviews is to obtain more information on the knowledge gaps identified during the literature review. Also, the opportunity to gain insight into the daily operations of a container terminal and current trends, as well as information on the development decisions of the project teams, is an important motivation for the interviews. The interviews will be semi-structured, since the interviewees have different expertise, and the goal is to obtain more information on certain topics. A structured interview will be too strict in that case, but with an unstructured interview it is easy to get side-tracked. Questions will be determined in advance, but the order and number of questions will differ per interview. The interview starts with a small presentation and recap of the research goal, in order for the interviewee to grasp the context. All interviews are conducted online and the questions are shared beforehand. An overview of the questions and findings is shown in Section 3.9. The second round of interviews is to validate the roadmap with practitioners. On the basis of their feedback, a conclusion can be drawn if the roadmap is sufficient to use at container terminals. The interview is structured, since it is important to ask the same questions to compare the feedback. The main feedback is described in Section 4.5.

The interviewees have different backgrounds, expertise, roles and teams to allow different input and opinions. Some have an inside-out perspective (container terminal operators about port industry), and others an outside-in perspective (external consultants about container terminals). The interviewees were selected on the basis of their expertise to ensure a broad body of knowledge. An overview of the interviewees and transcripts is shown in Appendix A.

2.4. Data analysis

The findings of the interviews are analyzed using qualitative data analysis. Content analysis is used, which means that patterns can be found in text by classifying content into words, concepts, and themes [13]. First, the data is collected in the transcripts of the interview in Appendix A for each interview. The findings are then classified and summarized in Section 3.9 per subject with corresponding interview questions. For each topic, similarities and differences are identified and compared to the literature. Eventually, the findings from both literature and interviews are assessed on relevance, and combined into criteria for the roadmap. Establishing the criteria is described in Section 4.2.

The criteria that are established after conducting the literature review and interviews will determine the prerequisites for the roadmap. Some criteria are more important than others, so prioritization is necessary to establish a clear order. One technique used for prioritization is called MoSCoW [43]. It The rules make a distinction between 'Must have', 'Should have', 'Could have' and 'Want to have', as shown in Table 2.1.

Table 2.1: Description of the MoSCoW prioritization that will be used for the established criteria in Section 4.2.

Must have	Criteria that are fundamental to the outcome and, without them, the roadmap will be ineffective and useless.
Should have	Important criteria for which a short-term solution is possible, but are important for the roadmap in a more time-constrained situation.
Could have	Criteria that can be more easily left out and may be included if 'Must haves' and 'Should haves' are taken care of.
Want to have	This refers to valuable criteria that can wait until later.

Lastly, the verification and validation of the roadmap is important. It will evaluate if the result complies with the requirements (verification) and if the result meets the needs of the stakeholders (validation). Verification of the roadmap will take place at the end of the research by comparing the roadmap and the criteria. Validation will be done during interviews after the first design of the roadmap, which are described in Section 4.5. The validation and verification are more extensively described in Section 5.1.

2.5. Roadmap design

The findings of the research will be combined into a roadmap that will provide a scaling strategy for the target audience. According to Simonse [53], ”a roadmap is a visual representation of a product or technology plans plotted on a timeline”. A strategic roadmap often has three basic characteristics:

- A visual representation of the organization’s future strategy.
- Users, products, market and technology elements outline the roadmap.
- A timeline presents the different phases of the roadmap.

The roadmap often consists of three phases that each conceptualize a new development phase. The first phase starts with the current situation with existing technologies and focuses on design improvements that increase value. The third phase projects the ideal situation with new technologies and improved operations. The transition phase serves as a bridge through the development of entirely new technological applications that are tested by users in an existing market. Simonse [53] recommends to sketch a roadmap template at the beginning of the process and iterate further during dialogue sessions and research. This is also in line with the Research through Design method discussed in Section 2.1:

1. Identify the target audience
2. Choose the format of the roadmap
3. Design the timeline and the template
4. Map all roadmap elements in the template
5. Iterate the design, structure and content until stakeholders are satisfied

The strategic roadmap outlines the activities and responsibilities for each stakeholder and focus area (themes) shown over time (phases). An example of a strategic roadmap is displayed in Figure 2.2. The design of the roadmap template is presented in Section 4.3.

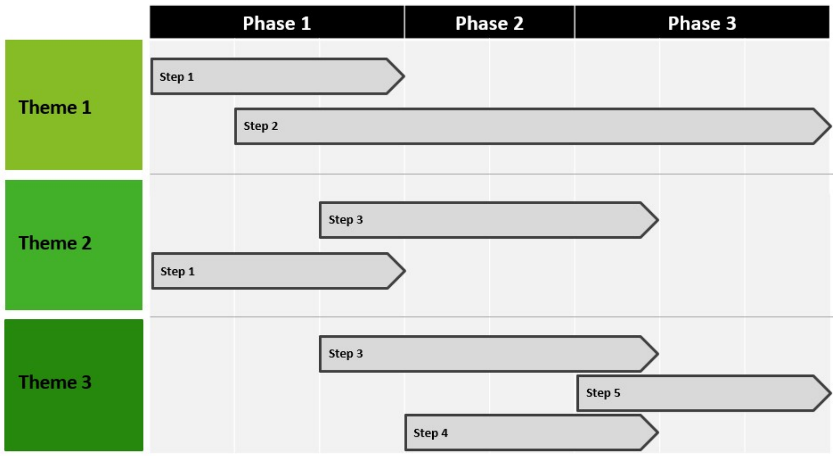


Figure 2.2: An example of a strategic roadmap with three phases, three themes and several steps.

3

Literature review & interviews

The goal of this chapter is to dive into the theoretical background of the research to gain knowledge on the different topics. It will start with an introduction on container terminals and its equipment in Section 3.1 and a description of the industry trends in Section 3.2. An introduction on operational planning uncertainties is given in Section 3.3 and the risks and threats of the maritime industry are discussed in Section 3.4. Hereafter, the literature review will dive into the world of digital twins in Section 3.5 and describe how to develop this tool in Section 3.6. To elaborate on the scaling part of the report, important factors and suitable scaling strategies are described in Section 3.7 and the barriers and drivers of scaling digital twins in the port industry are presented in Section 3.8. The chapter concludes with conducting informational interviews in Section 3.9 to complement theoretical knowledge with practical insights from experts.

3.1. Introduction to container terminals

Container terminals are areas in the port where standardized containers are transferred between ocean-going vessels and trains, trucks, barges and smaller vessels called feeders [50]. The standard length of a container is twenty feet (6.1 m), and the abbreviation TEU (Twenty-feet Equivalent Unit) is used to indicate the number of containers. For example, the capacity of the largest container ships is over 24,000 TEU. Container terminals can be divided into five main areas, namely berth, quay, transport, storage yard and gate, as shown in Figure 3.1. The berth and quay areas are considered seaside, where operations consist of (un)loading of vessels and container transfer between the quay crane and terminal equipment [4]. The storage yard and gate areas are considered landside, where containers are temporarily stacked, inspected by customs as needed, and then transported to the hinterland. The transport area is located between the seaside and the landside areas [6].

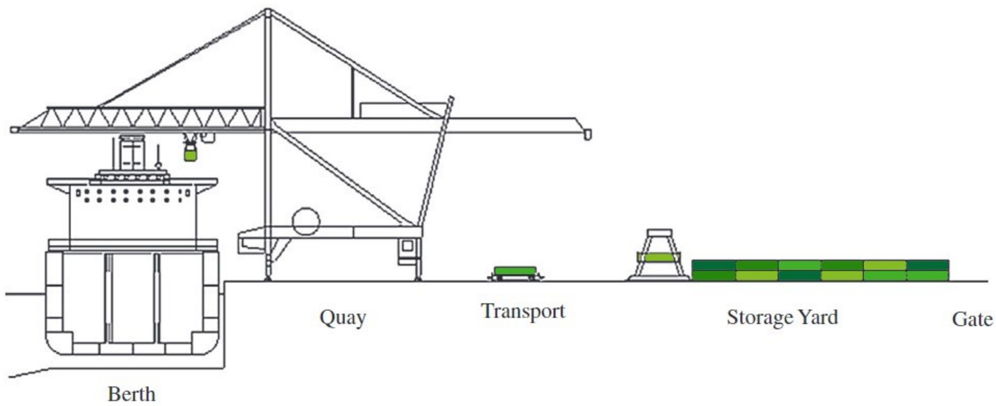


Figure 3.1: The five main areas of a container terminal consist of the berth, quay, transport area, storage yard and gate [6].

3.1.1. Logistics of a container terminal

Containers stacked in the storage yard may be inbound, outbound, or in transit. Inbound containers are unloaded from the ships, stacked in the storage yard, and then picked up by the terminal's customers, while outbound containers are handled in reverse order. Transit containers are unloaded from ships, stacked in the yard, and then loaded onto other ships for their next destination [24]. A container terminal can act as a gateway or a hub, depending on the link in the transportation chain. While a hub is a central location where inbound and outbound containers are transferred from one ship to another, a gateway generally means a transfer from one mode of transport to another (e.g. ship to lorry), acting as a gateway to the hinterland [46]. In addition, a distinction can be made between two types of flow at a container terminal, the so-called push flow and the pull flow. If terminal A takes the initiative to send containers to terminal B, this is called push containers. If terminal B requests containers from terminal A, one speaks of pull containers [12]. The lean production method describes the advantages of a pull flow, as it minimizes inventory and optimizes operational performance [19]. This is also recognized in the container terminal industry, as APM Terminals Tangier recently developed and implemented a new operating model based on the pull system. The goal is to transform into a 'lean terminal' to achieve a higher level of customer satisfaction and operational performance [28].

There are approximately 600 container ports worldwide, of which 200 terminals handle more than half a million TEU [46]. An overview of the 15 largest ports worldwide in terms of TEU handled in 2021 is shown in Figure 3.2. Ten ports are located in Asia, three in Europe and two in the United States. With the exception of Hong Kong and Hamburg, the fifteen ports exceeded pre-pandemic levels in 2021. However, global container shipping and container port volumes are expected to slow to 3% by 2022. Ports are struggling with new lockdowns in China, and in Europe, the largest ports will face a decrease in throughput as Russian container volumes are eliminated and ships are diverted [32].

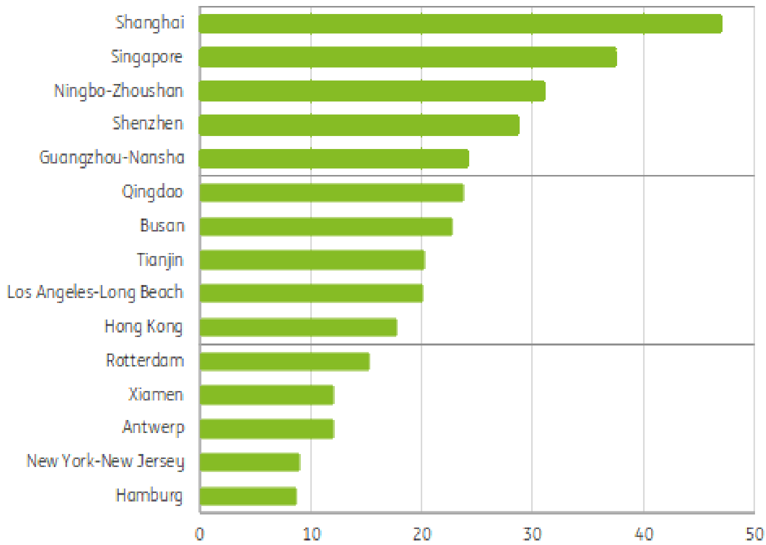
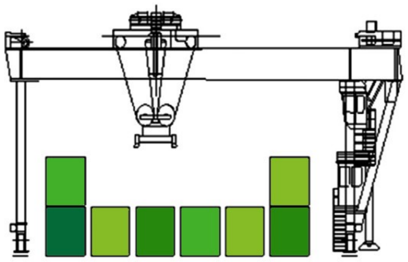


Figure 3.2: Top 15 largest container ports worldwide in 2021 (in million TEU annual throughput) [32].

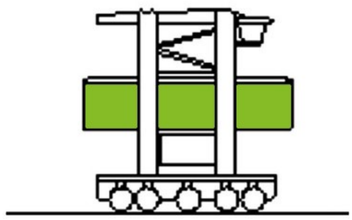
3.1.2. Container handling equipment

A container terminal operator needs large equipment to handle containers. Quay cranes (QC or ship-to-shore (STS) cranes) are the largest assets, as can be seen in Figure 3.1. A conventional quay crane uses a single trolley to transfer containers between a ship and a transport vehicle. The loading information can be obtained from the stowage plan provided by the ship. More advanced quay cranes have been developed to increase the number of lifts per unit time or the number of containers per lift. The most common is a dual-trolley crane, which uses a seaside and one landside trolley to handle containers. The cycle can be divided into two segments, where the seaside trolley picks up the container from the ship and places it on a platform on the crane. The landside trolley then moves the container from this platform to the vehicle, resulting in more lifting operations per unit of time. In addition, cranes have been developed that can lift multiple containers simultaneously [23].

A commonly used asset in the storage yard is the gantry crane (GC), which is shown in Figure 3.3a. There are two types of gantry cranes, namely rubber-tired gantry cranes (RTGCs) and rail-mounted gantry cranes (RMGCs). RTGCs are typically operated manually, as they have the flexibility to move freely within and between blocks. RTGCs are able to rotate tires 90° to perform orthogonal movements. Although the movement of RMGCs is limited by their (underground) rails, this makes the system easier to automate. The second most widely used equipment in the storage yard is the straddle carrier, shown in Figure 3.3b. Straddle carriers (SC) can lift and stack containers at any point in the terminal. Due to this capability, they are used in some container terminals both for the transfer of containers between the quay and the storage yard and for the storage of containers in the yard [6].



(a) Example of a gantry crane (GC).



(b) Example of a straddle carrier (SC).

Figure 3.3: Two types of frequently used material handling equipment in the storage yard [6].

There are several options for transporting containers between the storage yard and the quay. The most common type of vehicles are conventional trucks, and the automated version is the automated guided vehicle (AGV). Another type of transporter is the straddle carrier (Figure 3.3b) mentioned above. One of the disadvantages of using trucks or AGVs is the possibility that a crane or transporter has to wait for a container to be handed over. To solve this problem, crane operations can be decoupled from transportation by installing racks at the ends of yard blocks. Cranes and AGVs can load containers onto these racks before other equipment reaches the transfer position. A comparison of different types of transporters shows that productivity with a lifting rack was twice that of an AGV [23].

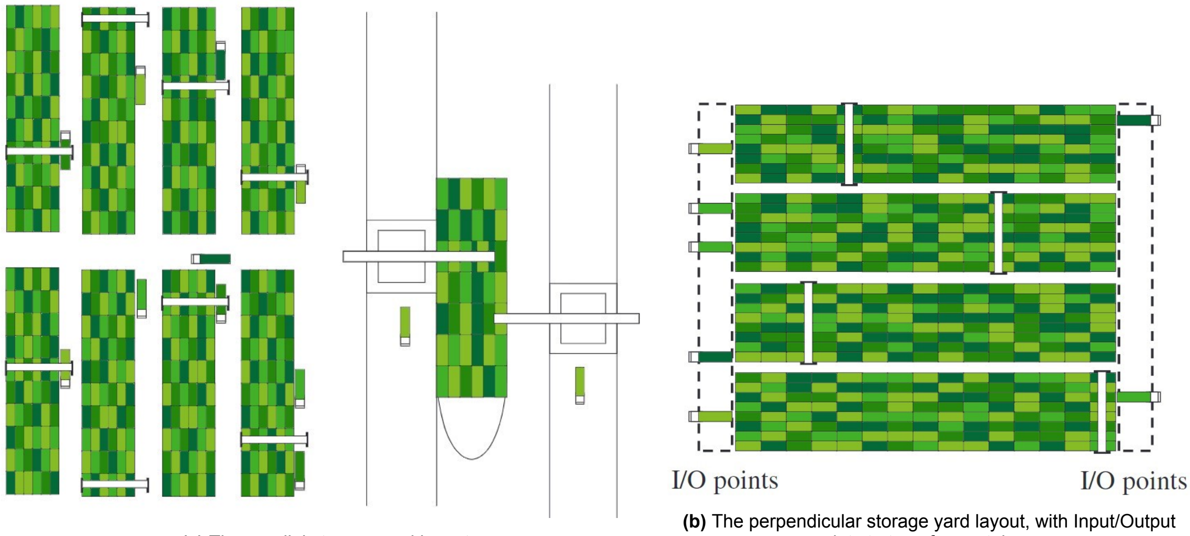
With sustainability becoming more important every day, terminal operators need to incorporate green initiatives into their operations. Diesel vehicles are being abandoned and electric vehicles are being introduced. Not only are rising fuel prices an incentive to switch to electric, but reduced noise pollution and better air quality are important to employee well-being [24]. Additionally, collaboration among terminal assets is important to improve operations. By successfully integrating information technologies and updating the loading and unloading equipment in a timely manner, the terminal can gain significant competitive advantages. For example, throughput can be increased, operating costs can be reduced, and labor productivity improved [49].

3.1.3. Storage yard

The storage yard plays an important role in the performance of a container terminal. It connects the berth and hinterland, acting as a buffer for storing containers. Different handling systems must be coordinated, which has an impact on terminal cost, throughput, and handling efficiency [64]. Terminal operators have focused much attention on developing quayside equipment (as mentioned in Section 3.1.2) to improve the performance required to minimize the time a vessel is at berth. However, overall productivity will not benefit from faster quay cranes unless container storage and retrieval can handle the same number of containers [26]. Therefore, an optimal yard layout and planning strategy is key to assure operations at a terminal are aligned properly.

The layout of the storage yard is important to improve the use of yard space and the cooperation between different assets. Liu et al. [31] simulated the impact of yard layout and automation on terminal performance. Research compares the performance of parallel (Figure 3.4a) and perpendicular (Figure 3.4b) yard layouts with and without automation operations. Research shows that, compared to manual operations, the application of AGVs substantially increases terminal throughput.

Meanwhile, research also shows that the perpendicular layout performs better than a parallel layout for the same number of AGVs. The advantages of this layout mainly lie in that the running distance of horizontal transportation equipment is shortened, saving operation and energy costs. Furthermore, the seaside operations and the landside operations can be separated to realize the division of operation functional areas and reduce the complexity of path planning [64]. Compared to the parallel layout, the perpendicular layout has higher investment cost, lower operational costs, faster crane speeds, more storage capacity per area, and minimizes the distance travelled by transfer vehicles and external vehicles at the expense of longer yard crane travel distances [6].



(a) The parallel storage yard layout.

(b) The perpendicular storage yard layout, with Input/Output points to transfer containers.

Figure 3.4: Examples of a parallel and a perpendicular layout for the storage yard of a container terminal [6].

3.2. Trends of the container terminal industry

Several trends and developments are taking place in container terminals that are important to understand. Besides global disruptions in the logistics chain or social developments as sustainability, also technical advancements are important to consider. Terminal and process automation are the next steps towards improving productivity at container terminals [7]. However, to automate terminals, digitalization is important first to digitalize terminal processes. Artificial intelligence is also the key to automatically collect and process data.

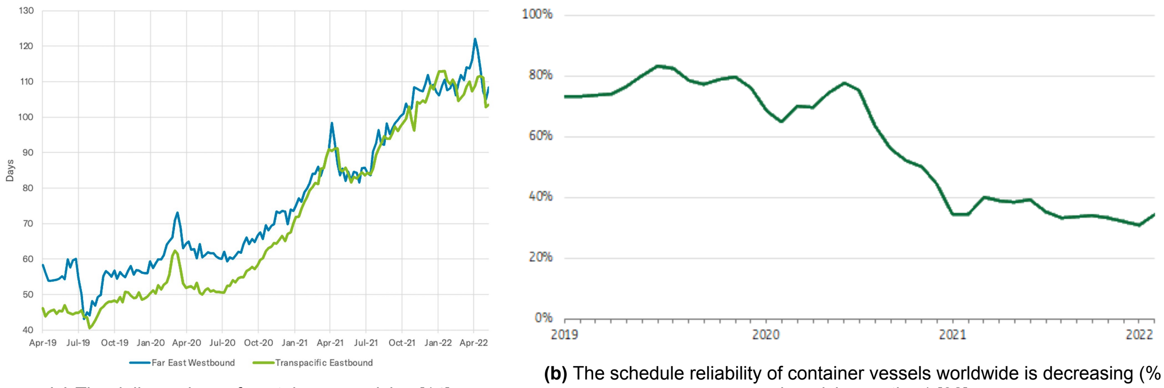
3.2.1. Sustainability

Sustainability is becoming more and more important and the International Maritime Organization (IMO) agreed in June 2021 on a new set of guidelines to reduce the carbon emissions of all ships involved in international trade. Although container shipping only represents about 15% of the international shipping fleet, it accounts for 35% of all shipping emissions [21]. Two new measures will enter into force in 2023, which will require the vessels to demonstrate an annual improvement in operational carbon emissions. That may involve costly retrofits, or vessels need to save fuel during operations. There are fundamentally two ways to save fuel during the voyage, namely green routing (the shortest safe distance) and green steaming (the lowest operational speed to arrive Just-in-Time). An industry rule of thumb is that for a container ship, a 1% reduction in vessel speed results in approximately 2% savings in fuel costs. As fuel accounts for 35-70% of transport costs, green routing and steaming align the profitability goals of a ship owner with sustainability [61]. Research of the Port of Rotterdam shows that emissions in the last 12 hours of the voyage could have been reduced by 4% if all incoming container ships calling at Rotterdam in 2018 had known their arrival time 12 hours in advance. Even bigger opportunities exist if berthing times are communicated more than 12 hours before arrival. AIS analyses carried out by DNV GL indicate that about 15% of the marine fuel consumption of the world fleet occurs under port stays, anchorage and when ships operate at very low speeds, below 1 knot [21].

Therefore, reducing operational planning uncertainties and improving port calls have a huge impact on saving operational costs and emissions. The optimization of port calls and its related processes would also increase the competitiveness of the ports concerned. As the industry increasingly looks for ways to reduce emissions, shipping lines may favor ports that provide more accurate and reliable information about the availability of its services. If delays and inefficiencies are minimized in the port, it would improve the reputation of the port and possibly lead to increased turnover and trade [21].

3.2.2. Global disruptions

Container terminals are part of an interdependent international supply chain, as containers are transported around the world and therefore are sensitive to global disruptions. As can be seen in Figure 3.5a, a container now takes more than twice as long to travel as it did before the corona crisis. Flexport [14] uses data from shipping operations to provide insight into the journey of a container. It shows the time taken to transit from the exporter's gate to the destination port. Data is shown for the Far East Westbound route in blue (for example, China to Europe) and Transpacific Eastbound route in light green (for example, China to the USA). The longer travel duration can also be seen in the lower reliability of the schedule shown in Figure 3.5b. Western European ports face the consequences of stranded containers destined for Russia and new lockdowns in China lead to congestion. On average, global port congestion was still close to peak levels, leading to delays and low arrival reliability [32].



(a) The delivery days of containers are rising [14].

(b) The schedule reliability of container vessels worldwide is decreasing (% vessels arriving on time) [32].

Figure 3.5: The delivery time of containers are rising, with a lower schedule reliability as a consequence.

3.2.3. Digitalization

Digitalization is the concept that all data is provided to all stakeholders in real-time on one open platform to improve efficiency and decision-making. Digitalization leverages on digitization (making existing data and processes digital) by bringing value to company roles instead of just replacing them. For example, digitization replaces manual cranes with automated cranes, but digitalization brings value to crane operators by placing them in remote towers while still being able to operate the crane, making their jobs safer and more efficient [54]. Collaboration and organizational resources (especially company culture for learning) are the most important factors for the successful digitalization of container shipping companies. Also digital integration among stakeholders is influential, as many different parties and paper work are involved [55]. Often, this dampens accurate scheduling, causes port congestion, generates additional work, such as rescheduling, and produces distrust between stakeholders. Digital integration might improve this situation by streamlining or automating paperwork and procedures, but it is necessary to digitalize the entire supply chain because bottlenecks could arise otherwise [20].

3.2.4. Artificial intelligence

The port business has experienced a wave of digitization initiatives and automation programs during the last three to five years. An assortment of Internet of Things (IoT)-related implementations, such as automated terminals, cargo platforms, smart energy grids, and others, serve as examples. This is primarily due to pressure on efficiencies brought on by the professionalization and scale expansion of nearby industries like container shipping and logistics. This calls for ports to become more adept at managing traffic flows and putting more of an emphasis on better utilizing infrastructure.

Every organization generates enormous volumes of data every second, and without AI, people cannot fully exploit the value of this data. The major ports in the world, including Singapore, Rotterdam, and Hamburg, are utilizing AI solutions to enhance business processes. For instance, by combining the Automatic Identification System (AIS) of ships entering the port with current camera infrastructure, AI can be used to enable machine learning and image recognition skills to reduce port congestion. In essence, ports might process their data with the use of AI to assist them in making precise judgments, planning for shipping arrival and departure dates and the best storage solutions, and quickly loading and unloading containers and cargo from ships. A port may need to completely rethink how people and machines interact in operational and strategic environments in order to truly become an AI-fueled organization. To assist data-driven decision-making, executives should also think about systematically implementing machine learning and other cognitive tools across possible fundamental business processes and company operations. Similarly, AI could inspire new products (just-in-time call platforms), business strategies (new pricing tools), and a host of other things [60].

3.2.5. Automation

Today, increasing container volumes and vessel sizes have to be served in reliably short periods of time. Increasing labor scarcity and cost require personnel reductions, and environmental regulations on noise and air pollution require low-emission terminal equipment. These demands, together with improved abilities in the fields of automated terminal equipment, lead terminal operators to reconsider traditional operations and to increasingly adopt automated handling equipment [50]. Advanced technologies such as artificial intelligence, big data, and other technologies are applied to automated container terminals. Yard space can be allocated more effectively, which has an important impact on the production cost, throughput, and handling efficiency of the terminal [64]. Comparisons between manual and automated concepts show cost reductions of up to 25% (including labor, operation and capital costs) [22]. Automating a greenfield (newly built) terminal is the most obvious, but also existing (brownfield) terminals can be automated partially or wholly. In brownfield terminals, the transition should be carried out step by step in different areas of the terminal to avoid loss of capacity [17].

Camarero Orive et al. [5] investigated the implementation of automation and a global perspective map of the aspects considered is presented in Figure 3.6. Cybersecurity is a primary issue in the short term, while transparency is considered in the long term. Decarbonization is increasing over time and is becoming increasingly important. Collaboration is also an important issue when automating a container terminal, as from the private perspective (terminal operator) there has to be communication and willingness on the part of the port authority (public party). Furthermore, collaboration between parties is essential for data exchange [5].

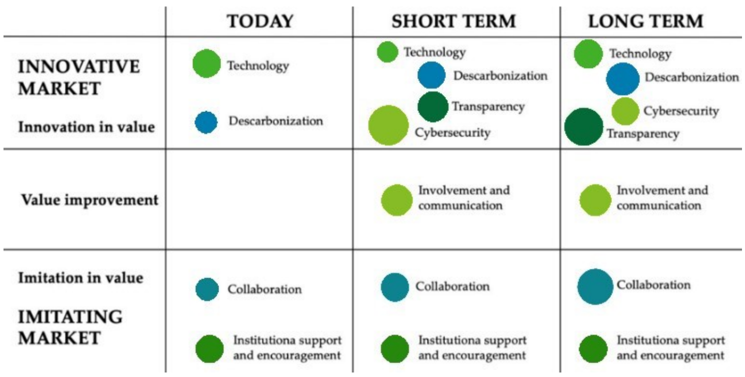


Figure 3.6: Global perspective of the aspects considered in the implementation of automation in container terminals [5].

However, the development of automation also brings challenges as, for example, the difficulty of operational decisions in emergency or unique situations, the requirement for significant capital investments and the need for highly qualified specialists [49]. Furthermore, only about 4% of container terminals have implemented some level of automation so far, and more than half of these are only semi-automated facilities. This is the result of the niche market, because dedicated and customized solutions take time, making every automation project unique. Risk avoidance is also a factor, as continuity of container flow needs to be protected [34] [57].

3.3. Operational planning of container terminals

The operational planning of a container terminal is complex, as it depends on many external variables, such as the arrival of vessels, trains, and trucks, and the efficiency of (un)loading containers [6]. Since most shipping companies operate their ships according to fixed schedules, arrivals would be considered predictable. However, in practice, the arrival of vessels seems less predictable, as many events can occur during the journey. In addition to weather-related delays or delays experienced during previous port visits, changes in the number of containers, traffic jams or mechanical failures also have an impact. Ku et al. [25] mentioned uncertain vessel arrivals as the biggest impact on yard operations due to the tight and complex schedule, leading to congestion and transshipment. Furthermore, every vessel has a required departure time, which is the latest allowable departure time contracted between the container terminal and the shipping company. If the completion time to handle a vessel exceeds the required departure time of the vessel, a penalty fee will be charged [63]. So, a robust planning does not only reduce operational costs, but also minimizes the risk for penalty fees.

3.3.1. Port call operations

The port call process is generally not optimized for container vessels. Many different decisions affect each other in the process of a port call, such as berth allocation, the deployment of quay cranes, allocation of yard space, deployment, and scheduling of yard cranes [63]. In addition, the actual arrival and handling times often deviate from those scheduled. The latest ETA (Estimated Time of Arrival), sent at least 24 hours prior to the expected arrival time of the vessel, often has to be updated and the actual arrival time remains uncertain. This results in having to 'wait' outside the port at anchorages for many hours, days or even weeks, or maneuver at very low speeds in the port area while waiting for the availability of berth and nautical services. Ships may spend 5% to 10% of their time waiting to enter port, which should be significantly improved from a safety, environmental and economic perspective [21] [42]. To improve this, a Just-in-Time (JIT) arrival allows a ship to maintain optimal operating speed to arrive when the availability of a berth and nautical services is ensured. JIT arrival is not to be confused with slow steaming or with a speed limit. Through the application of JIT arrival, the overall length or duration of a voyage is not impacted and remains the same. Instead, the overall voyage is optimized. The ship may spend more days sailing, but the aim is to minimize and preferably eliminate waiting time and reduce fuel consumption [21].

There are two main approaches to respond to disruptions, namely proactive and reactive. Proactive strategies focus on anticipating the uncertainty and variability of real-world scenarios before disruption. Models insert time buffers between vessels allocated to the same berthing position to obtain flexibility or incorporate possible recovery cost. This scenario-based research is important in the long run, but terminal operators also need instant decision-making support while preventing underused berth or quay crane resources. Thus, reactive strategies that aim to make quick and effective responses to disruptions are also important [33].

3.3.2. Berth planning

Being an input to yard space allocation and crane planning, berth allocation is one of the most important activities in container terminals. The berth plan is the very first level of terminal planning and is used as a key input to yard storage, personnel and equipment planning. Any adjustment will induce a series of changes in all subsequent operations. For example, if the actual chosen berthing position of a vessel is different from the scheduled position, the distance of horizontal transport at the yard increases, because containers are generally stacked near the pre-scheduled berthing position of the vessel. Therefore, terminal planners must carefully schedule the berthing time and position of each arriving vessel, based on estimated arrival and loading times provided by the vessel [63].

Providing a fast and reliable berthing plan while minimizing costs and congestion is important for both shipping lines and terminal operators. Because changing the configuration of terminals (e.g., extending the quay) requires a rather expensive investment, improving the efficiency of available berths and quay cranes is essential for terminals to remain competitive. Generally, terminal operators form a weekly berthing plan prior to calling the vessels. However, there are frequent disruptions that hinder the execution of initial plans. Therefore, uncertainties cannot be ignored, and a well-functioning berthing plan should incorporate both efficiency and recovery from disruption.

As a solution, Lyu et al. [33] propose a collaborative berth planning approach that explicitly considers collaboration between terminals, allowing vessels to transfer to other terminals and the transshipment connection between vessels. Experimental comparisons show that collaboration between terminals helps to save up to 40% of the total recovery cost. Therefore, partnering terminals to share berthing resources is a potential solution in response to disruptions [33].

3.3.3. Storage yard planning

Yu et al. [64] emphasize the importance of storage yard planning. A well-designed planning should consider both storage allocation and distribution of equipment workload. The storage plan should be easy to change when uncertainties arise, so automating or digitizing this process could be a solution to improve operations [30]. The logistical challenge mainly arises when there are several moored vessels, some of which are being unloaded and others loaded. Due to congestion during peak times and uncertainty about the arrival of vessels and external trucks, containers are often not stored at their optimal location. This container relocation problem, called housekeeping, is one of the most challenging problems. Housekeeping includes transporting containers to their final destination during idle time or for outbound containers to a location closer to the quay cranes for the next vessel. Another phenomenon found in storage yards is reshuffling, which are unproductive moves required to gain access to a desired container that is blocked with other containers over it. Therefore, an optimal yard planning and housekeeping strategy is important to save costs by minimizing vessels' turnaround times and prevent unnecessary reshuffling operations [6] [64]. Saanen and Dekker [51] provided a categorization of yard planning strategies:

1. **Dedicated versus non-dedicated:** A dedicated strategy does not allow containers that will be loaded into different vessels to occupy the same yard "location". A non-dedicated strategy allows containers to occupy the same "location".
2. **Consolidated versus dispersed:** A consolidated strategy groups containers to be loaded on the same vessel into clusters in the yard, while a dispersed strategy does not attempt to group them into clusters.
3. **Housekeeping versus immediate final grounding:** In a housekeeping strategy, a discharged container is stored temporarily in the storage yard, and at a later time, moved to another location before loading into a vessel or truck. In an immediate final grounding strategy, the discharged container stays in the same location until it is loaded.
4. **Discharge-optimized grounding versus loading-optimized grounding:** A discharge-optimized grounding strategy stores containers to maximize the efficiency of storage activities, while a loading-optimized grounding strategy stores the containers to maximize the efficiency of retrieval activities at a later time.

3.4. Risks & threats of the maritime industry

The pace of digital transformation in the maritime industry is still slow. Industry-specific characteristics, such as high asset costs, high development costs, aging workforce, and strict regulations negatively impact the ability to digitize effectively. Also, due to the traditional set-up of the organizations, conventional players often lack the skills and agile processes for successful digital adoption [9]. Corderly, Vonck, and Sanders [9] performed a research on the adoption of digital technologies in the maritime industry. Several conclusions were drawn about the current state of the sector:

- Companies that look at digital technologies as more than a one-time project are more likely to enjoy the benefits that technology can bring.
- Traditional players are often asset-heavy, face the faith of legacy systems, and have a workforce that is digitally not well equipped, which is slowing down adoption in the industry.
- Organizations are willing to digitalize, however, sometimes lack a clear digital strategy.
- The perceived knowledge of professionals about digital technologies is rather low.
- The perceived compatibility of digital technologies influences the decision to adopt technology.

3.4.1. Organization

Port logistics is a labor intensive task, so human participation plays an important role in efficient port operations. The significance of communication between the workforce, staff motivation, and training are required skills for an individual [52]. Also factors as age, work experience, and adaptability to learn new technologies and skills are important. Ichimura et al. [20] state that changes in corporate culture, such as increasing agility and creating a collaborative environment, are important to cope with digitalization. For this reason, the need for cooperation could be related to the need for a 'port innovation leader' capable of both introducing an innovation and coordinating efforts related to innovation development. Standalone innovative processes seem to be less effective in achieving success [1]. In addition, it is important to note that current barriers to collaboration in the port industry make technology-related innovation a dominant element [1], instead of social-related innovation that is successful in most manufacturing sectors.

3.4.2. Assets

Some respondents indicate that they have the budget and size to implement digital technologies. However, they also indicate that they are not always ready for the adoption of digital technologies due to limited access to the right (human) resources and know-how on how to implement the technologies. Also, they point out that digital technologies fit in with the current vision and strategy of their organization. However, the technologies are not always compatible with their existing systems and IT infrastructure. Reasons for this could be the existence of (outdated) legacy systems and traditional nature of organizations [9].

Terminals are restricted to their existing equipment, resources and space to maximum capacity. Qualified labor can be hard to obtain, and safety and human factors often restrict the performance of equipment. The size of current container ships places additional competitive pressure on terminal operators to maximize throughput and minimize turnaround times [17].

3.4.3. Strategy

Despite the sense of urgency and positive attitude towards the benefits, most organizations do not seem to have a clear digital strategy and professionals indicate that the organizational culture does not always seem to embrace new digital technologies as it is very often perceived as a (siloed) project [9]. Moreover, some specific factors seem to influence the possibility of achieving innovation success. Among these factors, the alignment between the companies involved in the innovation might foster the success. Considering these results, specific inter-company and intra-company strategies might be set up in order to incentives innovation paths (e.g. shared innovative infrastructures). Moreover, adaptive innovation strategies might help to foster innovation processes better than rigid approaches [1].

3.4.4. Next steps

Most professionals are strongly convinced that digital technologies will improve the quality of decision-making within their organization, positively influence their position in the market, and improve the quality of their products and services. Most agree that technologies will provide better insight into operational processes within the business, improving cost and communication effectiveness. All professionals agree that digital technologies will allow their organizations to better meet customer demands [9]. To drive the adoption of digital technologies, three key actions are identified:

1. **Increase knowledge:** Knowledge and the use of the right tools are fundamental to understanding digital thinking. It is important that all levels of the organization enable decision-making and successful implementation.
2. **Increase compatibility:** Both the digital technology and the organization must be compatible to work successfully together.
3. **Develop an Ecosystem:** Innovations require multiple organizations and stakeholders. Therefore, organizations must redefine relationships, collaborate, and build new competences by experimenting.

As vessel sizes and global containerized trade increase, integrated operations scheduling and decision-making algorithms will be required for real-time scheduling and dynamic planning of container operations. To represent real terminal systems and develop applicable methodologies, integrated schedules of container handling equipment should be combined with the assignment of containers to yard blocks. Furthermore, online optimization methods, as well as more efficient heuristic algorithms, appear to be worthwhile avenues for future research [24].

Knowing the possible deviation from the scheduled arrival time in advance is important for planners to more efficiently allocate the manpower, equipment and spatial resources required to perform handling operations. The main risk for planners is underestimating the resources. However, over-estimation within any given working period is also to be avoided since it would result in higher costs for the terminal. This means that planners must be supported at each stage with tools that are capable of supporting the decision-making process. Having all information available could reduce operating costs, maximize terminal efficiency, and therefore competitiveness [42].

3.5. Introduction to digital twins

A digital twin is a dynamic digital representation of an object or a system that describes its characteristics and properties as a set of equations [29]. A well designed digital twin depends on accurate modeling of the physical assets' components, interactions, and behavior [62]. According to Pan and Zhang [41], the added value of the model lies in 'automatic data collection, conceptual development, dynamic analysis, problem diagnosis and optimization for smart design, operation, control, and maintenance'. A digital twin includes both the hardware to acquire and process the data and the software to represent and manipulate these data [29]. The quality and breadth of the data largely determine the value of a model, but the development of the Internet of Things (IoT) will be a key source of real-time data in the future. Digital twins are more powerful than regular models because digital data streams connect the physical and digital entities directly. This results in the use of historical and real-time data to analyze possible outcomes. An overview of the definition of a digital twin is shown in Figure 3.7.

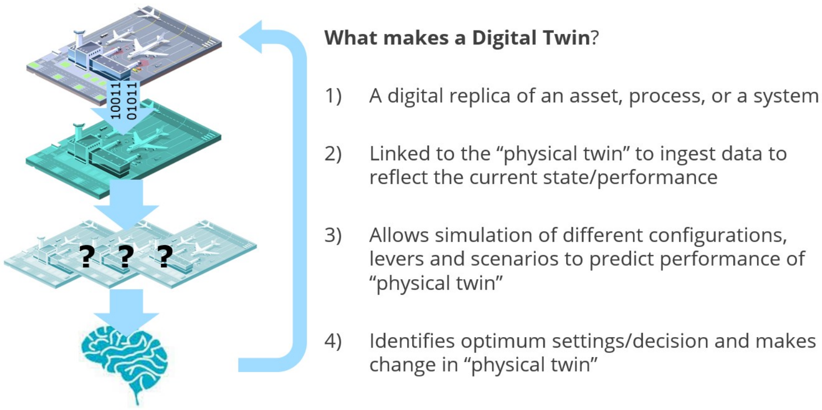


Figure 3.7: An overview of the definition and benefits of a digital twin [10].

A schematic overview of the input and output components of a digital twin is shown in Figure 3.8. The model is relying on the input of historical (data lakes) and real-time (data streams) data, and the mathematical models that describe the processes of the physical entity. Changing situational parameters enable decision-makers to simulate different situations to make the best decision. The benefit of a digital twin is also the ability to continuously calibrate the twin throughout its lifecycle by integrating real-time data. This means that the model can be continuously refined to match reality [29]. The information flows of a digital twin are thus more automated than the flows of a regular digital model, as can be seen in the definition of Hofmann and Branding [18]. The three stages of integration and automation of the data flow between a physical and a digital object are:

- **Digital model:** manual data flow; changes have no impact on the physical system.
- **Digital shadow:** automatic data flow from physical to digital object.
- **Digital twin:** automatic data flow in both directions.

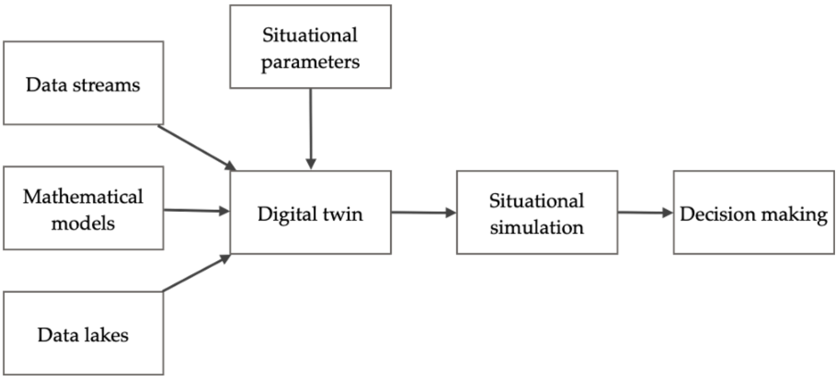


Figure 3.8: A schematic overview of the input and output components of a digital twin [29].

There are several examples of digital twins in the port industry. Royal HaskoningDHV [48] identifies digital twins as an ideal way to identify weaknesses and opportunities in the operation of a container terminal. They could be used to test and redesign container stacking and the potential profitability of installing new facilities. Driven by multiple streams of real-time data and historical databases, it is also an operational planning tool to coordinate and synchronize port operations [30]. It could be an essential foundation for virtual arrival processes and green steaming [61]. The digital twin can test various simulations to speed up loading and unloading and ways to accommodate more vessels. A literature survey by Kizilay and Eliiyi [24] shows that most research articles focus on individual quay and yard problems at container terminals rather than integrated ones. A digital twin can guide current operations with integrated problems, provided that the maritime industry cooperates to standardize data streams and component models. Groups with expertise knowledge, such as vessel designers, crane manufacturers and infrastructure developers, could assist during the development of these standard digital components [29].

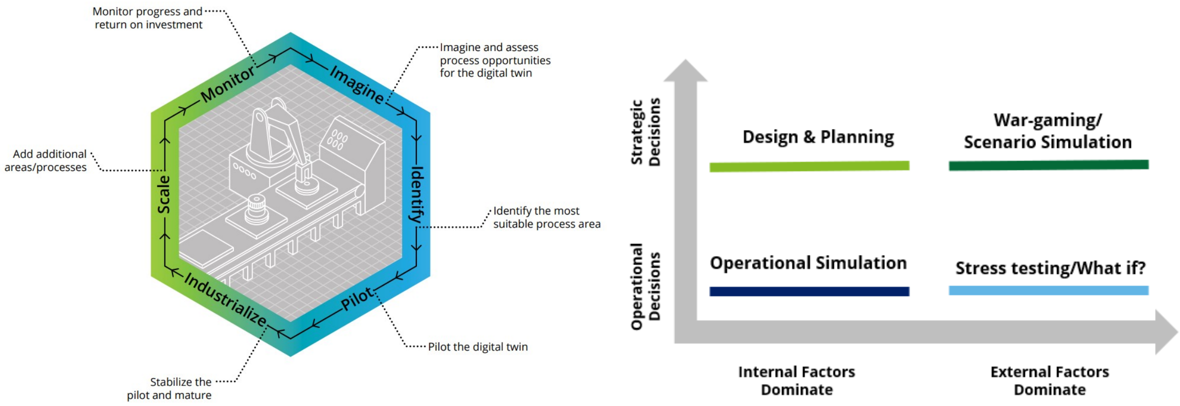
Besides real-time decision-making and the ability to continuously calibrate the digital twin mentioned in Section 3.5, other benefits are mentioned by the port industry. During the conference of Smart Digital Ports of the Future (May 2022, Rotterdam), several port industry experts mentioned:

- **Single point of truth for all parties:** Instead of sharing many emails and documents.
- **Resilience during crises:** The impact on planning can be immediately simulated.
- **Learn from the past:** Understanding root causes when simulating and analyzing past events.
- **Predict the future:** Test business and IT strategies or operational opportunities to explore the impact.
- **Reduce risk:** Simulate the impact of infrastructure upgrades or investment opportunities to increase business case robustness.
- **Less business disruption:** Helps to minimize business disruptions by experimenting digitally instead of in the operations.

3.6. Developing a digital twin

Digital twins are thus an interesting development with large potential benefits to improve operations. However, a digital twin is a custom tool that must be developed for unique processes and characteristics of a physical entity. Niederer et al. [38] state that digital twins at large scale will require a drastic reduction in technical barriers and new workflows for operation. The standardization of data streams and data sources will become important for successfully implementing new digital tools [30], [38]. New workflows in the operation will solve questions about data ownership and responsibilities, but the increased use will also lead to a maturation in expectations and understanding on the added value of digital twins. A better understanding with decreased uncertainty and risks is the key to accelerating and scaling the adoption of digital twins [38]. However, understanding a digital twin starts with the development, as this is important to be aware of the possibilities and potential benefits. According to Parrott and Warshaw [44], there are six general steps to consider when developing a digital twin, which are also shown in Figure 3.9a:

1. **Imagine the possibilities:** Determine the process that benefits the most from having a digital twin and assess the quick wins.
2. **Identify the process:** Determine the pilot configuration with the highest value and the highest chance of success by taking operational, business and organizational change management into account.
3. **Pilot a program:** Start a pilot program using iterative and agile cycles to accelerate learning, manage risk proactively, and maximize return on initial investments.
4. **Industrialize the process:** Industrialize the development and deployment process using established tools, while implementing the digital twin in the enterprise.
5. **Scale the twin:** Identify opportunities to scale the digital twin and use lessons learned and developed processes from the pilot.
6. **Monitor and measure:** Monitoring the twin is important to objectively measure the delivered value and to be able to make changes iteratively for the best outcome.



(a) Six important steps during the cycle of developing a digital twin [44]. **(b)** Different possibilities for the scope of a digital twin [10].

Figure 3.9: An overview of six important steps for developing a digital twin and the different possibilities for its scope.

Especially the first step of determining the modelled process and configuration of the digital twin must be done carefully. This scope is important, as it determines the physical entity that will be modelled and thus establishes the boundary between the physical system and its surrounding environment. The balance between the appropriate level of detail and minimizing complexity is an important result of the scope. More detail results in a higher quality of the simulations, but makes the model more complex and costly to develop [59]. The structure and mathematical model of the digital twin also depends on the determined goal and scope. As can be seen in Figure 3.9b, there are four main areas depending on which factors are dominant (internal or external) and which decisions must be made (operational or strategic). An overlap of the goals is possible, but the focus areas give an initial starting point for the discussion about the preferred scope and goal of a digital twin.

Several definitions of IT systems and data exist and to properly understand the differences, an overview of the definitions is given below:

- **Application Programming Interface (API):** a piece of software that enables communication between two applications [16].
- **Backend:** Refers to the server, program, and database that operate in the background to provide the user with information [8].
- **Frontend:** Refers to the user interface and consists of user elements, such as menus, pages, links, images, etc. [8].
- **Data governance:** a responsible method of managing data at all stages of its life, from acquisition and use to disposal [16].

- **Data lake:** Large amounts of structured, semistructured, and unstructured data can be stored, processed, and secured using a data lake, which is a centralized repository. It can process any type of data, regardless of its variety or magnitude, and save them in their original format [16].

3.7. Scaling digital innovations

Developing a digital twin can have great benefits to improve operations, as discussed in previous chapters. However, once the tool has been developed, it is difficult or even impossible to use the exact same digital twin at other organizations or locations. In addition to the technical challenge of making changes to the model depending on the unique processes and characteristics of the terminal, strategic and operational challenges arise as well.

The fast-developing technology could result in a lack of basic knowledge in organizations, leading to missed business opportunities or unrealistic expectations. The importance of a clear strategy aligned with clear business goals is highlighted before in Section 3.4, however, many organizations still lack one or seem to fail. Moreover, digitalization of organizations demands a new leadership approach due to its data-driven nature. Traditional management based on experience and expertise is becoming less relevant, since decision-making is increasingly relying on digital tools [27]. Therefore, research needs to be done on scaling innovations to achieve the greatest benefits of digital twins.

First, a definition of scaling must be established. Kuguoglu, Voort, and Janssen [27] wrote an interesting article on scaling Artificial Intelligence of Things (AIoT) initiatives. Although digital twins are slightly different, scaling strategies are comparable. The scaling of digital innovations is defined as “the industrialization of digital solutions whereby, following the proof-of-concept and the pilot experiments, these technologies are rolled out into industrial practices on a large scale”. Moore, Riddell, and Vocisano [36] go a step further and make a distinction between three different types of scaling, namely scaling out, scaling up and scaling deep. Scaling deep is about transformations in values, relationships and cultural practices that support durable change. This type of scaling will be excluded from this report, however, since cultural changes are not included in the scope of the research. Scaling out is defined as an attempt of an organization to affect more people and ”cover a larger geographic area through replication and diffusion”. Scaling up is when ”an organization aims to affect everybody who is in need of the innovation”. In the context of container terminals, scaling out can be seen as widening the scope of the digital twin, or including more use cases. Scaling up means including more terminals or ports in the digital twin, while the simulated processes and goal remains the same.

3.7.1. Factors affecting scale up

Several factors have influence on the success of scaling innovations. The study of Kuguoglu, Voort, and Janssen [27] describe how factors for scaling up can be subdivided into five main categories, shown in Figure 3.10:

- **Strategy:** Competing investment opportunities and technology partners.
- **Data:** Data quality and availability, data governance, data security and privacy, and data analytics capabilities.
- **People & organization:** Support (or resistance) from senior management and users, skilled staff and expertise, technology knowledge, organizational culture and agility, organizational structure, and alignment between departments.
- **Process:** Perceived business benefits, business models and use cases, and operating models.
- **Technology:** ICT capabilities and infrastructure, integration with other systems, and technology characteristics.

The five categories provide a framework for factors that affect scaling, but the time dependence of such factors is not included. However, the study of Kuguoglu, Voort, and Janssen [27] describes in which phases the factors are most important. The strategic factors seem to be important in the early stages of scale-up, as companies need to evaluate the business case of projects before their launch.

Assuring data quality and availability is also important early in the process, as a lack of good data tends to hinder scaling efforts. The support and willingness of senior management, together with sponsorship of technology, is critical throughout the project to drive success. This mainly results from the high costs and large amount of resources that are necessary for transformation projects. Another finding is that digitalization projects face many organizational and personnel barriers once the project starts to scale. Organizational factors, such as culture, agility, structure, and alignment between different organizational units, become important later in the process when scaling starts to affect other organizational units. Furthermore, organizations need to ensure the right skills for users of the digital tool and that the users are ready to adopt it in the operations as they scale. Lastly, many challenges related to the integration of operational systems and existing ICT infrastructure occur when companies try to scale up their pilot projects [27].

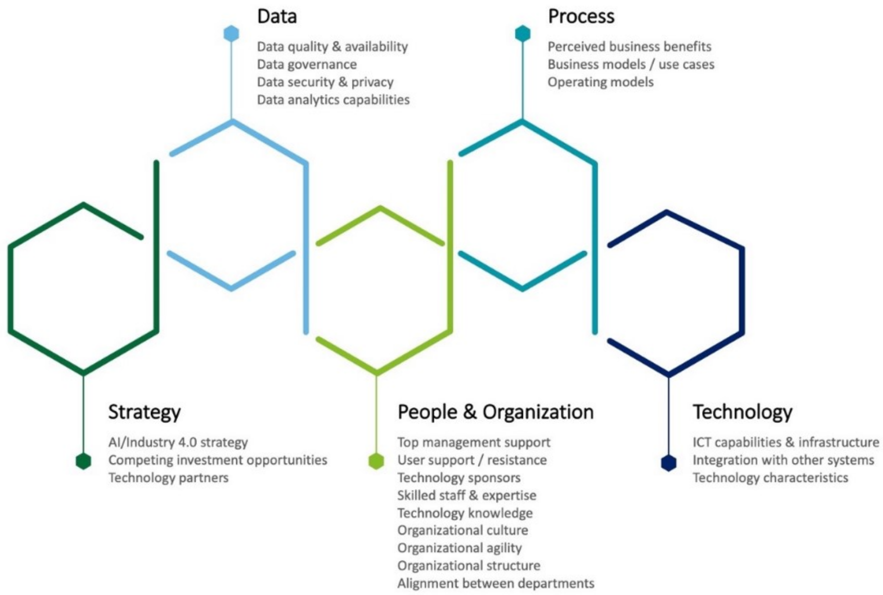


Figure 3.10: An overview of the five categories for factors that affect scaling innovations [27].

3.7.2. Scaling-Up Strategies

During the research of Kuguoglu, Voort, and Janssen [27], three main strategies for scaling-up have emerged: proof-of-value over proof-of-concept, treating and managing data as a key asset, and a top-down and bottom-up approach.

Proof-of-value

Pilots are often technology-led implementations driven by 'cool' emerging technologies rather than solid business cases. Despite using new technology can be tempting, the generated value should always be higher than the development and implementation costs to maintain a healthy organization. Kuguoglu, Voort, and Janssen suggest turning this logic upside down by embracing an alternative approach that identifies the business value first: proof-of-value. Organizations should focus on business value over technology, therefore linking the metrics of success with the proof-of-value, including, for example, overall equipment effectiveness, end-user statistics, and reduction in maintenance costs or machinery downtimes. After identifying the high-value use cases and proving their feasibility, organizations should focus on a limited set of use cases without fragmenting efforts and resources. Equally important, the end goal is essentially not only to prove that there is value, but also to deliver it. This ultimately means that some pilots will fail because they either do not deliver meaningful value or are unable to scale. Both options seem to work in the favor of organizations, as it will most likely save them from investing in projects that bring neither value nor scale. Moreover, the study found that organizational learning that occurs during a project is also of value, even if the project fails [27].

Treat and Manage Data as a Key Asset
A relatively simple early action for organizations is to identify what data they have and how this relates to their company. Only then can organizations have a good understanding of what they have, and more importantly, what they need to scale. The research recommends that organizations invest in robust data practices for collecting, storing, organizing, and maintaining such large volumes of data coming from a variety of sources, even before starting digitalization initiatives. Establishing solid data governance is not likely to be a one-off attempt, however. It also calls for effective operating models for the continuous generation and consumption of data when companies implement initiatives into production. Generating, transferring, storing, and processing such volumes of data through a network of inter-connected devices demand extra attention from organizations to ensure privacy and security. Addressing concerns about cyber security as early as possible is likely to help organizations avoid unanticipated setbacks due to data privacy and security issues. Also, organizations must clarify the data ownership throughout the organization to ensure accountable, responsible, and secure use of data to create business value as well as mitigate the potential risks [27].

The Importance of Commitment at All Levels
Transformations are more likely to scale up when people embrace them. No matter how strategically senior executives think to create value, those on the ground floor are the ones who can drive actual change and deliver value. Scaling up requires multi-disciplinary teams throughout organizations, supported by the executive sponsorship that ensures alignment with C-level strategy. Therefore, the study encourages companies to break down such silos, and form multi-disciplinary and cross-departmental teams to effectuate the transformation. As the study shows, people are less likely to fear such digital transformations when organizations clearly show the real value of tools and address their concerns about job replacement. Therefore, so-called “automation anxiety” still exists but seems evitable. The study suggests establishing clear communication with the workers and train them so as to ease their adaptation to the new tools and techniques. After all, transformations are not only about upgrading assets or processes; they are perhaps even more about enabling change and upskilling people to adapt to new ways of working. In short, support from both sides, top-down and bottom-up, is essential.

3.7.3. Digital transformation

The aim of the path shown in Figure 3.11 is to find the opportunities at the intersections and use them without trying to get it perfect. In the imagine phase, the inspiration process starts here and it is necessary to think big. The organization’s digital vision is defined by evaluating the initial client situation, including challenges, driving forces, and opportunities. The digital implications and ties to the corporate strategy will be assessed. Evaluating the organizational and configurational changes required helps prioritize what digital ambitions (and technologies) should become a reality. Next, the deliver phase will lay the foundation for the digital leadership and culture, as well as digital vision. This phase comprises the implementation of the (digital) target operating model, where we look at the governance, technologies, insights, processes and capabilities of the organization. In this phase, we work with an iterative concept refinement, prototyping, test and planning. The ideas, designs and technologies are tested against customer and stakeholder capabilities resulting in a clear set of commitments. An agile plan is developed. The key is to start small in this phase, and to scale fast in the next phase, the Run phase. In the Run phase, the agile plans developed in the Deliver phase create business impact. Activities on the roadmap are executed and quick wins are delivered [9].

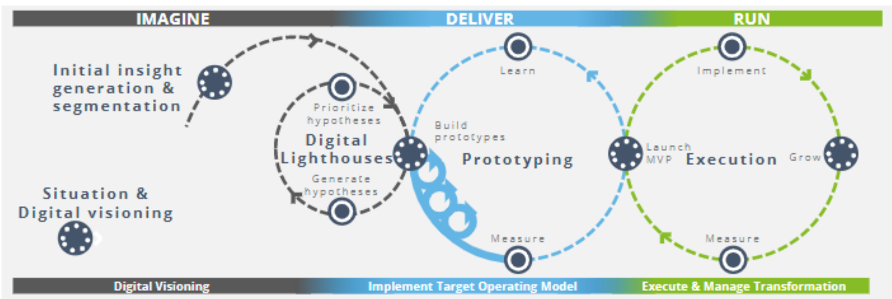


Figure 3.11: The digital transformation approach [9].

3.8. Barriers & drivers of scaling digital twins

Some of the barriers to digitalization and scale-up are a lack of comprehensive strategy, a limited pool of skilled workers and the ability to attract one, training and retaining talent, lack of standardization, lack of financial resources, cyber security and risks, integration with other technologies and legacy systems, siloed organizational structure and lack of cooperation between departments, organizational resistance to change and lack of organizational support [27].

3.8.1. Barriers in the port industry

The findings of Sarkar and Shankar [52] reveal some of the areas that need attention to restrict the barriers of port logistics. For emerging economies, efforts should be directed towards increasing funds for infrastructure and modern technologies, improving education quality, developing common standards for national and international operations, good collaboration between partners, and providing skill development training to workers in advanced technologies. It will help the government develop policies that can mitigate the lack of a quality education system, provide financial support for quality infrastructure, and reduce the risks that stakeholders lose money. Barriers to successful digital transformation according to Tijan et al. [58] are:

- Focus on technology only, instead of paying attention to a clear vision and collaboration with stakeholders.
- High implementation costs and risks and a lack of clarity about the pay-off from the investments.
- Lack of digital skills and qualified labour force.
- Employees' and managers' resistance to change as well as a lack of motivation.
- Decreased levels of cyber security.
- The existence of independent information systems and lack of standards.

3.8.2. Barriers in the use of data

Though largely unforeseen, most organizations are paralyzed by the availability of large amounts of data having various qualities when they have limited data analytics capabilities, which includes people with data skills and expertise, and IT infrastructure suitable for AI [27].

As definitions are still not consistently applied by ports and shipping companies, clear data can prevent confusion and streamline planning. It is important to develop standards that are applied and maintained by dedicated organizations. In addition, data ownership is important to prevent parties distrusting data. Data can become corrupt or outdated when multiple parties interchange data, and it is not maintained by an owner. Depending on the port authority, nautical services and businesses located in a port, clear agreements should be made who is responsible for the data, and who benefits from using it. Data can be communicated to multiple receivers, and while not all of them need to act, some benefit for their own purposes [21] [57].

Port operations still rely on manually obtained information from all kinds of sources. There is a huge dependency on the manual follow-up of any unforeseen changes to delivered services. The absence of a digital way of exchanging the data acts as a substantial barrier. To overcome this barrier, web-based community systems can facilitate information exchange using existing communication networks. Some of these digital solutions can accommodate potentially all stakeholders in the port to connect and provide updates on their service completion times, which in turn automatically calculate estimated departure times. Port community systems may be in a good position to facilitate this [21].

Unfortunately, most port actors are not interested in sharing data and information. This is partly due to concerns that third parties could deduce commercially sensitive information (e.g. berthing windows, terminal productivity, type/location of commodities loaded and discharged, and which ships receive priority berth at which terminals) [21]. Data sharing could be enhanced through collaborative or regulatory mechanisms, such as drafting a code of conduct, establishing contracts, port regulations or licenses to operate, but a level playing field should always be ensured. Incentives are also a solution, as a clear understanding and visualization of what the different events exactly mean and how they improve the port call can boost data sharing. Sharing information will be easier if all stakeholders involved benefit from the exchange by for example, better resource planning [21].

3.8.3. Drivers

Drivers are important for encouraging the digital transformation. Several are identified in literature [58]:

- New and emerging technologies, changing customer behaviors and expectations, and a competitive environment.
- Regulatory requirements, for example the stricter IMO requirements for sustainability [21].
- Processing large amounts of data, streamlining operations and data transparency.

Success factors may be explained as elements required for achieving desired goals. Factors for a successful digital transformation are [58]:

- Actively shaping future strategies with a clear vision.
- New business models with new and dynamic capabilities.
- Engagement of managers and employees and investing in employee and manager knowledge.
- Cultural readiness for changes and an organization's willingness to take risks and make decisions under uncertainty.
- Understand stakeholder needs and their expectations, and invest in appropriate technologies.
- Support from government and policy-makers.

3.9. Informational interviews

After the literature review, there were some questions still unanswered or unclear. A qualitative research technique known as an interview was chosen to gather more knowledge from practitioners. The type of the interviews was semi-structured, as was described in Section 2.3.2. The questions that have been drawn result from the literature study described in previous sections of this chapter. Some questions are gaps in the literature, others are a need for clarification or confirmation from practitioners. Not all questions were asked to all interviewees, but a selection was made based on their expertise. The interviewees have different backgrounds, expertise, roles and teams to allow different input and opinions. See Appendix A for the transcripts of the interviews and information about the interviewees.

3.9.1. Container terminals and operational planning

Three questions about container terminals and operational planning are important to mention:

- What are the advantages of standardization?

The duration of operational activities must be known to create a reliable planning of how long each activity will take. Many processes are still manual, especially with quay cranes, and result in different handling times due to variation in the skills of operators. Terminal managers try to eliminate this variation by setting standard times (an x number of seconds per container move) and use this to determine whether an operator needs more training to work faster [A.3].

- What are future (digital) trends of container terminals?

Three major trends in the global container industry are important. Terminal operators have always been under heavy pressure from the shipping lines and they push terminals to be as cheap and efficient as possible with their power over the entire logistics chain. As a result, operations have to become more sustainable, because this is more efficient and is driven by regulations. Green regulations are mainly upcoming in Europe, North America and Asia. The result is better berth planning, because ships berth on the quayside as short as possible to work more efficiently and use greener fuels or electrification where possible. The last trend in Western Europe is that security is becoming more important. Customs are increasing their activities to prevent illegal goods from entering the country. All three trends are related to digitalization. Furthermore, the efficiency of the terminal itself can be improved by using digital twins. You can simulate different (optimization) scenarios without affecting your operations [A.4].

- How does the current (yard/berth) berth planning looks like?

Regular contracts are based on a proforma schedule agreed by terminals and shipping companies and contain a berth window (e.g. 26 hours) with an agreed number of moves (e.g. 3000 containers). Based on this, the terminal calculates how many cranes and assets are needed to meet the agreements. If there are delays in the planning, the berth windows have to be shifted. At hub terminals, it is often a matter of negotiating with one party, because shipowners usually have agreements with their 'own' terminal. At gateway terminals, several shipping companies are involved, so the original schedule is leading. Sometimes the port authority steps in: "it does not matter which proforma schedule there is; for our services, it is 'first come, first serve'." This is often the case with narrow or busy waterways. Increasing the reliability of the schedule is very difficult. Weather is the main cause of delays, but three weeks in advance there is no weather forecast. In addition, vessel breakdown and blockage of the waterways occur, but these are mainly calamities [A.3].

3.9.2. Digital twins

Two questions about digital twins are important to mention in this section:

- What is the scope of a digital twin for container terminals?

The scope of a digital twin could be very wide, but is the most important to determine. The problem can be different for every terminal, for example, the yard size or uncertainty of arriving vessels. The particular pain point can be simulated with the digital twin and determine the best solution [A.2]. This is especially useful for trade-offs / discussions, because a digital twin helps to have a single 'truth'. Planners can have different levels of experience, so decisions are different per shift, which has a big impact on the overall planning. A digital twin helps to have a standard approach to planning based on (complex) data, instead of feeling/experience [A.3].

- Which input/output is required for a digital twin?

The berth plan and the storage yard plan serve as inputs to the digital twin. Time distributions for each discharge and loading activity can be determined using calculations based on historical data. The processes of the digital twin are calibrated using the mean of these distributions. At the start and end of the simulation for each service, the ship's berthing and departure procedures are likewise modelled. Sensors are not involved, because the DT takes input from the Terminal Operating System (TOS) and the berth plan. The difference between container terminals is data: different data, data models, data streams. The output is based on a simulation engine. Parameters, such as the prioritization and number of equipment (AGVs, cranes), can be changed to simulate the impact on planning: "Can I reduce operational costs by reducing the number of equipment, and still be able to handle the vessel in time? Can I use equipment for housekeeping instead of loading the current vessel?" [A.1] [A.3].

3.9.3. Scaling digital twins

Four questions about scaling digital twins are important to mention in this section:

- What is the current approach of implementing/scaling digital twins?

A project starts with a Proof of Concept (PoC) and moves on to a Minimum Viable Product (MVP). Typically a model is cloud-based, so interactions are possible through a web-interface. The human side is very important. Turning a DT into something a human can tangibly interact with is a huge part of the work. Besides adding extra details to the model, the stuff on the edges are the big considerations when scaling (users, data, storage, display of results). Ultimately, users have the best idea how to use the tool. Managers have the best view of the questions the model should answer. Collecting this information will be done through interviews, whiteboarding sessions, and concepts [A.2].

- What is necessary for scaling digital twins across terminals?

An important thing is to get good data (availability/standardization). Developing good interfaces are key to get the data available in the cloud, so that the same model can be used in the next terminal. Maintaining the digital twin model is a result of developing the modeling capability of the organization to really understand the tool. Another terminal has new parameters/factors, but hiring an external party for each change is not sustainable for business operations [A.3].

- What is the ideal timeline & sequence for scaling digital twins?

The interviewees state that it is difficult to determine an exact timeline for scaling digital twins, as the duration of the project greatly depends on the budget and resources the organization has to develop the tool. It is driven by business requirements and satisfies what the company wants to achieve. It also depends on the number and type of terminals an organization has. For example, are trains and external trucks included in the model of a gateway terminal? However, if a basic digital twin model is available, approximately 12 weeks are necessary to modify the digital twin for another terminal. The timeline should reduce at new projects, as more experience is gained. The first project is difficult, but it improves over time by tackling challenges and using lessons learned [A.1] [A.2] [A.4]. Aspects that drive the business or cause major disruptions need to be addressed first, because a system is as good as its weakest points. The sequence is tricky because it is not just about giving someone a tool. It is also about them accepting and thinking about how they use it to help their client decisions [A.2]. When looking for a new terminal where a digital twin can be implemented, it is easier to scale to the same type of terminal. While automated terminals may have more accessible data, for now, copying to the same type is easiest. Volume also plays a role; ”How important is the hub?” The higher the throughput, the greater on cost savings [A.3].

- What are lessons learned of digitalization projects?

The biggest mistake is a ’big bang’ implementation, where the digital twin is rolled out at all terminals at once. It is best to start with a specific pilot, preferably in ports that are already running well. If the DT has advantages in well-operating ports, it might help even more in other ports. Also use the lessons learned from pilot projects and use these to adapt your systems. It is important to demonstrate the added value to the people who make decisions and to have a clear perception with the project team [A.4]. A barrier to scaling digital twins is the unwillingness of people to do things differently than in all the years before. There is some change among younger people, but it is still very slow. Another barrier is making it scalable to multiple types of terminals [A.4].

Closing words of Chapter 3

Much new knowledge has been gained by performing the literature review. The context of the research is familiar, by investigating container terminals and the port industry. Definitions and abbreviations such as hubs, gateways, RTGCs and AGVs are no longer strange to the author, so discussions can be held on a level playing field with practitioners. In addition, the different types of operational planning and the consequences of disruptions for container terminals are investigated. The (digital) trends of the port industry were investigated by reading news articles to become up to date with the latest developments of container terminals. During interviews with experts in the terminal industry, more practical, focused knowledge was gained, and this was illustrated with interesting examples. Furthermore, findings from literature and news articles were checked with reality.

In addition to container terminals, a lot of attention has been paid to digital twins and scaling of these innovative tools. First, the definition, advantages, and components of a digital twin have been investigated, together with the important steps for the development of a twin. Once the digital twin has been developed, it should also be possible to scale to other terminals. Several factors and strategies for scaling are investigated, and are compared to the scaling strategies of practitioners. The barriers and drivers discovered to scale digital twins at container terminals are also checked during the interviews and practical insights were added to the findings.

As both theoretical and practical knowledge collected now should be transformed into a deliverable, Chapter 4 will describe how the findings will be translated into criteria and eventually the roadmap.

4

Designing the roadmap

Once the required knowledge is collected by conducting a literature review and interviews in Chapter 3, the design of the roadmap can begin. First, the assumptions and target audience are defined in Section 4.1. Based on the findings of Chapter 3, the criteria for the roadmap are established in Section 4.2. The roadmap template, which is the first step of the design, is described in Section 4.3 and the actual roadmap design in Section 4.4. Hereafter, the first roadmap is validated by conducting interviews in Section 4.5 to gather feedback and input for improvements. These improvements are then described in Section 4.6, which leads to the final design in Section 4.7.

4.1. Setting the context of the roadmap

The target audience of the roadmap is very important to consider during the design. It will define the focus of the activities and steps, and acts as a starting point for the assumptions and knowledge of the users. The support and awareness of people is important for the success of a roadmap. Implementing digital twins is more than developing technology, as people should accept and use the tool during their work. During real projects, the roadmap can also change due to legal obligations, changing market conditions and cyber threats. Therefore, enough flexibility must be included, with data being the decisive factor during decisions [A.5].

Since this roadmap describes the scaling of digital twins for container terminals, several assumptions about the target audience are made. First, the business case for developing and scaling digital twins is determined to be viable and approved by the organization. A Proof of Concept proved that a digital twin is the most appropriate tool with the ability to solve a specific set of problems or improve the operation. Benefits and characteristics of digital twins are described in Section 3.5, and are among others 'optimization for smart design, operation, control, and maintenance' [41], and testing and redesigning container stacking [48]. The organization has executed a problem analysis and drafted a hypothesis that the digital twin can improve its operation or solve the problem.

The roadmap of this report is meant for senior management of global container terminals that have influence on the (digital) strategy of the company. The roadmap is meant for organizations that have multiple container terminals, since this scaling strategy focuses on scaling up to multiple locations instead of scaling out to several processes on the same terminal. The digital twin is intended for the planners of a container terminal (users). Planners are involved as a subject matter expert for different terminals to advise on the unique challenges of operations [A.1]. Important questions are:

- Can we use the digital twin operationally for planning?
- Can we use the digital twin to test a new flow at a container terminal?
- How does the simulation engine work and what are the mechanics behind that?
- What is required to develop the digital twin and what are the necessary resources?

4.2. Establishing criteria for the roadmap

After an extensive literature review and conducting interviews, the main findings can be combined into criteria for the roadmap. The criteria will be established for different purposes and will be used to review the roadmap afterwards. A distinction between four criteria can be made:

- Criteria for the **digital twin**
- Criteria for **developing** the digital twin
- Criteria for **using** the digital twin
- Criteria for **scaling the use** of the digital twin

As some criteria are more important than others, they will be prioritized using the MoSCoW method [43] described in Section 2.4: **M**ust have, **S**hould have, **C**ould have and **W**ant to have.

Criteria for the digital twin:

- **M:** The information technologies (IT) of the container terminal must be digitally integrated to streamline and automate procedures. Data standards and greater compatibility of digital systems enable this integration [21], [57].
- **S:** The digital twin should be developed in the cloud to allow interactions through a web interface for employees located off-site [A.2].
- **C:** There could be a possibility to (manually) incorporate (external) disruptions into the model (weather, congestion, mechanical failures) [A.1].

Criteria for developing the digital twin:

- **M:** Terminal operational processes must be standardized to determine a reliable duration of an activity, as it is an input to simulate the planning of the berth and yard. Deviations from standard processes are measured during operations and must be improved [A.3].
- **M:** Pay attention to business culture and how users want to use the tool. Enabling the right interactions between users and the system to operate the digital twin is important [A.2].
- **M:** System integration and interoperability are important to ensure a smooth operation of IT systems and the digital twin. Update current ICT systems and IT infrastructure if needed and incorporate cybersecurity to prepare for the use of the twin.
- **S:** Make clear agreements on data governance from the beginning (data ownership - safe sharing of data) [27] [A.1] [A.5].

Criteria for using the digital twin:

- **M:** Clearly show the real value of the digital twin and address the concerns of users about job replacement while improving the company culture (work experience, collaborative environment, staff motivation, etc.) [27].
- **M:** Establish clear communication with the users and train them to facilitate their adaptation to the new tools and techniques. Develop the workforce by increasing knowledge with relevant training and using the right tools [27].
- **M:** Ensure robust data practices for collecting, storing, organizing, and maintaining large volumes of data from different sources. Operators must provide good data as input for the DT.

Criteria for scaling the use of the digital twin:

- **M:** Develop a clear digital strategy with clear business goals to align people, teams, and companies involved in the innovation process. Relationships and collaboration must be redefined, and new competencies must be developed by experimenting. Involve all stakeholders of the organization to create support [9] [27] [55].
- **M:** Ensure support from senior management and users, skilled staff with expertise and knowledge of technology, and an open organizational culture and structure with alignment between departments. Support from both sides, top-down and bottom-up, is essential. Therefore, multidisciplinary and cross-departmental teams are necessary to implement the transformation, supported by management that ensures alignment with the strategy [27].

- **M:** Standardization and harmonization of processes and definitions to ensure that everyone is at the same (semantic) level. Multiple parties, such as Digital Container Shipping Association [11], International Maritime Organization [21] and Terminal Industry Committee 4.0 [57], are developing industry-wide standards which must be used.
- **S:** Ensure a sufficient level of modeling capability of the organization to maintain and develop the digital twin in-house. It is important to be independent of other companies and to be able to change it for new requirements [A.3].

4.3. Roadmap template

The design of the roadmap template can begin after the criteria for the roadmap are established. The method thereof is described in Section 2.5 and according to Simonse [53], a roadmap consist of phases (the timeline) and themes (the different topics).

4.3.1. Phases of the roadmap

Establishing the different phases of the roadmap is an important aspect of designing the roadmap template. Four important goals of the criteria are mentioned in Section 4.2 and these could be suitable for the timeline of the roadmap. However, the criteria for the digital twin itself are less relevant for a roadmap, because the twin is already the direct object of the roadmap. The other three remain a possibility for the phases (developing - using - scaling the use). Another option that arose is an 'exponential' timeline (for example, 12 weeks – 12 months – 12 quarters). But the timeline of the projects still depends on many factors (available budget & resources [A.1]), so it could be difficult to establish three phases based on an exponential timeline for the roadmap. The last timeline idea is based on three phases of scaling projects (see Section 3.7), namely 'pilot – scale up – scale out'. Scale up is going from a successful pilot to scaling up the twin to multiple terminals, but with the same scope. The last step is the ideal situation where the digital twins form a network with all the terminals and include more processes and external stakeholders.

Eventually, the three phases of develop, use and scale the use are the most appropriate, as establishing an exact timeline is difficult. Also, the roadmap can be used for more (custom) digital twin projects if phases are used with activities (as develop, use and scale the use), instead of project phases (pilot, scale up and scale out), since not all projects include widening the scope. So, the three phases are:

1. **Developing** the digital twin.
2. **Using** the digital twin.
3. **Scaling the use** of the digital twin.

4.3.2. Themes of the roadmap

The themes can be categorized in different ways. A first possibility is to make a distinction between organization (users, management, operations and strategy) and resources (data, hardware and time/money). A second possibility is a distinction between people (users, decision-makers and product owners), business model (operations and strategy), technology (data, hardware and software) and resources (time and money). However, the framework that is most commonly used in organizations is the People, Process and Technology (PPT) framework [45]. This method aims at providing insight into the three most important aspects of process improvement. First mentioned are people, as people are the most important assets of a company and they are involved in almost all processes. Second, it is crucial to examine the process itself in order to have an efficient operation, so waste can be identified and eliminated throughout the process. Lastly, the tools and methods used to communicate and streamline tasks are called technology. People use technology to facilitate procedures and keep them running smoothly. Therefore, logical themes for the roadmap could be based on the PPT framework, so people (key actors), process (operations and strategy) and technology (data, hardware and software). The key actors of the roadmap are the users (planners of the terminal), developers (software engineers) and product owners (management that makes decisions). Furthermore, the three themes also correspond to the three scaling strategies of Kuguoglu, Voort, and Janssen [27] described in Section 3.7.2. Each strategy has its own focus and is applicable to one of the three themes:

- **People:** ”The importance of commitment at all levels”
  - Users *(planners - use the technology)*
  - Developers *(software engineers - translate business requirements to technology)*
  - Product owners *(management - determines the business requirements)*
- **Process:** ”Proof-of-value”
  - Operations
  - Strategy
- **Technology:** ”Treat and manage data as a key asset”
  - Data
  - Hardware
  - Software

4.4. Roadmap design

When the roadmap template is determined and all criteria are collected, the roadmap design can begin. First, the steps and activities that are undertaken in the roadmap are identified and divided over the three phases. Hereafter, the responsibility and focus of the steps are assigned to the three themes. Also, the duration of the steps is estimated and the design of the roadmap starts.

4.4.1. Roadmap steps

The interviewees stated that it is difficult to determine an exact timeline for scaling digital twins, as the duration of the project greatly depends on the budget and resources that the organization has to develop the tool. It is driven by business requirements and satisfies what the company wants to achieve. It also depends on the number and type of terminals an organization has. Every phase contains several steps with points of attention and tasks to perform. The logical steps of the roadmap were identified for each of the three phases. The steps are based on the criteria described in Section 4.2 and are completed with findings from literature and interviews. For example, six general steps for developing a digital twin were mentioned by Parrott and Warshaw [44] in Section 3.6. These six steps fall within the three phases mentioned before:

1. **Developing the digital twin**: ”Imagine the possibilities & identify the process”
2. **Using the digital twin**: ”Pilot a program & industrialize the process”
3. **Scaling the use of the digital twin**: ”Scale the twin & monitor and measure”

These steps are complemented and checked to see if important information or focus points are missing. Eventually, thirteen steps are identified and divided into the three phases. See Appendix B for an extensive overview of the research steps, including responsibilities and focus points. The first phase is the development of the digital twin and five important steps are identified in Table 4.1. The second phase is using the digital twin and five important steps are identified in Table 4.2. The last phase is scaling the use of the digital twin, where three important steps are identified. An overview of the steps is shown in Table 4.3.

4.4.2. Roadmap design

The visual design of the roadmap begins when all the steps of the roadmap are determined. For each step, the duration is roughly estimated and it is determined which themes (established in Section 4.3.2; people, process and technology) are applicable. Sometimes, roadmap steps overlap multiple phases when it is relevant for two or three phases. The numbers correspond with the steps mentioned in Section 4.4.1 and Appendix B, where more information is presented for each step. The roadmap presents a chronological order of steps displayed over the three phases and shows which stakeholder, process or technology is applicable during that step. The first version of the roadmap is presented in Figure 4.1.

Table 4.1: Overview of the roadmap steps for phase 1: Developing the digital twin.

Developing the digital twin

Roadmap step	**Description**
1. Select the container terminal which is best suited for the development of a digital twin.	Start with a container terminal with an operational efficiency program. These terminals have a clear analysis of the operations, so a clear idea of where improvements could be made.
2. Identify an area of focus of the terminal where gains could be made and determine quick wins.	The aspects that drive business or cause major disruptions must be addressed first. Organizations must prioritize business value over technology. The main goal is to improve operational efficiency (cost & time). Define the scope of the simulated processes. Start focused (select certain areas where improvements can be made) to be able to improve the model and change the working procedures. In a later phase, the model can be expanded to more processes and stakeholders. Start documenting the exact processes of the operations for the simulation. Also, start collecting, digitalizing and centralizing necessary data. Determine the pilot configuration with the highest value and the highest chance of success by taking operational, business and organizational change management into account.
3. Start developing the digital twin.	Understand the business requirement thoroughly before starting the development, since this determines what should be modelled and why. Make choices for the technical solution, based on performance, scaling, cost and previous investments. Ensure quality data for creating, validating and calibrating the digital twin. Pay attention to business culture and how the organization wants to use the tool, as this is often underestimated. *Additional step in response to validation is described at Section 4.6.*
4. Investigate the current ICT systems and IT infrastructure of the container terminal, and update if necessary to support the digital twin.	System integration and interoperability are important to consider, to enable smooth digital operations and clear communication between companies and departments. Pay extra attention to cybersecurity, as it prevents attacks on system and ensures integrity of the system.
5. Determine the governance control of the twin.	To use and scale the digital twin, a clear governance model is necessary with agreements on responsibilities and scope.

Table 4.2: Overview of the roadmap steps for phase 2: Using the digital twin.

Using the digital twin

Roadmap step	**Description**
6. Clearly communicate and involve all members of the organization.	Communicate the value of tools and address concerns about job replacement from the start of the project. *Additional step in response to validation is described at Section 4.6.*
7. Provide training for the workforce to facilitate their adaptation to the new tools and operation.	Several training purposes are important, where a transition period must be included for users to change their working procedures.
8. Ensure robust data practices for collecting, storing, organizing, and maintaining large volumes of data coming from a variety of sources.	Operators must provide reliable data as input for the digital twin, to be able to make the right decisions. Storing and comparing data records can show deviations between planning and execution, to investigate the cause of deviation and improve operations where necessary.
9. Start a pilot program using iterative and agile cycles to accelerate learning, manage risk proactively and maximize return on investments.	Change the working procedures by implementing the digital twin in the daily operations. Industrialize the development and deployment process using established tools, while implementing the digital twin in the enterprise. *Additional step in response to validation is described at Section 4.6.*
10. Document hiccups and disturbances experienced during the developing and using phases to gather lessons learned to improve future projects.	

Table 4.3: Overview of the roadmap steps for phase 3: Scaling the use of the digital twin.

Scaling the use of the digital twin

Roadmap step	Description
11. Identify opportunities and collect lessons learned, to create a solid strategy for the scaling phase.	Improve the implementation process where necessary, and prepare the digital twin model for adaptations. Determine the quick wins and biggest problems of container terminals, and determine the right order of scaling.
12. Ensure support from senior management and users, skilled staff and expertise, technology knowledge, culture and agility, and alignment between departments.	Form multi-disciplinary and cross-departmental teams to effectuate the transformation, supported by the executive sponsorship that ensures alignment with C-level strategy. Ensure everybody is on the same (semantic) level, so standardization and harmonization of data, definitions and processes are important. Develop a clear digital strategy with clear business goals to align people, teams, and companies involved in the innovation process. Relationships and collaboration must be redefined and new competences should be developed by experimenting. A new mindset of organizations is necessary to share data more freely between departments and companies.
13. Ensure modelling capability of the company, to maintain and upgrade the digital twin inhouse, and to be self-sufficient.	Maintaining the twin by a third party will be too expensive and not sustainable for the company. Integrate the digital twin in the standard architecture of applications.

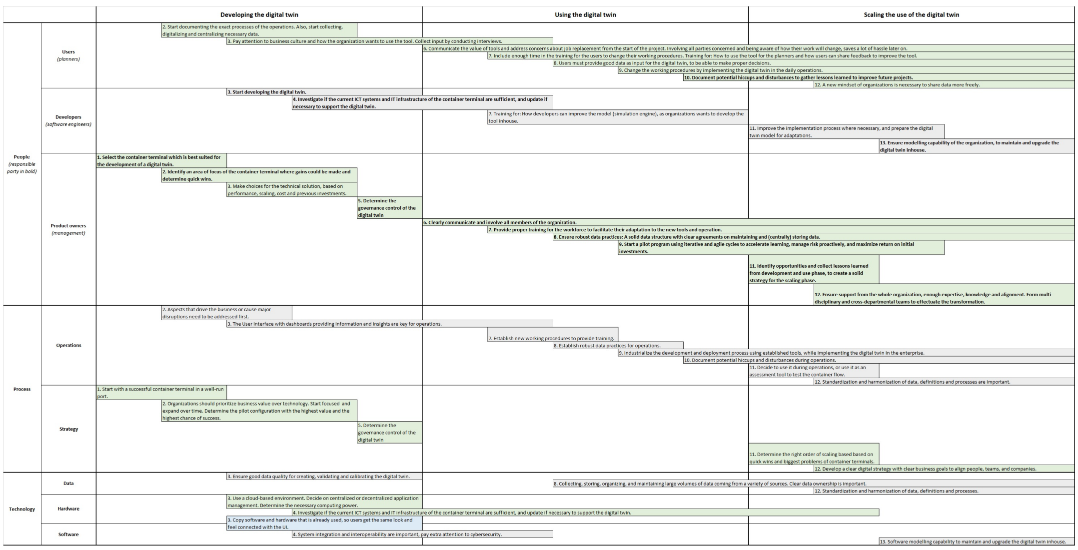


Figure 4.1: The first version of the designed roadmap, which will be validated during interviews.

4.5. Validation interviews

Several interviews with experts from the container terminal industry were conducted to validate the roadmap. After a personal introduction, a short presentation on the thesis and research that led to the roadmap was given. The literature research and the informational interviews were discussed, as well as the criteria that resulted from the research. Hereafter, the roadmap framework was presented, consisting of the three phases and themes that were identified. When the research and roadmap framework was clear to the interviewees, the findings and details could be discussed. The interview transcripts are presented in the interviews A.6 and A.7. The main feedback from the interviewees is:

- It is not entirely clear who the target audience of the roadmap is and in which phase the roadmap is consulted. For example, what are the interests and prior knowledge of the audience? Which decisions have already been made in the process? [A.6].
- Testing the digital twin is missing. Preferably, testing is executed during the development phase and during the use phase to allow multiple iterations of updates [A.6].
- Describe a communication plan on the roadmap, including stakeholder management, for clear communication with different users and stakeholders of the container terminal [A.6] [A.7].
- A scaling project of digital twins starts with drawing up a problem statement and a hypothesis. Where could a digital twin help in the process? The hypothesis must be tested at the end of the implementation phase of the Proof of Concept. A clear definition of the problem with a hypothesis ensures that the organization does not go off track (scope creep) [A.7].
- First, you have to understand the business problem, analyze the processes involved, and control these processes. Only then can the development of data and the digital twin start; without a good business translation, there is no point in having clear data and a digital twin (in other words, business value over technology [27]) [A.7].

Nevertheless, the interviewees were in general positive about the roadmap. A quote from interview A.7: "The validation during the interview was mainly discussing the last details, because this roadmap is already very valuable for container terminals and organizations that have no experience with digital twins and scaling. If there is a roadmap for executing a Proof of Concept (for organisations without this experience), and used in combination with this roadmap for scaling, it could be very valuable and complete. The knowledge gap of this roadmap is that it starts with scaling instead of a PoC, so that would make it complete."

4.6. Improvements of the roadmap

After the first design, the roadmap could be improved based on input from practitioners and knowledge gained during the design. Various improvements of the roadmap were made based on the feedback of the validation interviews:

- Section 4.6.1: Adding six stages of scaling to the roadmap phase 'scaling the use of the digital twin'. This brings more focus to the scaling phase, since this is the focus of this research.
- Section 4.6.2: Information on designing a User Interface with two examples of a UI for a digital twin at container terminals.
- Section 4.6.3: Adding an example of a communication plan [2] [A.7], including more information on stakeholder management [35]. The stakeholder matrix and the example of the communication plan are both included in the sixth roadmap step in the using phase:

    6. *Establish a communication plan and identify important stakeholders.*

- Adding the testing of the digital twin in both the developing and using phase (Step 3 & 9):

    3. *Keep testing the digital twin during development, to check if the digital processes and integration of the system are working as planned.*
    9. *Compare the results of the pilot with the hypothesis drafted to validate the project. Test the digital twin if it operates according to plan and aligns with the hypothesis.*

- Specific feedback on multiple roadmap steps was discussed in interview A.7 and is incorporated in the new roadmap.

4.6.1. Different stages of scaling up

During the design of the roadmap, it was deemed necessary to describe the phase of scaling in more detail. The article by Mosquera-Vásquez et al. [37] describes different stages of scaling, which could be suitable for this roadmap. The authors describe how the majority of scaling up ideas share certain essential elements, which make it possible to understand how to design these procedures. However, there is disagreement about its significance, sufficiency and how it should work together to achieve the suggested goals. The criteria of analysis for the evaluation are these common stages:

1. **Definition of a vision, objectives, and results of scaling up:** a crucial component since it enables not only the transition from idea to implementation, but also the creation of the scaling-up plan. In addition, it facilitates quantification and directs the objectives toward action.
2. **Impact on public policy:** important for the governance and adoption of large-scale innovations.
3. **Networking creation and synergies:** a strong alliance of involved parties is built on shared responsibility, transparency, the creation of a common goal, and meticulous planning of the required resources.
4. **Context analysis:** is included in the process of building the vision of the exit scenario, where the culture and a study of the availability of resources are parameters that must be known beforehand.
5. **Definition of the scaling up route:** objectives, procedures, methods, situations that need to be changed, and tactics for involving stakeholders in the decision-making process for scaling the innovation.
6. **Development of local capacities:** the necessity to enhance social, organizational and individual capacities.
7. **Monitoring:** crucial to monitor progress, as well as adapt the implementation of actions when necessary to achieve the goals.
8. **Financing of the scaling up process:** financial resources are recognized as crucial from the beginning of actions to achieve goals and address any additional requirements that may arise during the scaling up process.

Considering the goal of the roadmap of this report, scaling the use of digital twins at container terminals, six stages can be identified that are most significant. The impact on public policy is not applicable since the use of digital twins only affects terminal operations. Financing the scaling up process is also outside the scope of this report. So, the six stages that remain are added to the final design of Section 4.7.

1. **Definition of a vision, objectives, and results of scaling up:** Management, users and other stakeholders must create a shared vision, where the objectives and results of the scaling process must be integrated. The multiple perspectives and needs facilitate support of the project.
2. **Networking creation and synergies:** The roles of the involved stakeholders must be defined in detail. A roadmap with clear responsibilities and timelines could facilitate this synergy.
3. **Context analysis:** The scaling up process is influenced by the situation of each terminal. The analysis, which must include sociocultural and economic factors, must be present from the planning phase. Finding opportunities or risks is crucial.
4. **Definition of the scaling up route:** The scaling strategy can take different paths with challenges in the organizational and business side.
5. **Development of local capacities:** Development of strategic and operational capabilities is crucial at an early stage of the process, both for users, developers, and product owners, beginning with an examination of the possibilities and limitations that exist in the organization.
6. **Monitoring:** It is necessary to build a system to monitor change within the operations of the terminals and assess if the desired outcomes are being obtained. The information produced must aid in decision making for future scaling projects.

4.6.2. Information on the User interface

The design of the User Interface (UI) was mentioned several times during interviews as very important. If the layout of the digital tool is not logical, users will not easily accept and use it. Also according to literature, the main method for communication between humans and computing systems is the (graphical) UI. Numerous interrelated choices must be made when designing a UI in order to achieve an intuitive system that utilizes the capabilities of the DT to its maximum [39]. Turning a digital twin into something with which a human can tangibly interact is a challenge [A.2]. Users have the best idea how to use the tool, and typically, the managers have the best view on the operational purposes. Collecting this information will be done through interviews, whiteboard sessions, and brainstorming. However, designing the UI is not part of this research. To provide an inspiration for interested people, some examples of UI designed with input from container terminal planners are shown in Figure 4.2 and Figure 4.3.

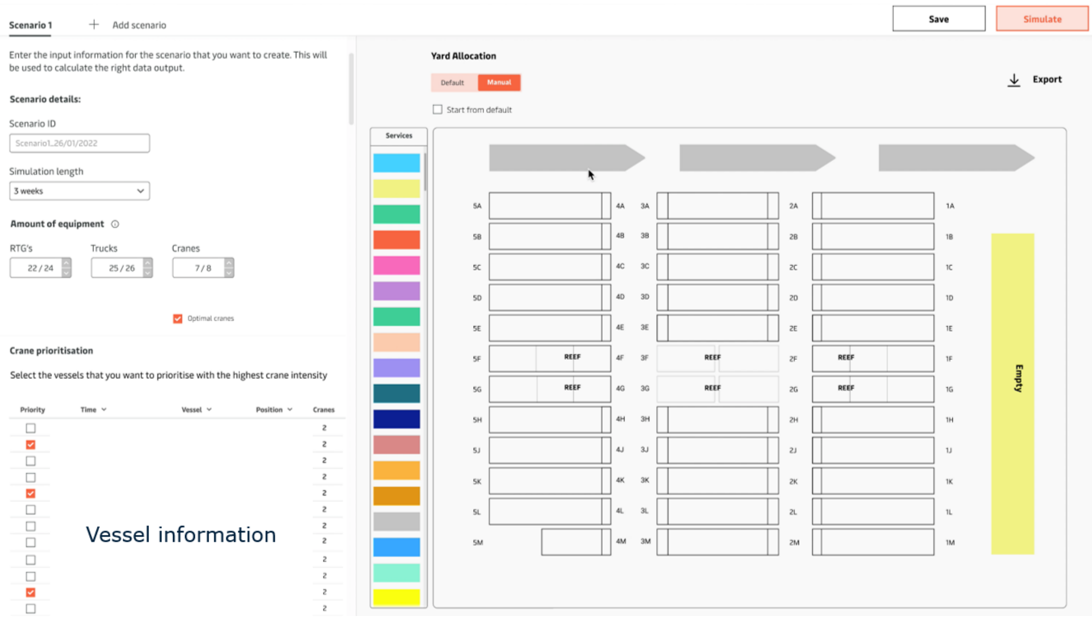


Figure 4.2: A user interface for allocating containers at the storage yard to simulate different scenarios by changing RTGCs, trucks and cranes (Deloitte figure).

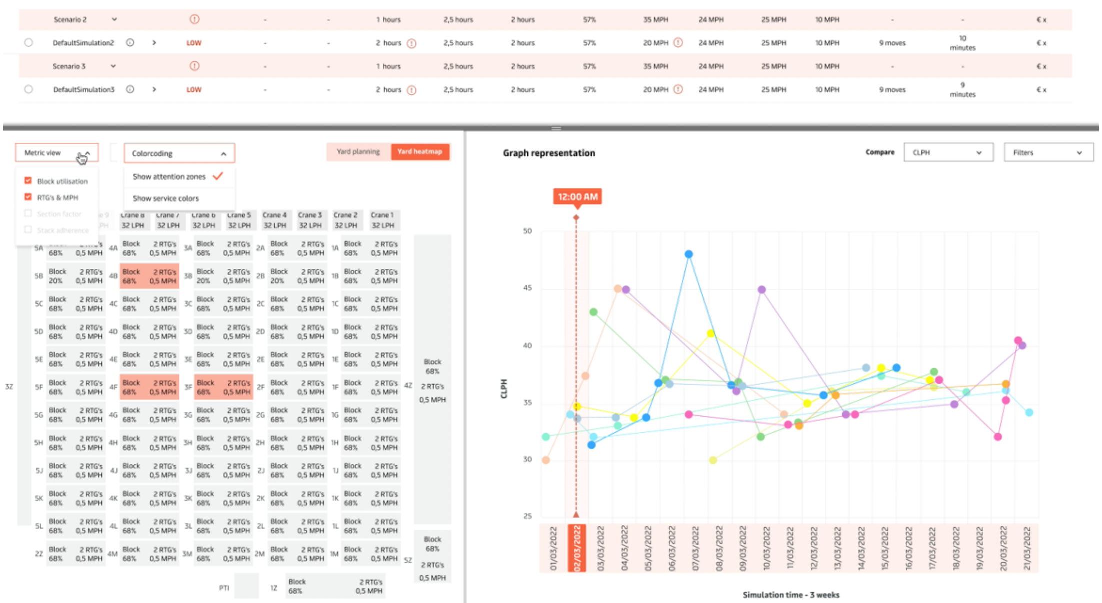


Figure 4.3: A user interface to compare equipment utilization and vessel turnaround times for different scenarios of storage yard planning (Deloitte figure).

4.6.3. Communication with users and stakeholders

A clear communication between the involved people is important for the support of the project [27]. To ensure that the communication between stakeholders and the executives of the project runs smoothly, often a communication plan is drafted [2] [A.7]. However, first all stakeholders involved must be identified to include them in the plan. Besides the product owners, developers and users, also other parties as legislators, port authorities and shipping companies could be involved. A clear overview of all stakeholders must be determined in consultation with the people involved in the project. Once all stakeholders are identified, they should be prioritized according to their power and interest in the project. Some stakeholders require more attention than others to prevent issues, or some stakeholders have more power to influence the project. The power/interest matrix for stakeholders of Mendelow [35] shown in Figure 4.4 could be used to create an overview.

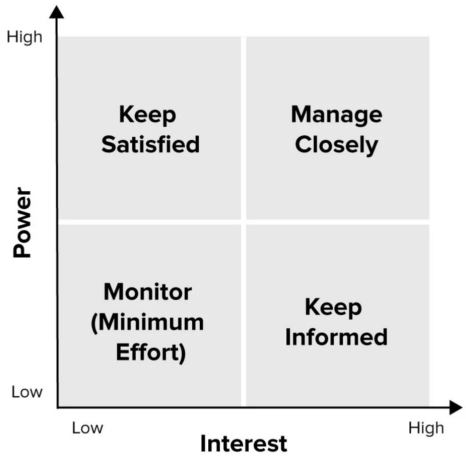


Figure 4.4: A Power/Interest grid for stakeholder prioritization [35].

When stakeholders are identified and prioritized, the communication plan can be developed. The requirements for the plan were mentioned during interview A.7 and confirmed by Asana [2]. A template for such a communication plan can be found in Table 4.4. The plan uses five columns to identify the best strategy for each stakeholder (group). It describes the message to the stakeholder and the purpose of the communication. For example, sharing the progress of the project to management or updating the users involved about the changing working procedures. The communication plan also identifies the frequency and preferred channel of the messages. Lastly, but very important, is the responsible person for writing and sending the message that is described in the plan. The stakeholder matrix and the example of the communication plan are both included in the sixth roadmap step in the using phase.

Table 4.4: A template for establishing a communication plan for a project [2] [A.7]

Stakeholder	Message	Frequency	Channel	Responsibility
Who is the target audience?	What do you communicate?	How often do you communicate?	How do you communicate?	Who will communicate?

4.7. Final design of the roadmap

The final roadmap is based on the roadmap of Section 4.4, but with the improvements discussed in Section 4.6. The thirteen general roadmap steps remained the same, but some steps received additional information or had minor changes. The final steps including all information is presented in Appendix B.

The new roadmap design still exists of three phases, but the scaling phase now has six smaller stages. The themes remained the same (people, process and technology). The estimated duration of every step is equal for the phases 'developing' and 'using', but different for the 'scaling the use' phase. Instead of estimating the duration, it is now determined which stage is applicable for the step. Again, multiple stages could be applicable to one step, so could be presented over multiple phases and stages.

The themes of every step remained the same and the numbers still correspond with the steps mentioned in Section 4.4.1 and Appendix B, where more information is presented for each step. If the steps in the roadmap are bold, it shows which stakeholder (users, developers or product owners) is responsible for that action. The roadmap presents a chronological order of steps displayed in the first two phases and which stage is applicable during the scaling phase. The roadmap also shows which stakeholder, process or technology is applicable during every step. See Figure 4.5 for the new design and Appendix C for a more detailed version of the final roadmap.

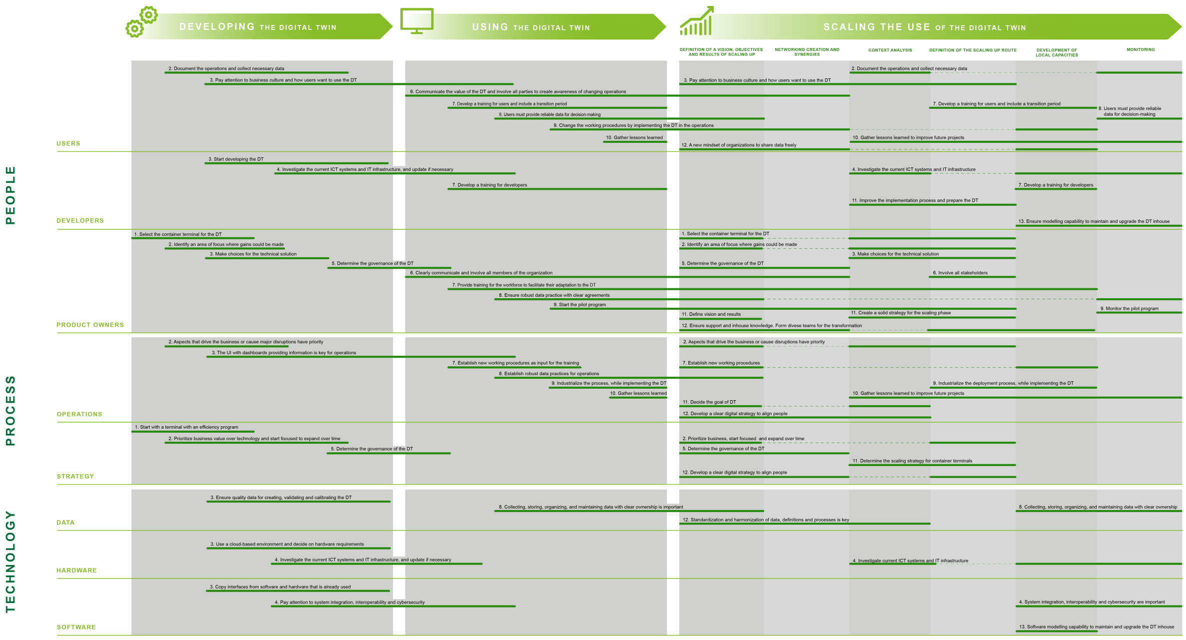


Figure 4.5: The final version of the designed roadmap, with the three phases and three themes.

Closing words of Chapter 4

First, the target audience and assumptions were stated to provide a clear context for the research. Then, criteria were established based on the findings from Chapter 3 and prioritized. These criteria set the stage for the roadmap steps and roadmap that were designed hereafter. The roadmap steps are also cross-referenced with Chapter 3 and supplemented with necessary information. The roadmap template was designed and consisted of three phases and three themes, whereupon the roadmap steps were assigned to one or more phases and themes. This resulted in the first version of the roadmap, which was validated in two interviews with experts from the container terminal industry. These experts provided feedback on various areas, which was used to suggest improvements. After reviewing additional literature, the final phase of the roadmap added six stages for scaling innovation. These stages provide a more detailed overview of the scaling phase and ensure that the focus of the final roadmap is on scaling digital twins. When the design of the roadmap is complete, the next chapters provide a discussion of the results and draw a conclusion about the findings of the research.

5

Discussion

When the design of the roadmap is complete, it is time to discuss the results of the research. First, the verification and validation of the roadmap are discussed in Section 5.1 and the result is compared with the literature in Section 5.2. Hereafter, the limitations of the research are described in Section 5.3 and the methodology is evaluated in Section 5.4.

5.1. Verification & validation of the roadmap

Verification and validation are an important part of a research. It will evaluate whether the result complies with the requirements (verification) and if the result meets the stakeholders' needs (validation).

5.1.1. Verification

The verification is performed by comparing the final design with criteria of the roadmap. The criteria are established in Section 4.2, and the final design is presented in Section 4.7. An overview of the verification is presented in Table 5.1. All criteria are mentioned in the roadmap, except for the possibility to incorporate external disruptions into the digital twin. Therefore, the roadmap is verified and complies with the requirements. Some additional steps are added to the roadmap as a preparation for the next step, or to provide more clarification. To demonstrate; steps 1 and 2 lead to determining the pilot project of a suited container terminal, and thus are crucial first steps before the project can start at all. Step 9 focuses on starting this pilot program and mentions several important aspects of how to do this. Step 10 and 11 both focus on lessons learned, first to document the lessons learned in the use phase, and then to use them in the scaling phase.

5.1.2. Validation

The roadmap was validated during two interviews, whereof the results are discussed in Section 4.5. In general, the interviewees were positive about the roadmap and its content. Especially during the second interview, the value of the roadmap for container terminals was recognised. It was pointed out that a description of the Proof of Concept phase was missing, but if a roadmap exist for this phase or the terminal has experience with it, the roadmap of this research is a good starting point for a scaling project. The interviewees confirmed that important actions, steps and phases are mentioned that guide the product owner during the various phases. Obviously more information must be collected for every unique project environment, since this roadmap is on a strategic level. Furthermore, there was also feedback from the interviewees to improve the roadmap. Feedback was received on the clarity of the assumptions underlying the roadmap which have been addressed accordingly. It is important to clearly mention the scope and the assumptions made for the roadmap, because otherwise it is not clear which knowledge, resources and decision-power is available. Other feedback that is incorporated in the design is described in Section 4.5.

Table 5.1: An overview of the roadmap steps verified against the criteria established in Section 4.2.

Criteria for	Prio	Criteria	Step
Digital twin	M	Digitally integration of IT-systems and data standards	4 & 12
	S	Cloud-based digital twin	3
	C	Possibility to incorporate external disruptions	-
Developing	M	Standardized terminal processes	1 & 12
	M	Business culture and user requirements	3, 6, 7 & 12
	M	System integration and interoperability	4 & 13
	S	Data governance	5
Using	M	Clearly show the real value of the digital twin to users	3 & 6
	M	Establish clear communication and train the workforce	6 & 12
	M	Ensure robust data practices	8
Scaling	M	Develop a clear digital strategy	12
	M	Ensure support from management, users and a skilled staff	12
	M	Standardization and harmonization of processes and definitions	12
	S	Ensure a sufficient level of modeling capability	13

5.2. Comparing findings with the literature

At the end of the research, it is important to relate the results to the existing body of knowledge. The reflection determines the academic value of the findings. The scaling strategy specifically developed in this report for digital twins of container terminals cannot be found in the literature. There are no connections between various scaling strategies for digital twins and the characteristics of container terminals. For example, the advantages and disadvantages of hub and gateway terminals, the level of standardization or the influence of automation are not mentioned by other authors. Therefore, this research fills this knowledge gap, by combining information on developing and scaling digital twins, with insights from the container terminal industry. The roadmap is supported by informational interviews with practitioners to gain practical insight, and is validated during interviews with industry experts.

To dive more into the academic value of the roadmap, it will be further related to the literature. A roadmap consists of multiple phases, depending on the goal and the target audience. Simonse [53] mentioned the three-phase tactical roadmap, which formed the basis for the roadmap developed in this report. However, these phases often have the same emphasis or focus and contain the same level of detail. To emphasize the scaling phase of the roadmap, six separate stages were added to the last phase. The stages for scaling up innovations are identified by Mosquera-Vásquez et al. [37] and are suited to scale the use of a digital twin. The combination of three phases, with the addition of six stages in the last phase for a more detailed timeline, has not been seen before in literature for this purpose. The stages provide more information during the last phase and ensure that the focus of the roadmap is on scaling digital twins. This does not mean that the first two phases are less important; it is the combination that adds the most value. Already during the development and use phase, the roadmap steps build up to the detailed scaling phase. When scaling is considered from the start of the project, it will result in a digital twin that is fit to scale. Often, digital tools are developed and used, and the (preparation for the) scaling phase receives less attention.

So, the roadmap is an addition to the literature in multiple ways. First, the three phases of develop, use and scale the use provide a timeline with each its own focus. The required steps are based on literature and interviews with practitioners to ensure input from terminal operations. This input is important for the adoption of the twin and add value to this research. The six additional stages of the last phase provide more detailed information on scaling. This is of value to container terminal operators, as it gives a better overview of the responsibilities and necessary steps to scale the digital twin. Lastly, since the focus lie on scaling from the beginning, the involved people are better aligned during the project. All involved parties are aware of the end goal of scaling the digital twin from the beginning. This is important for decision-making and mobilizing resources. Scaling should not be underestimated, as this phase will make the digital twin accessible to many users. As more people use the successful digital twin, operations will be more integrated and optimized, therefore increasing the benefits.

Another remark is that the container terminal industry was described as a conservative sector during multiple interviews, but this was not (often) read in the articles. This could be due to the fact that researchers are more focused on innovation. Their articles describe new findings and often do not describe standard day-to-day operations. Another reason could be that most researchers cannot really integrate all required change management into their technical articles, since changing people is a completely different expertise. However, this is very important for the adoption of a new tool and should not be underestimated. The fact that this study also mentions the conservative attitude and warns against it is an improvement on the literature. Nevertheless, the focus on change management and input from users can also be improved in this research, but that will be further explained in Section 5.3.

5.3. Limitations of research

The roadmap is verified, validated, and the results are related to the literature, but there are some limitations as well. The interviews with practitioners provided useful insights into the daily operations of a container terminal. However, in hindsight more port industry professionals could be interviewed. In the end, just one container terminal operator and two port organizations was spoken to. The consultants interviewed had interesting insights and provided a lot of knowledge. However, the focus of consulting is often more in the future than in the current day-to-day operations. Therefore, a roadmap for the management of a terminal could lack a practical focus if the input from practitioners is missing. So, interviews with more terminal operator should be held and ideally also operators without experience in scaling projects. If these operators see the benefit of the roadmap and understand all the steps, that would be perfect validation. Although the roadmap is validated during interviews, the best validation would be to establish the strategy based on the roadmap for a scaling project or to execute a project.

Another limitation of the research is the lack of input from users. It is often mentioned that users play the greatest role in the adoption of the digital twin into the operations. Without their support, a project will most likely fail or be delayed. The roadmap focuses on the senior management of container terminals, so it is wise to interview higher levels of terminals and port organizations. However, the input from users should not be underestimated, and collecting their experiences could be an interesting addition. For example, some steps of the using phase may prove more important than others. Which training is required for a user or an operator depends on the skills and insights of this user. Finally, this report focused more on the technical part of scaling digital twins. More attention could be paid to the organizational side, and interviewing users could be a good start.

5.4. Methodology evaluation

The Research through Design method was an appropriate method to remain flexible during the research. The design phase could contain multiple iterations and additional information could be collected during the design based on the knowledge gaps that arose. It ensured that the design could gradually start, while still collecting information. However, it was important to avoid scope creep, because a lack of focus could also change the direction of your research too much. Unfortunately, this occurred in this research, since the focus slightly changed towards a more technical focused roadmap. A lot of technical information was read in Chapter 3, and somewhat less literature on change management or strategy. More information on this is described in Section 5.3. Furthermore, an important aspect of RtD is describing the knowledge and decisions made to contribute to the academic world. Finding a balance between describing important design steps and not writing too much information proved to be difficult. An extensive and long-winded report is unappealing to read and does not necessarily provide more information. Lastly, more iterations or feedback loops should be included in the design of the roadmap, but this was also difficult due to thesis planning.

The roadmap is designed based on the established criteria found in literature and during interviews. The criteria provided sufficient guidance during the design phase. It was important to describe the criteria very specific, since they should be measurable to verify the result. With the right attention, this resulted in clear criteria that were useful for the roadmap. However, sometimes it remained a bit unclear what knowledge was meant for the criteria and what was suited to fill the roadmap. Furthermore, the MoSCoW prioritization method was not the most comprehensive way to prioritize criteria. It provided a good first overview of the ranking, but next time, a more academic method could be used. Most of the criteria received the same prioritization, so there is not much difference between the criteria.

Conducting a literature review was a good method of gaining knowledge. It is not without a reason that this is widely used in the academic and commercial world. However, it was sometimes difficult to keep focus, as there was a lot of personal interest in port and terminal developments. These were not always applicable to the thesis, so keeping focus is important for another research. Conducting interviews was a good addition to the literature review to gain practical knowledge from the industry. These insights would probably be missing due to graduating from a consultancy firm instead of a container terminal or port authority. The method of interviews was also sufficient, since the semi-structured interviews provided room for different questions per interviewee based on their expertise. The validation interviews could be more structured in hindsight, as the questions and setup of the interview were not exactly the same. This resulted from an unexpected delay of one week between interviews, so some improvements were incorporated prior to the second interview. However, an extra iteration is in line with the RtD method, and thus the second validation added more feedback to the roadmap.

6 Conclusion & recommendations

The study of this report concludes with this chapter. The main content of the study is described in Section 6.1, including the problem, how it is addressed, the final design and the results. In addition, recommendations for future research and for companies are described in Section 6.2.

6.1. Research questions

To be able to draw a conclusion, first, the four sub-questions have to be answered. See Figure 6.1 for an overview of the main research question and sub-questions.

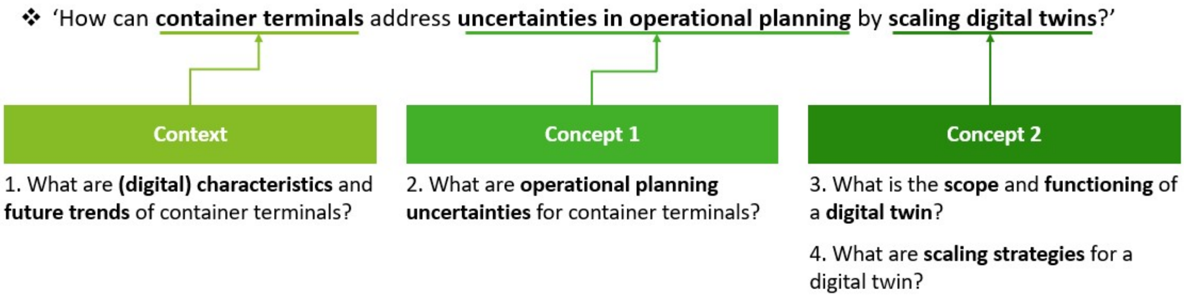


Figure 6.1: The main research question can be divided into the context and two research concepts, including four sub-questions.

1. **What are (digital) characteristics and future trends of container terminals?**

Container terminals can be divided into five main areas, namely berth, quay, transport, storage yard and (terminal) gate, as shown in Figure 3.1. A container terminal can act as a gateway or a hub. While a hub is a central location where inbound and outbound containers are transferred from one ship to another, a gateway generally means a transfer from one mode of transport to another (e.g. ship to lorry). Furthermore, ports have experienced a wave of digitization initiatives and automation programs in the last three to five years. This is primarily due to pressure on efficiencies brought on by the professionalization and scale expansion of container shipping and logistics. Digital twins and AI could inspire new products (just-in-time call platforms) and business strategies (new pricing tools). However, the pace of digital transformation in the maritime industry is still slow. Industry-specific characteristics, such as high asset costs, high development costs, aging workforce, and strict regulations negatively impact the ability to digitize effectively. Also, due to the traditional set-up of the organizations, conventional players often lack the skills and processes for successful digital adoption.

2. **What are operational planning uncertainties for container terminals?**

The operational planning of a container terminal is a complex context, as it depends on many external variables, such as the arrival of vessels, trains, and trucks, and the efficiency of (un)loading containers. Since most shipping companies operate their ships according to fixed schedules, arrivals would be considered predictable. However, in practice, the arrival of vessels seems less predictable, as many events can occur during the journey. In addition to weather-related delays or delays experienced during previous port visits, changes in the number of containers, traffic jams or mechanical failures also have an impact. Uncertain vessel arrivals have the greatest impact on yard operations due to the tight and complex schedule, leading to congestion and transshipment. Knowing the possible deviation from the scheduled arrival time in advance is important for planners to more efficiently allocate the manpower, equipment and spatial resources required to perform handling operations. This means that planners must be supported at each stage with tools that are capable of supporting the decision-making process. Having all information available could reduce operating costs, maximize terminal efficiency, and therefore competitiveness.

Most often, the operational planning uncertainties of container terminals are delays of incoming vessels. These delays are often caused by weather, so outside the influence of people and organizations. Delays are also caused by calamities, such as vessel breakdown or blocked waterways. The delay of a vessel has many consequences for the planning of a terminal, since the logistics chain is interconnected. The berth planning is often set far in advance and ships cannot simply wait or berth another terminal. The storage yard planning is based on the berth planning and containers are stored close to the berth location. If the vessel will arrive at another berth, the transport to the yard will take much longer and the delay will be even greater. Therefore, reducing operational planning uncertainties by making smart decisions supported by digital tools is important to improve terminal operations.

3. **What is the scope and functioning of a digital twin?**

A digital twin is a dynamic digital representation of an object or a system that describes its characteristics and properties as a set of equations. A well designed digital twin depends on accurate modeling of the physical assets' components, interactions, and behavior. The added value of the model lies in 'automatic data collection, conceptual development, dynamic analysis, problem diagnosis and optimization for smart design, operation, control, and maintenance'. A digital twin is relying on the input of historical (data lakes) and real-time (data streams) data, and the mathematical models that describe the processes of the physical entity. Changing situational parameters enable decision-makers to simulate different situations to make the best decision. The benefit of a digital twin is also the ability to continuously calibrate the twin throughout its lifecycle by integrating real-time data. This means that the model can be continuously refined to match reality. The information flows of a digital twin are thus more automated than the flows of a regular digital model. The first step of determining the modelled process and configuration of the digital twin must be done carefully. This scope is important, as it determines the physical entity that will be modelled and thus establishes the boundary between the physical system and its surrounding environment. The balance between the appropriate level of detail and minimizing complexity is an important result of the scope. More detail results in higher quality of the simulations, but makes the model more complex and costly to develop.

4. **What are scaling strategies for a digital twin?**

In the context of container terminals, scaling out can be seen as widening the scope of the digital twin, or including more use cases. Scaling up means including more terminals or ports in the digital twin, while the simulated processes and goal remains the same. The support and willingness of top management, together with sponsorship of technology, is critical throughout the scaling project. Organizational factors, such as culture, agility, structure, and alignment between different departments, become important later in the process when scaling starts to affect other organizational units. Furthermore, organizations need to ensure the right skills for users of the digital tool to adopt it in the operations as they scale. Lastly, many challenges related to the integration of operational systems and existing ICT infrastructure occur when companies try to scale up their pilot projects. Three main strategies for scaling-up are described: proof-of-value, treating and managing data as a key asset, and a top-down and bottom-up approach. Lastly, six important scaling stages are found that are suitable for providing more detail in the scaling phase of projects.

For a successful scaling project, barriers must be identified and overcome. Some of the barriers to digitalization and scale-up are a lack of comprehensive strategy, a limited pool of skilled workers and the ability to attract one, training and retaining talent, lack of standardization, lack of financial resources, cyber security and risks, integration with other technologies and legacy systems, siloed organizational structure and lack of cooperation between departments, organizational resistance to change and lack of organizational support. Among others, the barriers to successful digital transformation are high implementation costs, a lack of digital skills and qualified labor force, resistance to change, decreased levels of cyber security and a lack of standards. The latter is important, as definitions are still not consistently applied by ports and shipping companies. Clear data can prevent confusion and streamline planning and it is important to develop standards that are applied and maintained by dedicated organizations.

- **How can container terminals address uncertainties in operational planning by scaling digital twins?**

To answer the main research question, the answers of the four sub-questions are combined into the designed roadmap of Appendix C. The knowledge gathered led to insights that were required to develop the roadmap. Three different phases are important to consider and during the last phase of scaling the use of the digital twin, six stages are identified. Throughout the entire roadmap, various themes are important and responsibilities are shared among different stakeholders. If organizations pay attention to all steps described and further identify which steps require more research for their own project, scaling digital twins should be one step closer.

Conclusion

In conclusion, the roadmap developed in this study is useful for container terminals looking to scale digital twins. It provides insight into the steps required to develop, use, and ultimately deploy digital twins on a larger scale. Especially for terminals that have no experience with such projects, it serves as a starting point for defining strategy and freeing up resources within the organization. During the validation interviews, ease of use was also confirmed and the roadmap covers all major phases when combined with another roadmap for conducting a Proof of Concept. The lack of this information is a shortcoming, but it was beyond the scope of this research. In addition, some organizations have experience with PoC projects and can use this roadmap to supplement their knowledge. The roadmap of this study also lacks a timeline of how long each step will take, but this depends heavily on an organization's resources and varies by company. Because the roadmap was developed at a strategic level, not all steps are very detailed, so an organization will need to do further research to determine its strategy. However, the roadmap does cover important aspects of scaling projects and what actions are needed. Each organization can determine for itself which steps are familiar with internal knowledge and which steps require more attention. Since each project is unique, a roadmap with many smaller details could provide unnecessary or too much information, resulting in an unclear roadmap. Therefore, this roadmap serves as a solid starting point for senior management looking to scale digital twin solutions.

6.2. Recommendations

Based on the discussion and conclusion of this report, several recommendations can be made. First, recommendations for future research are described based on interesting topics and knowledge gaps that were not covered in this research. In addition, recommendations are described for companies to improve their operations.

6.2.1. Recommendations for future research

A more detailed research into the required steps for implementing digital twins at container terminals is necessary. Due to the conservative nature of the sector and the asset-heavy organizations, the roadmap could be adjusted to the specific needs of different container terminals. These adjustments can be made in cooperation with users and developers to gather the experience and requirements of people who work with the digital twin. Detailed research should be conducted on each phase of the roadmap to further elaborate the required steps. The roadmap of this report can be used as a starting point for a strategic level, but further research can draft a manual for developers or users.

After scaling digital twins independently of each other to container terminals, research can focus on connecting these twins around the world. There is a need for a global platform to share information when ports are close to one another since the schedule of the ship leaving a port directly effects the planning of the same ship in the following port [21]. One research can focus on required internal developments and another on external collaboration of organizations. An internal focused research can investigate the technical challenges of connecting digital twins, or the organizational challenges of digitally connecting terminal operations across the globe. The external perspective can investigate the barriers and potential solutions of sharing data and digital innovations in the port industry.

Another research can focus on including more operations of the container terminal in the digital twin, such as asset management, safety and maintenance. When sensors and real-time data are integrated, an accurate prediction can be made for maintaining terminal equipment and ensuring a high level of safety. In addition, AI can support operations when implemented in a digital twin. The research can focus on the technical necessities for adding this to the twin, or on the organizational challenges that arise when mapping all processes of a terminal.

Lastly, a recommendation is to investigate the Proof of Concept (PoC) phase for scaling digital twins, since this is missing in this research. The PoC phase is important for the start of a project to demonstrate value to the business and identify opportunities. However, the scaling phase requires multiple PoC projects, since every digital twin is different from the others and developed for a unique terminal. Therefore, it is a continuous process and not a single linear project. This requires a new definition and further research can investigate the necessary steps for a scaling project. Since scaling is involved from the beginning during the development, it is not innovate first and determine the next steps later. Already during the innovation, scaling is included in the digital twin and thus the PoC must include the requirements for scaling as well.

6.2.2. Recommendations for companies

Global trends in the container terminal industry require a faster pace of digitalization [A.4]. Digital tools enable higher efficiency and more accurate planning. More companies need to be convinced of these benefits and opportunities that a digital twin brings. When a company sees the advantages, it is likely that there will be a pull towards innovation [A.3]. Therefore, it is recommended that companies explore the advantages a digital twin brings and investigate if their operations could benefit. This requires an open-minded approach and the courage to explore unknown grounds, but can bring huge benefits. The influence of users is very high on the adoption of the digital tool. Although awareness is already present in organizations, it is important to keep this high on the agenda and act towards it. During all meetings and interviews, this was mentioned as the most important.

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A
Interview transcripts

For this research, two rounds of interviews were conducted. The purpose of the first interviews was to obtain more information on the knowledge gaps identified during the literature review. Also, the opportunity to gain insight into the daily operations and current trends of a container terminal, as well as information on the development decisions of the project teams, was an important motivation for the interviews. The second round of interviews is to validate the roadmap with practitioners. Based on their feedback, a conclusion can be drawn if the roadmap is sufficient to use at container terminals. More information on the interview method can be read in Section 2.3.2. The findings of the informational interviews are discussed in Section 3.9 and the validation interviews in Section 4.5.

The interviewees have different backgrounds, expertise, roles and teams to allow different input and opinions. Some have an inside-out perspective (container terminal operators about port industry), and others an outside-in perspective (external consultants about container terminals). An overview of the interviewees and the transcripts are shown below.

Table A.1: An overview of the interview topics.

Section	Interview topic
A.1	Digital twins for container terminals
A.2	Technical information on digital twins
A.3	Operations and digital twins of container terminals
A.4	Developments of the port industry and digitalization projects
A.5	Digital twin of a port authority
A.6	Validation of roadmap
A.7	Validation of roadmap

Table A.2: An overview of the company and function of the interviewees.

Section	Company	Function
A.1	Deloitte (Consulting NL)	Senior manager
A.2	Deloitte (Consulting UK)	Manager
A.3	Container terminal operator	Lean Transformation Leader
A.4	Deloitte (Financial Advisory NL)	Senior manager
A.5	Port authority	Development Lead Digital
A.6	Digital standards organization for terminals	Director & consultant *(2 interviewees)*
A.7	Container terminal operator	Lean Transformation Leader

A.1. Interview 01-06-2022 - Digital twins for container terminals

Senior manager at Deloitte Consulting NL - Expertise in cloud engineering, IoT & industry 4.0

What is the scope of a digital twin for container terminals?
The goal is to improve operational efficiency with a potential use case for yard strategy. Asset management and (predictive) maintenance are input for yard management in general, as you have less equipment available during operations in that case. External organizations, like pilots and bunkering, could have a connection, but it is a long shot to implement these in a digital twin.

How does the current berth planning looks like?
Current berth planning is based on the input of shipping lines and port authorities: "Which vessel enters the port and when?" The ETA changes over time due to weather, mechanical failures, etc. For planners, 3 week vs 1 week variance of planning is more important to consider than 24h in front, as last minute changes are done by radios at the terminal/yard.

Which input/output is required for a digital twin?
No sensors are involved, because the DT takes input from the Terminal Operating System (TOS) and the berth plan. Current DT is a mathematical model, and both static and dynamic data are used as input (e.g., current yard strategy, container attributes). It is a DT, because it is based on current data of the process, however, not (yet) IoT / real-time streaming data. The difference between container terminals is data: different data, different data models, different data streams.

The output is based on a simulation engine. You can change parameters, for example the prioritization and number of equipment (AGV, trucks, …) to simulate the impact on planning: "Can I reduce operational costs by reducing the number of equipment, and still be able to handle the vessel in time? Can I use extra equipment for housekeeping instead of loading the current vessel?"

Who are (key) users of digital twins / the roadmap and how do they operate with it?
The roadmap is intended for the C-level (CIO, IT, resources) and DT for planners: "What is required to develop this tool? What are the necessary resources?" Planners are just involved for different terminals as a subject matter expert (SME). Important questions for the DT are:

- Can we use it operationally for planning?
- Can we use it to test a flow methodology? How easy is it to implement the flow at a terminal?
- How does the simulation engine work? What are the mechanics behind that?

What is the ideal timeline for scaling digital twins?
It is all about dollars and how much you want to spend to speed up implementation. Roughly 12 weeks for a port is necessary (as every port is different). For example, at a gateway terminal: "How do you include external trains/trucks to the DT?" So, there are two options: use it operational or as an assessment tool for testing the flow. You can scale it at some terminals, and use it to assess flows at others (where you can implement it at a later stage). First, get it working and centralize the application. Think about different data feeds, terminal infrastructure, type of data, ...

What is necessary for the implementation of digital twins?
Key for DT: resources, scaling and support (it is not an of the shelve application, so it needs a lot of updates). Governance (model) control is also very important (ownership of app/data, does the client has the skills to run itself, version control). Also maintenance of the application, feature updates of UI, what is the overarching data model (is a plug in needed?). Technical side: You need a cloud vendor, AI/machine learning platform? In short, a lot of architectural decisions need to be made

What are lessons learned of digitalization projects?
Lot of projects already use DTs. Big thing is always, how do you scale? Pilots and Minimum Viable Product (MVP) could show benefits, however the scaling and the support for scaling is key.

"The simulation is only as good as the data going in."

A.2. Interview 08-06-2022 - Technical information on digital twins

Manager at Deloitte Consulting UK - Expertise in simulations, artificial intelligence & data

Which input is required for a digital twin?
The operational information is important to determine the processes of a terminal: “What ships are arriving? What’s on them? Where does the cargo need to go? What is stored in the yard/terminal? Which equipment do you have?” The information is not different than what you need as a human to plan/make a decision. Also how much time activities take is important.

What is the scope of a digital twin for container terminals?
Depends on the problem you are trying to answer: “How can I best use the space I have? How do I best schedule services? What do I need to make myself better?” The scope could be very wide, but is the most important: ”What is your biggest problem?” The problem can be different for every terminal, e.g. yard size or uncertainty of vessel arrivals. You can simulate your particular pain point, and see what would be the best solution.

What is the difference between a digital twin and a digital model according to you?
Key differences between a digital twin and other modelling methods is that you are not training algorithms with a DT. You are not using data to create a model, apart from validation and calibration, so you are not reliant on data. You are not saying: “learn the relationships between these two things”. A data driven model where you can make something generic is not working, as you won’t understand the underlying factors of how you can make a better prediction.

In a DT, you are saying: “these are the processes”. By putting the processes together and showing they make the same answers as reality, you can have confidence to make changes to the model to simulate scenarios. You can also show subprocesses and show what is leading to the main process. If you look at overall terminal performance, it is too broad. There is a lot of detail in the background of where that overall performance comes from and where the improvements can be generated. This makes a DT ideal, as it is based on the processes and can deal with the complexity/number of items.

What is the current approach of implementing/scaling digital twins?
You start with a Proof of Concept (PoC) and move on to a minimum viable product (MVP). Typically that is done cloud-based, so you can interact through a web-interface. Main consideration is that the model is more complicated, based on time base. There is more hardening of simulation itself, what can it handle? Also important is on the outside/edge of a DT: “Where is the data coming from? Do I care about update rate or is it completely live? Do you need live data, or is a delay in gathering data fine? Which data program do you use and where is the data stored?”

Furthermore, the human side is very important: “How are humans going to interact with it?” Typically you start with a model and have some plots or even a little dashboard, but to turn that into something a human can tangibly interact with is a huge part of the work. How do you allow a user to pull the levers they want to pull? Also the implementation: frontend –> API –> backend –> simulation, and then back to user. So besides adding extra details or extra stuff to the model, the stuff on the edges are the big considerations when scaling (so users, data, storage, display of results).

Ultimately users have the best idea how to use the tool. Typically the managers or seniors have the best view what the questions is they want to answer, and there is a crossover with the users: how people are going to use the tool, determines the goals and outcomes of what they want, so users have the information to support the decisions being made on a higher level. Collecting this information will be done by interviews, whiteboarding sessions, concepts, let people work their way through it. Ultimately everything goes back to: “how does this solve/support the overall question in mind?”

What is the ideal timeline & sequence for scaling digital twins?
It is in the end driven by business requirement and matches by what the company want to achieve. Also depending on the amount and type of terminals they have. The timeline overall should reduce, as you gain more experience during the project. First project is more difficult, but then you improve over time, as you overcome differences in the past (gaps in data for example).

In terms of sequence: some aspects are driving the business or causing major disruptions. You want to address these first, because a system is as good as it weakest points. The sequence is tricky, because it is not just about giving a tool to somebody. It is also about them accepting and moving on with thinking on how they use it to help their client decisions. "How does it actually fit in their current systems?" How people use it is as much a challenge as developing the tool. The business culture is therefore important.

What are barriers & drivers and how do we strengthen/weaken these?
A benefit could be in systems, processes, or situations where there is a lot of interdependency. Take a distribution network for example: if you change something, it could have a ripple effect. All these interdependencies make it very complicated, so if you are able to simulate it and investigate different scenarios is a major benefit. “What are the consequences of complex decisions?” Especially when you don’t have all data. Data is only collected at companies when necessary, so if you need historic data, you are often limited.

A main barrier is that DTs are relatively new, so you want to be sure that it works. Companies are reluctant to use it, unless there are (a lot of) success stories. Also you need to invest in time, before seeing results in projects. Especially as you need to develop the digital twin, which takes more time than a ‘simple’ model.

What is the value of (scaling) digital twins for companies/people?
The main advantage of a digital twin is that they are process-driven, so not dependent on (historic) data alone. Also, to be able to be proactive and understand the consequences of your choice. Is this something I want to do, or whether it is not a sensible move (e.g. the costs diminish the returns).

Other remarks:
You can dive more into business culture and how you want to use the tool, because this is often underestimated. You can give people the best tool in the world, but if they are not ready to use it or do not understand the value of how to use it, is the project than worth it?

“You need to walk before you can run.”

A.3. Interview 13-06-2022 - Operations of a container terminal

Lean Transformation Leader at a global container terminal operator - Expertise in Lean flow concepts (JIT), systemisation and automation in terminal operations

How does the current (yard/berth) planning looks like?
Schepen varen vaak met een weekly schedule, bijvoorbeeld 6-8 schepen varen tussen Azië en Europa op vaste roulatie. Elke week komt er dan eentje langs bij een terminal. De schedule reliability hiervan vergroten is erg lastig. Weather delays zijn de grootste oorzaak van vertraging, maar 3 weken van tevoren heb je nog geen weersvoorspelling. Ook vessel breakdown en blokkades van vaarwegen komen voor, maar dit zijn vooral calamiteiten. Wat de grootste oorzaken voor vertraging zijn, kun je het beste bij de rederij zelf navragen.

In de 'pro forma schedule' die terminals en rederijen afspreken zit een berth window van het schip (bijvoorbeeld 26u) met een afgesproken aantal moves wat geladen moet worden (bijvoorbeeld 3000 containers). Op basis daarvan berekenen we hoeveel kranen en assets er nodig zijn om aan de afspraken te voldoen. Het kan ook gebeuren dat schepen minder moves hebben. Onderhandelingen vinden dan plaats om te kijken of het sneller kan (als de berth planning vol zit) of met minder kranen (als het efficiënter kan en niet vol zit). Als er verstoringen zijn moeten de berth windows worden verschoven. Bij hub terminals is het vaak onderhandelen met één partij, omdat reders meestal afspraken hebben met een 'eigen' hub terminal. Dit maakt schuiven makkelijker, omdat de belangen bij één partij liggen. Bij gateway terminals doe je vaak zaken met meerdere rederijen en dan is de oorspronkelijke berth schedule leidend. Soms zegt de port authority: "het maakt niet uit welke pro forma schedule er is, het is voor onze services 'first come, first serve'." Dit is vaak bij smalle of drukke vaarwegen in een haven, waarbij ze niet andere schepen voor willen/kunnen laten gaan.

What is the scope of a digital twin for container terminals?
Het doel van een digital twin is in sommige gevallen niet het voorkomen dat schepen te laat komen. Het gaat er juist om: "Als we weten hoe laat de schepen komen, hoe kunnen we die dan het beste helpen met de juiste afweging tussen service en resources?" Bijvoorbeeld, een terminal heeft X berth locations, en Y kranen in totaal, wat is dan de beste verdeling van de kranen over de schepen? De keuze daarvan hangt vooral af van de planning van de schepen: "Welke moet er het snelste weg, en welke heeft slack in zijn schedule?" De keuze daarbij wordt ook gebaseerd op productiviteit en hoogste throughput (des te eerder heb je ruimte voor de volgende schepen). De status van de yard neemt de DT hierin mee, bijvoorbeeld housekeeping en de ideale inzet van het aantal kranen. Meer kranen kan bijvoorbeeld tot congestion op de yard leiden. Betere data hebben om besluiten te kunnen maken is dus de ideale scope van DT. "Wanneer halen we het volgende schip naar binnen en hoe doen we deployment op het schip".

Are there important differences between terminals and how do you create the best strategy?
Een rederij denkt vaak: "bij meer kranen is het schip sneller weg". Echter kan de terminal met een DT laten zien dat minder kranen/andere inzet beter werkt voor de doorlooptijd van één schip, of voor de productiviteit van de gehele week. Dit is vooral handig bij tradeoffs / besprekingen met één partij vanwege de belangen, oftewel vaak bij een hub terminal. Een digital twin helpt om 'één waarheid' te hebben, omdat planners verschillende levels van ervaring kunnen hebben. Beslissingen kunnen dan per shift verschillen/ gewijzigd worden, wat een grote impact heeft op de overall planning. Een digital twin helpt dus bij een standaardaanpak van de planning gebaseerd op (complexe) data, in plaats van op gevoel/ervaring.

What data flows exist at container terminals?
Ze proberen te kijken naar vessel utilization, maar die data verkrijgen is erg lastig. Ook maakt het de digital twin complexer, wat wellicht niet evenredig veel voordeel geeft. Je hebt dan informatie/data nodig van andere havens om wat te kunnen zeggen over de aankomst in jouw haven, maar andere partijen willen dat (nog) niet delen. Hier zit wel een potentiële grote meerwaarde in. Idealiter koppel je de digital twins van alle havens/terminals aan elkaar, waardoor je er veel meer informatie uit kan halen.

Echter is het binnen een organisatie al erg lastig om data te delen/krijgen. Dit begint al op technisch vlak, doordat veel data niet wordt bewaard. Na een planningsupdate wordt het alweer overschreven, dus kan je niet meer zien wat er gepland/besloten is. Data delen tussen concurrerende shipping lines is lastig ivm compliance. Er is ook vooral angst dat iemand anders er competitief beter van wordt als die betere (digitale) systemen heeft. Iedereen zal dus op dezelfde capability level moeten zitten, en daar is nu nog niet iedereen klaar voor.

What are the advantages of standardization?
Je moet kunnen voorspellen in de planning hoe lang elke activiteit gaat duren, zowel van de kadekraan, de yard, transport etc. Als je geen betrouwbaar plan kan maken wat ook wordt opgevolgd, is het erg lastig om verder te gaan met voorspellen. Hoe meer standaardisatie van het proces, hoe minder versies er in het digitale model moet zitten. Ze proberen standaarden te verzinnen en die te koppelen aan de planning; "hoe lang duurt een activiteit en hoe betrouwbaar is deze voorspelling". Er zijn nu veel processen manueel, vooral bij kadekranen. Ondanks dat het een geautomatiseerde terminal is, gaat de helft nog manueel en er zit dan ook veel verschil tussen de skills van operators.

What is necessary for scaling digital twins across terminals?
Het belangrijkste is het verkrijgen van goede data (availability/standaardisatie). Krijgen van goede interfaces is daarbij belangrijk, om de data in de cloud beschikbaar te krijgen, zodat hetzelfde model in de volgende terminal gebruikt kan worden. Het onderhouden van digital twin model is ook erg belangrijk, plus het ontwikkelen van de modelling capability om de tool echt te snappen. Een andere terminal heeft weer nieuwe parameters/factoren; hoe kunnen we capability opbouwen om die te onderhouden? Voor elke verandering een externe partij inhuren is niet sustainable voor de bedrijfsvoering. Dus data availability/standaardisatie en modelling capability opbouwen is het belangrijkste.

What is the ideal timeline & sequence for scaling digital twins?
Bij een nieuwe terminal kijken we vooral naar welke capability we hebben, het makkelijkst is om te kijken naar hetzelfde type terminal. Geautomatiseerde terminals hebben misschien betere/meer toegankelijke data, maar voor nu is kopiëren naar hetzelfde type het makkelijkst. Hierbij speelt volume ook mee; hoe belangrijk is het knooppunt? Hoe groter de terminal/throughput, hoe meer voordelen bij enkele procenten besparing.

Het volgende project is eigenlijk een proof of concept 2.0, omdat niet iedereen meteen overtuigd is na het eerste project: "Die terminal werk anders, dus wat heeft onze terminal eraan?" Qua snelheid van het uitrollen is eigenlijk hoe sneller, hoe beter, want het levert voordelen op. Echter zie je bij sommige organisaties wat terughoudendheid over de werking bij andere terminals, dus proof of concept van de uitrol is nodig. Waarschijnlijk komt er na een tweede project met positieve resultaten een pull naar DTs.

What are future (digital) trends of container terminals?
Modulaire automatisering van terminals wordt belangrijk, waarbij yard blokken, horizontaal transport of kranen stuk voor stuk geautomatiseerd worden, vanwege hoge arbeidskosten. Automatisering zoals het tot nu toe is (compleet van brownfield naar greenfield met nieuw design/equipment) zie ik minder gebeuren, maar bij volledige nieuwbouw nog wel. Oplossingen die binnen de huidige blue print meer met automatisering kunnen doen worden belangrijk. Als je de huidige congestie zien op manuele terminals onder de kranen (inhalen/voorbij rijden/ achteruit/ verkeerde volgorde) is dat haast niet te automatiseren. Dit kan pas als er een standaard flow is.

A.4. Interview 13-06-2022 - Port industry & digitalization

Senior manager at Deloitte Financial Advisory NL - Expertise in seaport and maritime development

What are future (digital) trends of container terminals?
Er zijn drie grote trends belangrijk op het moment. De eerste is dat container terminals altijd zwaar onder druk zijn gezet door reders, want zij hebben veel macht. Rederijen pushen terminal operators om zo goedkoop mogelijk en efficiënt te zijn. Op het moment verdienen rederijen erg veel geld, en breiden ze erg uit in de hele logistieke keten. Terminals moeten nu dus meer integreren, transparanter en kosten efficiënter worden in de keten, omdat rederijen alles opkopen.

Groener worden is de tweede trend in de sector, gedreven door regelgeving. Terminals worden uit zichzelf niet groener als er geen geld verdiend kan worden. Groene regelgeving speelt vooral in Europa, Noord-Amerika, een klein beetje in Azië, en eigenlijk niet in Afrika en Zuid-Amerika. Voorbeelden zijn een betere berth planning, zodat schepen zo kort mogelijk aan de kade liggen; dus efficiënter werken en waar mogelijk met groene brandstoffen/elektrificatie.

De laatste trend in West-Europa is dat alles veiliger moet worden aan de douanekant. Illegale goederen moeten minder binnenkomen (dus betere security, i.p.v. safety).

Deze drie trends komen eigenlijk allemaal samen in digitalisatie. Digital Twins zijn hierbij vooral belangrijk voor security (en beetje safety), want je kan het koppelen aan slimme camerasystemen. Waar gaat alle lading heen, wie komt er bij de containers, track & trace van containers, etc. Verder kan ook de efficiëntie van terminal zelf verbeterd worden door een DT. Wat gebeurt er tijdens een disruptie? Je kan verschillende (optimalisatie) scenario's simuleren, zonder dat het invloed heeft op je operations. Uiteindelijk kan je ervoor zorgen dat alle planningen (terminal, schepen, …) het beste op elkaar zijn afgestemd d.m.v. een digital twin.

What are lessons learned of digitalization projects?
Belangrijkste is om meerwaarde aan te tonen aan de mensen die de beslissingen maken. In de maritieme sector is vaak; "We doen dit al 20 jaar op deze manier, dus waarom moeten we het anders doen?" Het zijn vaak familiebedrijven met een conservatieve/traditionele insteek. Het moet dus duidelijk aantonen wat de meerwaarde is; dat het effectief is, en niet alleen een fancy systeem voor de show.

De grootste fout die je kan maken is een 'big bang' implementatie, waarbij je de digital twin in één keer uitrolt bij alle terminals. Het beste is om te starten met een specifieke pilot, het liefst in havens die al goed draaien. Als je dan kan aantonen dat het in goedwerkende havens al voordelen heeft, dan zou het bij andere havens nog veel meer kunnen helpen. Gebruik vervolgens ook je lessons learned van je pilot project en gebruik deze om je systemen aan te passen voor nieuwe types haven, etc.

Het is ook belangrijk om de perceptie duidelijk te hebben bij het project team. Als je een digital twin wil implementeren bij een nieuwe terminal, zullen mensen meteen focussen op de verschillen: "Onze terminal heeft minder kranen, een andere locatie, …" Dit kan ertoe leiden dat je alles opnieuw moet opbouwen, terwijl je je bestaande IT systeem eigenlijk gemakkelijk kan aanpassen. Dit is een valkuil waar je voor moet waken.

What are barriers & drivers and how do we strengthen/weaken these?
Driver voor zulke projecten is simpel gezegd geld verdienen. Barrier is vooral de unwillingness dat mensen het anders moeten doen dan alle jaren hiervoor. Er zit wel iets verandering in bij jongere mensen, maar gaat nog erg traag. Een andere barrier is het schaalbaar maken voor meerdere type terminals. Wat is nodig voor schalen? Bij welke type terminal begin je?

What is the ideal timeline for scaling digital twins?
De timeline is inderdaad vooral afhankelijk van het budget, maar 12 weken voor een nieuw project is een goeie richtlijn, mits je al een 'standaard' Digital Twin hebt.

A.5. Interview 25-07-2022 - Digital twin of a port authority

Development Lead Digital at a port authority - Expertise in Lean & Agile digital transformation projects

What is the scope of your digital twin?
We willen de werkelijkheid van buiten naar binnen halen, dus alles wat nodig is om assets en relevante context in beeld te hebben (windsnelheid, waterstand, zoutgehalte, stroming, conditie van assets). Dit willen we bij elkaar brengen om met data van externe partijen/ klanten slimme dingen te doen. Focus komt neer op samenwerking en dataverrijking, oftewel, slimme schepen laten praten met slimme assets.

What is the approach of using digital twins?
Wat is ultieme eindpunt van de digital twin? Vanuit daar zijn we begonnen met technische PoC om bewijs te leveren dat het technisch kan. Vooral laten zien dat de combinatie van platformtechnologie samen met gestructureerde data en toegang tot data (single point of truth) haalbaar is. Dit hebben we bewezen met PoC, maar in die periode bleek dat operationele verandering van de organisatie (wat moeten mensen doen om met DT te werken) tot te veel onrust leidde.

What are lessons learned of digitalization projects?
Data governance moet je niet onderschatten. Sommige werknemers gebruiken Word, Excel of een app, maar dat betekent dat je dan al 3 bronnen voor data hebt. Je moet een goede datastructuur hebben, met duidelijke afspraken over beheren en opslag. Anders kom je er nooit. Ik merk dat partijen (gemeente, extern, …) onvoldoende zicht hebben op brondata en gegevens die nodig zijn om slimme technieken te laten werken (namelijk op eenduidige plek data binnenkrijgen). Ontwikkeling van techniek gaat supersnel, daar ligt het niet aan. Maar uitwisselen van gegevens om DT te laten werken, is van minstens zo groot belang.

What is the current approach of implementing/scaling digital twins?
Het is van groot belang om tijdens de start van de implementatie met alle betrokken partijen aan de slag om te kijken wat hun bijdrage kan zijn. De eisen die ze gaan stellen, moet je vanaf het begin in beeld hebben. Meteen alle betrokken partijen erbij betrekken en in de gaten hebben hoe hun werk gaat veranderen, scheelt later veel gedoe. Draagvlak en besef dat het meer is dan techniek zijn belangrijk voor het succes van een roadmap. De roadmap kan ook veranderen (wettelijke verplichting, hack, …) dus je moet genoeg flexibiliteit hebben, waarbij data bepalend is.

“Mensen willen wel veranderen, maar ze willen niet veranderd worden.”

A.6. Interview 03-08-2022 - Validation of roadmap

Director & consultant at a digital standards organization for terminals (2 interviewees) - Expertise in digitalization & standardization of container transport

Feedback on the framework of the roadmap
Je bent niet echt aan het uitleggen wat een goeie methodologie is om iets te ontwikkelen. Voor een methodologie kan je naar product development kijken, waarbij de laatste fase scaling is. Wat moet je doen om een product te schalen? Welke stappen moet je doorlopen? Op basis van welke parameters ga je schalen? Je wil een vraagstuk oplossen (bijvoorbeeld planning beter beheersbaar maken). Let goed op de focus van de roadmap, want deze ligt nu meer op developing. Pas desnoods de probleemstelling aan als je je focus anders wil hebben. De drie fases die je nu hebt zijn duidelijk genoeg om over te brengen wat het doel is, dus wat dat betreft zijn de fases goed.

Als je het meer naar de industrie wil schrijven moet je letten op twee dingen. Het is een conservatieve industrie, dus begin bij het management (top down approach). Management moet aanhaken en hun erbij krijgen is het meest belangrijk. Ten tweede; voor wie is het geschreven? Voor grote terminal operators is deze roadmap geschikt, maar voor kleine terminals minder. Scaling naar andere terminals is dan minder of niet van toepassing. Definieer dus; wat is scaling? Is het van terminal naar terminal, of scaling binnen operaties/processen? Wat is je doelgroep? Deze roadmap kan zeker geschikt zijn voor grote terminals (PSA, DP World, Hutchison) die nog veel te schalen hebben.

People, process & technology wordt veel gebruikt bij product development. De nadruk moet vooral liggen op people, omdat er best veel macht zit bij de werknemers en zij erg conservatief kunnen. Noem bijvoorbeeld niet dat een DT een mens vervangt, maar juist de bestaande processen ondersteunt.

Feedback on the content of the roadmap
In welke fase (developing of using) zit testing van de DT? Tijd is veel geld binnen havens, dus grote nauwkeurigheid is erg belangrijk en fouten zijn kostbaar. Alles moet goed getest worden, want alle havens zijn voorzichtig met innovaties uitrollen. Een vertraging van een schip heeft veel impact op de hele logistieke keten. Eigenlijk bevat zowel developing als using het testen. Tijdens het developen test je het product, maar bij de agile leervorm wil je de tool tijdens het gebruik ook blijven verbeteren. Het moet een iteratief proces zijn om door te ontwikkelen en te verbeteren.

Bij de eerste stappen ga je er al vanuit dat er een behoefte is aan een DT. Welk probleem los je op met je DT? Je hebt het nu over scaling, maar dit is maar een klein deel van de roadmap nu (groot deel op ontwikkelen en in gebruik nemen). Er missen een aantal stappen/ denkprocessen, dus benoem dit als aanname voor men begint aan de roadmap.

Punt 6: Misschien moet je een stap dieper, wat is clearly communicate? Je kan een bulletpoint toevoegen dat je user profiles maakt ter ondersteuning van communicatie (je hebt bepaalde rollen in een terminal; planner, crane driver, …) Oftewel, user roles definiëren met duidelijke doelen (what's in it for them?). Je hoeft niet zelf deze rollen te verzinnen, maar geef aan dat dit een handige communicatie tool kan zijn, met duidelijke voorbeelden bij communicatie.

Punt 12: Support from senior management; hoort dit bij scaling? Management is al lang aangehaakt bij scaling, want iemand moet al veel eerder ja zeggen tegen de development of DT. Er is een groot tekort aan developers binnen de havenindustrie, dus is ook een kostbaar project om resources vrij te maken. Iets benoemen over limited resources for development is een goede toevoeging, terminals moeten nu vaak kiezen tussen projecten (ze willen wel, maar kunnen niet alles doen).

Feedback on roadmap in general
Over het algemeen heb je goede punten opgeschreven, maar je kan het nog iets herschrijven naar container terminals specifiek (nu soms erg algemeen voor DTs). Deze industrie is anders, ze zijn lastig te veranderen. Begin roadmap vanuit operatie, kijk naar een proces wat je wil digitaliseren, breng dit proces in kaart, digitaliseer het proces, en kijk dan of het anders moet.

A.7. Interview 11-08-2022 - Validation of roadmap

Lean Transformation Leader at a global container terminal operator - Expertise in Lean flow concepts (JIT), systemisation and automation in terminal operations

Feedback on the framework of the roadmap
'Criteria for digital twin itself' zijn misschien geschikt voor de probleemanalyse en hypothesedefinitie, voordat het ontwikkelen van de DT begint. Welke data heb je nodig voor de digital twin om de problemen op te lossen, of juist welke heb je niet nodig? Je begint niet bij developen, maar met bedenken op welk gebied je wil verbeteren.

Een alternatief voor de thema's is het PBOI-framework: Processen, Besturing, Organisatie en Infrastructuur. Je mist nu bijvoorbeeld de controle.

Feedback on the content of the roadmap
Een scaling project van digital twins begint als eerste bij het opstellen van een problem statement en een hypothese. Waar zou een DT kunnen helpen in een proces (waar zit waste, hoe groot is die, welke benefits bereik je met DT?) De hypothese wil je testen aan het eind van de implementatie van Proof of Concept. Een duidelijke probleemstelling met hypothese zorgt ervoor dat de organisatie niet off track raakt (scope creep).

Punt 1: Level of standardization is het belangrijkste criteria om aan de slag te gaan met DT.

Punt 2: Start met waste buckets en definieer problem statement. Punt 1 en 2 moet je dus uitvoeren voor je begint aan het developen van DT. Dan weet je wat je required data is en welke patronen je verwacht.

Punt 3: Je moet het business probleem eerst goed snappen, en bijbehorende processen en de besturing van deze processen analyseren. Hierna kan je pas aan data en DT beginnen; zonder goede business vertaling heb je niks aan prachtige data / DT.

Punt 4: Je begint meteen over interfaces, maar praktisch is om te beginnen met manuele databestanden, om te checken of het de juiste data is en of je dit echt nodig hebt. Ontwikkelen van interfaces is erg kostbaar namelijk.

Punt 5: Data ownership is erg belangrijk. Denk aan de IP rechten van data. Oplossing is het werken met NDA (non-disclosure agreement) en definiëren van intellectual property, op zowel data als logica van het digitale model (model vaak van ontwikkelaar, data van de klant).

Punt 6: Typische tools voor management involvement zijn stakeholder analysis en een communicatieplan. Deze zou ik benoemen met voorbeelden, bijvoorbeeld een tabelformat (kolommen: verschillende stakeholder groepen – welke boodschap wil je overbrengen – wat is de frequentie van updates – communicatiemiddel – wie gaat het doen). Stakeholder format kun je opzoeken en toevoegen. Stakeholder analysis is vaak icm een communicatieplan.

Punt 7: Niks toe te voegen

Punt 8.2: Real time data to show deviations; hoeft niet real time data te zijn. Je kan ook achteraf planning en execution met elkaar vergelijken met de data records.

Punt 9: Hypothesis testing kun je hier toevoegen (of bij stap 10). Hier komt de validatie van hypothese dan terug.

Punt 11 en 12 zijn logisch.

Punt 13: Toevoegen: integrate in standard architecture of applications. Na PoC krijg je een scaling pilot om aan te tonen dat het ook op andere locaties werkt. Daarna krijg je een full rollout, maar dan wordt het van belang dat het onderdeel wordt van de standaard architectuur en niet een aparte tool blijft. Het moet onderdeel worden van applicaties, zodat bij updates de DT automatisch mee gaat.

Feedback on roadmap in general
Literatuurbronnen toevoegen aan de criteria is handig. Persoonlijk is het mooi om te zien dat onze ontwikkelingen terugkomen in de literatuur.

De validatie was vooral de puntjes op de i zetten, want deze roadmap is al erg waardevol voor organisaties die geen ervaring hebben met digital twins en scaling. Eigenlijk moet je het ook nog laten zien aan een organisatie waarvoor het nieuw is, om te testen of alles duidelijk is.

Doordat je bijdrage inhaakt op scaling, is er in zo'n organisatie al veel ervaring met PoC (data analyse etc.) Als er een roadmap voor PoC is (voor organisaties zonder ervaring), en deze kan je gebruiken in combinatie met deze roadmap voor scaling, kan het erg waardevol en compleet zijn. De gap is nu dat er begonnen wordt met scaling ipv een PoC, dus dat zou het compleet maken.

B

Overview of the roadmap steps

An extensive overview of the roadmap steps is shown below. A description of establishing the criteria and the identification of the roadmap steps can be found in Section 4.4.

Phase 1 – Developing the digital twin

1. Select the container terminal which is **best suited for the development of a digital twin**.

- Start with a container terminal with an **operational efficiency program**.
  - These terminals have a clear analysis of the operations, so a clear idea of where improvements could be made. The data streams and operations are better organized, so collecting information and the implementation are easier.
  - Lessons could be learned from successful terminal operations and incorporated into the procedures to improve other terminals.
  - Several characteristics of a terminal (shown in Table B.1) have influence on the digital twin, so must be taken into consideration.

Table B.1: Advantages and disadvantages of different characteristics of container terminal.

Characteristic	Motivation
Hub – gateway terminals	Hub terminals have fewer external stakeholders than gateways, so operations are less dependent on external influences. Therefore, developing a digital twin and realizing first improvements could be less complicated.
Automated – manual terminals	Automated terminals may have better and more accessible data, but benefits of a digital twin may be less as the operations are automated.
Level of standardization	The processes of a terminal should be standardized to model the operations and enable predictions of the digital twin. A high level of standardization is thus preferred when selecting a terminal, otherwise the operations should first be improved.
Large – small throughput of containers (volume)	A higher throughput results in more cost reduction at the same percentage of improvement. However, larger terminals have more complex systems and larger operations.

2. Identify an **area of focus** of the container terminal where **gains could be made** and determine **quick wins**.

- The aspects that **drive the business** or **cause major disruptions** need to be addressed first. Organizations should **prioritize business value over technology**, to prevent developing a high-tech digital twin that does not cover an existing business problem.
  - The main goal is to improve operational efficiency (reduce cost & time), by focusing on, for example, overall equipment effectiveness, end-user statistics, and reduction in maintenance costs or machinery downtimes.
- Define the **scope** of the simulated processes. **Start focused** (select certain areas where improvements can be made) to be able to improve the model and change the working procedures. In a later phase, the model can be expanded to include more processes and stakeholders.
- Start **documenting the exact processes** of the operations for the simulation. Also, start **collecting, digitalizing and centralizing necessary data.**
  - What processes and points of integration will the twin be modeling? Standard process design methodologies should be employed to illustrate the interactions between the processes, the supporting people, business applications and physical assets. Diagrams are made that show how the process flow relates to the applications, data requirements, and different kinds of sensor data needed to build the digital twin. Aspects that could increase cost, time, or asset efficiency are added to the process design [44].
    - *For example: vessel details, loading information, processing times, yard capacity, container movements, crane activity.*
  - Define these processes and working procedures during interviews with users
    - Possible questions are: *"What are users doing? How does that affect what systems they are using? With which data?"*
    - Interviewees are, among others: planners, center of excellence of planning, leadership (goals for business), operational managers
- Determine the **pilot configuration** with the **highest value** and the **highest chance of success** by taking operational, business and organizational change management into account.

3. Start developing the digital twin.

- Understand the **business requirement** thoroughly before the development, since this determines what should be modelled and with which purpose.
- Make choices for the **technical solution**, based on **performance, scaling, cost and previous investments.**
    - Scalability & performance of application depend on technology – capability of the organization depends on available resources.
    - Use a **cloud-based environment**, thus enabling interactions of users/developers on an external location through a web-interface to minimize the dependence on a local network.
    - **Architectural decisions** need to be made (scalability):
        - Centralized vs decentralized in terms of application management
        - Use of data (metadata, taxonomy, mapping data between systems)
    - Determine the **desired calculating time** of the model for running simulations (performance).
        - Faster simulations need more computing power, so higher costs.
        - Decision is based on crucialness of the data for the operations: "*Do you need live data, or is a delay in gathering data fine?"*
    - Include where possible **modularity**. Modular systems can adapt to changing requirements by replacing or expanding individual modules in case of seasonal fluctuations or changed product characteristics.
- Ensure **quality data for creating, validating and calibrating** the digital twin. Because the twin is modeling the processes, it does not depend on historical data during operations. By combining the processes and show they have the same results as reality, there is confidence to change the model to simulate different scenarios.
    - **Data management** is very important (quality, access & infrastructure of data).
- Pay attention to **business culture** and how the organization wants to use the tool, as this is often underestimated.
    - The User Interface with dashboards providing information and insights is key for operations.
        - Copy interfaces of software and hardware that is already used, so users get the same look and feel connected with the UI. This is important for the adoption of the users: *"How are humans going to interact with it?"*
        - Collecting this information will be done by interviews, whiteboarding sessions and concepts.
- Keep **testing** the digital twin during the development, to check if the digital processes and integration of the system are working as planned.

4. Investigate the current ICT systems and IT infrastructure of the container terminal, and update if necessary to support the digital twin.

- **System integration and interoperability** are important to consider, to enable **smooth digital operations and clear communication** between companies and departments.
    - Which data program do you use and where is the data stored?
    - Pay extra attention to **cybersecurity**, as it prevents attacks on system and ensures integrity of the system (since you are serving clients)
        - Deloitte mentions 9 important security factors:
            - Application security
            - Development, security, and operations (DevSecOps)
            - Governance, risk management, and compliance (GRC)
            - Identity & access management
            - Data protection
            - Network and Database Security
            - Vulnerability Management
            - Threat Monitoring
            - API Security
        - **Edge security** becomes important for future projects, when **IoT** is added for predictive maintenance.
            - Increased security challenges have arisen as a result of new sensor and communication capabilities, which are still being developed. Use of firewalls, application keys, encryption, and device certifications are the most popular security measures. As more assets become IP enabled, the demand for new solutions to safely enable digital twins is anticipated to increase [38].

5. Determine the **governance control** of the digital twin.

- To use and scale the digital twin, a clear governance model is necessary with agreements on responsibilities and scope:
    - Development of the application
    - Configuration of the simulation engine
    - Codification of processes into the digital twin (including provision of operational knowledge)
    - Calibration and validation of the digital twin model
    - User requirements and support
    - Project management for developing (and implementing) the digital twin
    - Ownership of the model and data
        - Who will maintain and update the twin?
        - Who owns the intellectual property (IP) rights of the data and the digital twin?
            - A solution is to draft a non-disclosure agreement (NDA) with involved parties.

Phase 2 – Using the digital twin

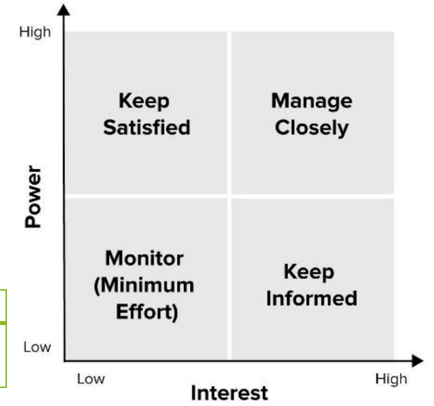

Figure 4.4: A Power/Interest grid for stakeholder prioritization [35].

6. **Clearly communicate** and involve all members of the organization.

- Establish a **communication plan** and identify important stakeholders.
  - Identify stakeholders and prioritize them based on their power and interest on the project. Use the stakeholder matrix of Mendelow [35] (see Figure 4.4):
  - A template for a communication plan was proposed by validation interview A.7 and Asana [2]:

Table B.2: A template for the communication plan during the project

Stakeholder	Message	Frequency	Channel	Responsible
Who is the target audience?	*What do you want to communicate?*	*How often do you want to communicate*	*How do you communicate?*	*Who will send the message?*

- **Communicate the value of tools** and address concerns about job replacement from the start of the project.
  - Users should accept the digital twin and start thinking about how they use it during operations with their current systems.
  - It is very important, at the start of the implementation, to work with all parties involved to see what their contribution can be. A clear picture of their requirements is necessary from the start, to save problems in a later phase of the project.
    - *For example, organize weekly (lunch) meetings where updates and concerns can be shared. How are people affected by the project?*

7. Provide **training** for the workforce to facilitate their adaptation to the new tools and operation.

- Training for:
  - How to use the tool for the planners.
  - How users can share feedback to improve the tool.
  - How developers can improve the model (simulation engine), as organizations wants to develop the tool inhouse.
- Include a transition period for the users to change their working procedures. Monitor the adoption of users to determine if more transition time is needed.
  - *"After training, it takes time to unlearn old habits."*

8. Ensure **robust data practices** for collecting, storing, organizing, and maintaining large volumes of data coming from a variety of sources.

- Operators must provide reliable data as input for the digital twin, to be able to make the right decisions.
  - A solid data structure with clear agreements on maintaining and (centrally) storing data is important. Data can become corrupt or outdated when multiple parties interchange data, but it is not maintained by an owner.
    - *For example: if users store data in Word, Excel and apps, you have multiple locations/ versions of data. Connecting data from different sources and with different purposes, is very hard.*
- Storing and comparing data records can show deviations between planning and execution, to investigate the cause of deviation and improve operations where necessary.

9. Start a **pilot program** using iterative and agile cycles to accelerate learning, manage risk proactively, and maximize return on initial investments.

- Change the working procedures by implementing the digital twin in the daily operations.
- Industrialize the development and deployment process using established tools, while implementing the digital twin in the enterprise.
- Compare the results of the pilot with the drafted hypothesis to validate the project. Test the digital twin if it operates according to plan and aligns with the hypothesis.

10. Document hiccups and disturbances experienced during the developing and using phases to **gather lessons learned** to improve future projects.

Phase 3 – Scaling the use of the digital twin

11. **Identify opportunities** and collect **lessons learned** from development and use phase, to create a solid strategy for the scaling phase.

- Improve the implementation process where necessary and prepare the digital twin model for adaptations.
- Determine the quick wins and biggest problems of container terminals and determine the **right order of scaling**.
    - To scale the twin, there are two options available. Use it during **operations** for current processes or use the twin as an **assessment tool** to test the container flow of the terminal. The digital twin can be scaled to some terminals for actual use during operations and use this tool to digitally assess flows at other terminals, where it can be implemented at a later stage if it proves beneficial.
    - Use Table B.1 to compare the different container terminals. Preferably, scale to the same **type** of terminal first, as the existing model needs less changes to work for the other terminals. **Volume** plays an important role to determine the order of scaling.

12. Ensure **support from senior management and users**, skilled staff and expertise, technology knowledge, organizational culture and agility, organizational structure, and alignment between departments.

- Form **multi-disciplinary and cross-departmental teams** to effectuate the transformation, supported by the executive sponsorship that ensures alignment with C-level strategy.
- Ensure everybody is on the same (semantic) level, so **standardization and harmonization of data, definitions and processes are important**.
    - The more standardization there is in the process, the fewer versions/updates there should be in the digital model.
    - The **availability and standardization of data streams and data sources** will become important for successfully implementing new digital tools [27], [33]. A better understanding with decreased uncertainty and risks is the key to accelerating and scaling the use of digital twins [33].
- Develop a clear **digital strategy with clear business goals** to align people, teams, and companies involved in the innovation process. Relationships and collaboration must be redefined, and new competences should be developed by experimenting.
- A new **mindset** of organizations is necessary to **share data more freely** between departments and companies.
    - Data sharing could be enhanced through collaborative or regulatory mechanisms, such as drafting a code of conduct, establishing contracts, port regulations or licenses to operate. Incentives are also a solution, as a clear understanding and visualization of what the different events exactly mean and how they improve the port call can boost data sharing. Sharing information will be easier if all stakeholders involved benefit from the exchange by for example, better resource planning (IMO).

13. Ensure modelling capability of the organization, to maintain and upgrade the digital twin inhouse, and to be self-sufficient.

- Maintaining the twin by a third party will be too expensive and not sustainable for the company.
    - Develop the tool inhouse is an important aspect, because that's what provide momentum. If you don't know how to develop it, you don't know how to scale it.
    - Besides enlarging the scope of the model, the stuff on the edges are the big considerations when scaling.
        - Users, data, storage, display of results
        - Also, the implementation: frontend –> API –> backend –> simulation, and then back to user.
- Integrate the digital twin in the standard architecture of applications.
    - It is important that the digital twin becomes part of the standard architecture and does not remain a separate tool. It must become part of applications, so that in the event of updates, the DT will automatically be included and updated.

C

Roadmap for scaling digital twins at container terminals

The final roadmap for scaling digital twins at container terminals is presented here, and the design of the roadmap is discussed in Section 4.4. The three phases are 'developing the digital twin', 'using the digital twin' and 'scaling the use of the digital twin', and the last phase includes six additional stages described in Section 4.6.1. Most used in transformation projects is the People, Process and Technology (PPT) framework, so people (key actors), process (operations and strategy) and technology (data, hardware and software) are the three themes. The key actors of the roadmap are the users (planners of the terminal), developers (software engineers) and product owners (management).

For each roadmap step, it is determined which themes are applicable during the phases, and for the 'scaling the use' phase, it is also determined which stage is applicable . Sometimes, roadmap steps overlap multiple phases when it is relevant for two or three phases. The numbers correspond with the steps mentioned in Appendix B, where more information is presented for each step.

DEVELOPING THE DIGITAL TWIN
USING THE DIGITAL TWIN
SCALING THE USE OF THE DIGITAL TWIN
DEFINITION OF A VISION, OBJECTIVES AND RESULTS OF SCALING UP
NETWORKING CREATION AND SYNERGIES
CONTEXT ANALYSIS
DEFINITION OF THE SCALING UP ROUTE
DEVELOPMENT OF LOCAL CAPACITIES
MONITORING
PEOPLE
USERS
2. Document the operations and collect necessary data
3. Pay attention to business culture and how users want to use the DT
6. Communicate the value of the DT and involve all parties to create awareness of changing operations
7. Develop a training for users and include a transition period
8. Users must provide reliable data for decision-making
9. Change the working procedures by implementing the DT in the operations
10. Gather lessons learned
2. Document the operations and collect necessary data
3. Pay attention to business culture and how users want to use the DT
7. Develop a training for users and include a transition period
8. Users must provide reliable data for decision-making
10. Gather lessons learned to improve future projects
12. A new mindset of organizations to share data freely
DEVELOPERS
3. Start developing the DT
4. Investigate the current ICT systems and IT infrastructure, and update if necessary
7. Develop a training for developers
4. Investigate the current ICT systems and IT infrastructure
7. Develop a training for developers
11. Improve the implementation process and prepare the DT
13. Ensure modelling capability to maintain and upgrade the DT inhouse
PRODUCT OWNERS
1. Select the container terminal for the DT
2. Identify an area of focus where gains could be made
3. Make choices for the technical solution
5. Determine the governance of the DT
6. Clearly communicate and involve all members of the organization
7. Provide training for the workforce to facilitate their adaptation to the DT
8. Ensure robust data practice with clear agreements
9. Start the pilot program
1. Select the container terminal for the DT
2. Identify an area of focus where gains could be made
3. Make choices for the technical solution
5. Determine the governance of the DT
6. Involve all stakeholders
11. Define vision and results
11. Create a solid strategy for the scaling phase
9. Monitor the pilot program
12. Ensure support and inhouse knowledge. Form divese teams for the transformation
PROCESS
OPERATIONS
2. Aspects that drive the business or cause major disruptions have priority
3. The UI with dashboards providing information is key for operations
7. Establish new working procedures as input for the training
8. Establish robust data practices for operations
9. Industrialize the process, while implementing the DT
10. Gather lessons learned
2. Aspects that drive the business or cause disruptions have priority
7. Establish new working procedures
9. Industrialize the deployment process, while implementing the DT
10. Gather lessons learned to improve future projects
11. Decide the goal of DT
12. Develop a clear digital strategy to align people
STRATEGY
1. Start with a terminal with an efficiency program
2. Prioritize business value over technology and start focused to expand over time
5. Determine the governance of the DT
2. Prioritize business, start focused and expand over time
5. Determine the governance of the DT
11. Determine the scaling strategy for container terminals
12. Develop a clear digital strategy to align people
TECHNOLOGY
DATA
3. Ensure quality data for creating, validating and calibrating the DT
8. Collecting, storing, organizing, and maintaining data with clear ownership is important
12. Standardization and harmonization of data, definitions and processes is key
8. Collecting, storing, organizing, and maintaining data with clear ownership
HARDWARE
3. Use a cloud-based environment and decide on hardware requirements
4. Investigate the current ICT systems and IT infrastructure, and update if necessary
4. Investigate current ICT systems and IT infrastructure
SOFTWARE
3. Copy interfaces from software and hardware that is already used
4. Pay attention to system integration, interoperability and cybersecurity
4. System integration, interoperability and cybersecurity are important
13. Software modelling capability to maintain and upgrade the DT inhouse