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Handbook of Terminal Planning

Second Edition

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To my daughter Caterine

Preface to the Second Edition

Since the global economic and financial crisis, the world of international container transport has changed considerably over the years and with it the conditions for the development and operation of seaport container terminals. This change continues to this day and is much more complex in its structure than in the years before the crisis, when high annual growth rates of handling volume dominated almost everything in the terminals' perception (capacity counts!).

In recent years, changes in the conditions relevant to container terminals can be seen in multiple areas, namely: *terminal technologies*, *customer demands*, and *environmental rules*. These changes naturally impacted the innovation activities of the terminals which have been more complex and/or of different nature in many cases. As a result, the challenges associated with innovations have changed as well and container terminals had to cope more and more often with other – sometimes completely new – requirements. Part I of the Handbook analyzes the changes in terminal conditions. The introductory chapter compares typical terminal innovations before and after the global economic and financial crisis – regarding their respective scale of challenge – and draws conclusions on still upcoming challenges.

To remain competitive on the market in the long-term, container terminals require innovative solutions for their further development just like effective methods and concepts to efficiently implement and use these innovations in practice. Against this background, the chapters of Part II of the Handbook discuss novelties in the basic conditions of container terminals (i.e., *Instruments*, *Technologies*, *Management*, and *Environment*) and highlight new findings and solutions in the respective fields. The Handbook chapters of Parts III–V present innovative planning approaches and results for typical problems in the main planning areas of container terminals (*Terminal Quayside*, *Yard*, and *Landside*) and beyond (*Seaside and Hinterland Area*). It should be pointed out that – analogues to the first edition of the Handbook – the focus is again on planning of the terminal suprastructure.

I owe great thanks to my family for tolerating my absence and the endured hard times. . . , but now I have good news: The work is done!

The second edition of the *Handbook of Terminal Planning* is dedicated to my daughter Caterine who accompanied me through my life as source of eternal joy and inspiration.

Suderburg, Germany Jürgen W. Böse
July 2019

Last note. . .

"*Everything is going to be fine in the end.*
If it's not fine – it's not the end!"

Oscar Wilde

Preface to the First Edition

The *Handbook of Terminal Planning* is a collection of individual contributions that deal with selected issues in the context of the suprastructure planning of seaport container terminals. It thus has the character of an anthology in which chapters are contributed by an international authorship.

Seaport container terminals form a bimodal or trimodal interface of water-, rail- and road-based transport systems. If the function of the interface is limited to a bimodal cross-linking of transportation systems, such terminals typically enable a connection of container sea transport in the main run with road transports in the pre- and on-carriage of the intermodal transport chain.

The main tasks of terminal planning on the level of suprastructure comprise layout design, quantitative dimensioning of terminal resources, and the derivation of requirements for single suprastructure elements considering given operator requirements for the entire terminal. Requirements engineering usually starts with the elaboration of (necessary) functional properties which are specified in the course of the planning process and are eventually "translated" into specific technical and process-related requirements. In later project phases, the results of suprastructure planning form the basis for the equipment procurement process, construction measures, and the commissioning of projected terminal structures.

The success of suprastructure planning is given if the planning results elaborated create the necessary conditions for terminal operations meeting the requirements. The latter are especially derived from the site conditions of the particular terminal and the target system of the terminal operator.

The contributions of the Handbook give an overview of important technological and organizational system basics from a planning point of view. They also describe promising analysis and planning approaches for typical problems of the suprastructure planning and discuss instrumental issues of planning support.

This book is the result of time and effort of many, who have participated in the creation process, partly directly and indirectly, with great energy and (hopefully) also joy. I thank the authors of the chapters, who have contributed to the success of the project through their commitment and professional co-operation. I would also like to thank Mrs. Melanie Engelhardt and Mrs. Marie-Luise Stünkel for their dedicated and flexible service in the linguistic correction of the contributions and for the rendered translation work.

Special thanks go to my wife, Birgit, who accompanied the creation process of the book with much patience. Her courageous participation in numerous day and night shifts in the final phase of the book project has significantly contributed to the existence of this anthology today. Likewise, special thanks go to my mother and my grandmother, who supported me all my life with huge energy and all available means and without whose backing this book as well as much else in my life would not have been possible. The *Handbook of Terminal Planning* is dedicated to my daughter Florentine who accompanied me on my path of life as a bright sunshine for just over 1 year.

Hamburg, Germany Jürgen W. Böse
October 2010

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Part I
Introduction

Chapter 1
General Considerations on Terminal Planning, Innovations and Challenges

Jürgen W. Böse

Abstract The chapter provides a brief overview of the major tasks of container terminal planning as well as planning activities and results associated with task processing. Furthermore, the main causes for innovation activities of container terminals are analyzed and subdivided in three areas: *changes in technology*, *changes in customer demands*, and *changes in environmental rules*. For each area, typical terminal innovations before and after the global economic and financial crisis are being compared regarding their respective scale of challenge for container terminals. The results enable a better understanding of the cause-and-effect relationships of terminal innovations and the kind of relationships leading to (particularly) challenging innovation processes. Finally, the chapter provides a brief overview of the contents of all Handbook chapters.

1.1 Introduction

In the past few years, the environment of container seaports and their terminals have changed considerably. In many cases, this has also been associated with appreciable impact on the development of the ports and terminals themselves. After the decrease in transport volumes – due to the *G*lobal *E*conomic and *F*inancial (GEF) crisis – was overcome and international container transport returned back to a path of growth (see Fig. 1.1), the development of many container ports was different from before – for some rather positive but for others also negative.

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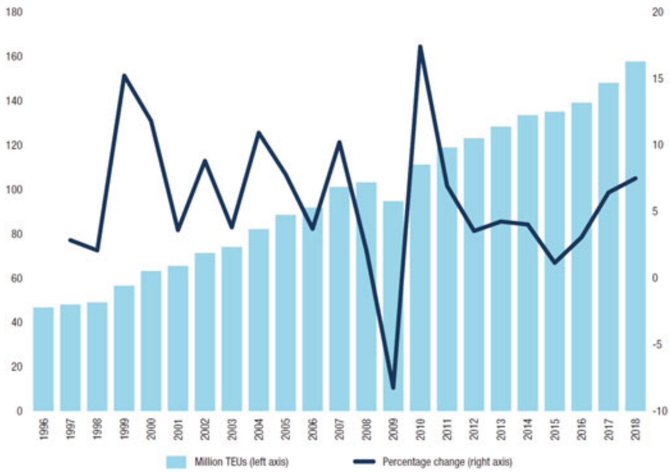

Fig. 1.1 Global containerized trade (1996–2018) in million TEU and percentage annual change, data for 2018 are projected figures (see UNCTAD 2018, p. 13)

At the beginning of the crisis (2008), for example, the ranking of the largest European container ports – according to handling volume – was Rotterdam, Hamburg, Antwerp, and Bremerhaven. All of these ports were also represented on the list of the world's 20 largest container ports. After the crisis the two German ports considerably slipped down on this list and besides, Hamburg and Antwerp changed their places in the order of the largest container ports in Europe.[1]

The reasons for the development are complex just as the changes container ports and terminals faced in the last years. Not all of them found (and find) the "right" answers to the emerging requirements and have lost competitiveness. In other words, those seaports and terminals which were not be able to cope with the changing conditions continued to grow more slowly or even had to accept losses in handling volume.

In many cases, the changes in structure and service provision on the liner shipping market were the driving force for new requirements (see Sect. 1.3). Shipping companies – as key customers of container ports and terminals – suffer

[1]The following figures show the annual handling volumes and the international ranking of the four largest European ports for the years 2008 and 2017 (see AAPA 2008 and Nightingale 2018):

2008		2017	
Rotterdam	[10,784 thous. TEU, place 9]	Rotterdam	[13,734 thous. TEU, place 11]
Hamburg	[9,737 thous. TEU, place 11]	Antwerp	[10,451 thous. TEU, place 13]
Antwerp	[8,663 thous. TEU, place 13]	Hamburg	[8,860 thous. TEU, place 18]
Bremerhaven	[5,529 thous. TEU, place 19]	Bremerhaven	[5,510 thous. TEU, place 27]

from the fierce competition that is existing in container liner shipping for years. For this reason, they have tried (and still try) to continuously optimize the operation of their fleets by both technical measures (especially ever larger vessels using more economic propulsions) and organizational measures (e.g., slow steaming or increased formation of alliances). This behavior of the shipping companies has obviously led to new – in most cases growing – requirements for the "loop" ports and terminals called by vessels of mainliner services for discharging and loading.

Besides that, further changes in the environment of seaport container terminals[2] have created new requirements for the facilities as they impact the service provision of terminals and thus their competitiveness as well. In this connection, in particular legal and technological conditions are subject to change. For one thing, container terminals have been continued to be confronted – as in the decades before – with emerging technological innovations and their implementation in terminal practice. For another thing, more and more new (or extended) environmental regulations and directives issued by national governments (and governments of a community of states) have to be followed and lead to additional requirements for the terminals.

The remainder of this chapter is organized as follows: Sect. 1.2 provides some basics in the field of container terminal planning. The focus is on relevant planning tasks including aspects of task processing and their classification based on existing planning dependencies and objects of terminal planning. In the following section, in a first step, the main causes for innovation activities of container terminals are analyzed and subdivided in three areas. In a second step, for each area of cause, typical terminal innovations before and after the GEF crisis are being compared regarding their respective scale of challenge for the terminals. Finally, Sect. 1.4 provides a brief overview of the contents of all Handbook chapters.

1.2 Basic Planning Aspects

The following considerations relate to tasks of terminal planning which may emerge during the entire life cycle of container terminals, i.e., they belong to either the *design phase*, *construction phase* or *operation phase* of related facilities. The focus is especially on the nature and scope of planning tasks as well as on the activities and results associated with task processing.

The tasks of terminal planning have not really changed in the past years. This is hardly remarkable if we have a look on the today's basic conditions of container terminal planning. On the one hand, the basicstructure of the (three) main container

[2] Hereinafter briefly referred to as *container terminal*.

flows[3] passing through a container terminal is still the same just as the starting and ending points of the underlying handling processes. On the other hand, there has been no paradigm shift in the planning of terminals which is still mainly determined by the following facts:

- The existing infrastructure (and the results from new planning of infrastructure) defines the framework for planning of terminal suprastructure,[4] while the existing suprastructure (and the results from new planning of suprastructure) in turn sets the framework for planning of terminal operation. In other words, the infra- and suprastructure being already in use and the results from new planning determine the *support potential* for terminal operation planning and, at the same time, restrict planning opportunities to a certain extent.
- Considering the different customer groups of container terminals, even today in the sixth decade of international container transport,[5] the demand of shipping companies has by far the highest priority from the perspective of terminal operators ("no vessel – no handling business!"). With the growth of vessel size, the requirements for container terminals further increase and container shipping industry dominates – perhaps more than ever – the global container transport chains ("no handling capabilities for mega vessels[6] – no/less mainliner services and possibly descent to feeder port"). To sum up, also today, planning of container terminals must primarily be geared to the customer demands at the terminal quayside.

[3] • *Transshipment container flow*: Container movements between quay wall, terminal yard, and (back to) quay wall.
- *Domestic container flows*:
  - Import container movements between quay wall, terminal yard, and the landside terminal interfaces (i.e., truck gate, railway station, and/or barge terminal).
  - Export container movements are in the reverse direction.

[4] To the best knowledge of the author, there is no official definition of "terminal suprastructure." Within the scope of this Handbook all resources of a container terminal are classified as suprastructure which are in the principal responsibility of the terminal operator. The remainder (e.g., the *quay wall*) is attributed to the "port infrastructure" which is frequently in the principal responsibility of the respective port authority. In a somewhat broader sense, the "human factor" is also rated among terminal suprastructure, if the aforementioned condition is met.

[5] In April 1966, the shipping company *Sea-Land* inaugurated the first (commercial) intercontinental liner service between New York and Rotterdam, Bremen (North-West Germany), and Grangemouth (Scotland).

[6] For more in-depth information regarding the impact of "mega vessels" on container ports and terminals see Merk et al. (2015) as well as Sect. 1.3.

The abovementioned determinants of terminal planning are manifested in two (widely known) planning principles for container terminals:

- Careful analysis of existing requirements and support potentials forms the basis for sound terminal planning, both should be done "from quayside to landside,"! That is,
  ... *beginning with quayside planning*:
  analyze the requirements and support potential for quayside planning alternatives and use analyzed results for new planning of quayside,
  ... *going ahead to yard planning*:
  analyze requirements and support potential for yard planning alternatives and use analyzed results for new planning of yard,
  ... *closing with landside planning*:
  analyze requirements and support potential for landside planning alternatives and use analyzed results for new planning of landside.[7]
- Container terminal planning should be done "from bottom-up!" That is,
  ... *beginning with infrastructure planning*:
  analyze port needs and/or requirements of (planned) suprastructure and use analyzed results for planning of terminal infrastructure (e.g., length and construction of quay wall or shape and size of terminal area),
  ... *going ahead to suprastructure planning*:
  analyze requirements of (planned) operation and support potential of (planned) infrastructure and use analyzed results for planning of terminal suprastructure (e.g., type and fleet size of vehicles for horizontal transport at quayside),
  ... *closing with operation planning*:
  analyze customer demands and support potential of (planned) suprastructure and use analyzed results for planning of terminal operation (e.g., strategies for serving quay cranes by horizontal transport or for container stacking within the yard area).
- Both planning principles overlap each other and describe together the complete planning process of a container terminal (in case of a "greenfield project"). That is, starting with planning of terminal infrastructure and closing with operation planning at landside:[8]

[7] In this regard, the following aspect should be considered:
Requirements may emerge in reverse direction as well (i.e., "towards the quay wall"). This often relates to requirements between suprastructure resources used in different terminal areas, e.g., traditional rubber-tyred gantry cranes require tractor-trailer-units for horizontal transport from/to the quay wall. Even if *A*utomated *G*uided *V*ehicles (AGV) perform just as well and (perhaps) more efficiently, their use is not possible due to safety reasons. The same applies to straddle carriers, their use makes no sense due to logistics reasons.

[8] In very few cases, terminal planning includes the elaboration of a completely new container terminal ("greenfield"). In very many cases, terminal planning is reduced to re-planning of a specific terminal area. Typical examples in this regard are "technology conversion projects" (e.g., change from straddle carrier operation to *R*ail-*M*ounted *G*antry (RMG) crane operation in the yard area), "expansion projects" (e.g., the extension of quay- and landside interfaces like the quay wall

planning of all areas (infrastructure)
→
planning of quayside area (suprastructure planning → operation planning)
→
planning of yard area (suprastructure planning → operation planning)
→
planning of landside area (suprastructure planning → operation planning)

In the light of the previous discussion, the 3-level-model of terminal planning described in the first edition of this Handbook is still to be regarded as valid. The model classifies relevant tasks of terminal planning on three levels — taking the major *planning objects* of container terminals as a basis, namely the *terminal operation*, the *terminal suprastructure*, and the *terminal infrastructure*. To be more precisely, the model distinguishes the *planning levels*: *Planning of Terminal Operation*, *Planning of Terminal Suprastructure*, and *Planning of Terminal Infrastructure* (see Fig. 1.2).

Besides major tasks of terminal planning, the model levels are being attributed by relevant aspects of task processing. These especially includes the *objectives*, *horizons*, *activities*, and *results* of planning work as well as the parties in charge. Furthermore, information on structures and processes already existing at a terminal (and being relevant for re-planning) are considered on the different model levels as well. In the following, each planning level of the 3-level-model is being described by that "part" of terminal planning which is attributed to the level using some examples from practice for illustration:

- **Planning of Terminal Operation**
  Tasks on this level focus on the analysis of customer demands and the support potential of (planned) suprastructure as well as on the short-, medium-, and long-term planning of the operation of container terminals. Accordingly, further classification of planning tasks and associated aspects of tasks processing makes sense and leads to the determination of three additional *sub-levels* being outlined in the following:

  – *Short-term Planning*
    Operational planning work concerns day-to-day operation in terms of terminal logistics (i.e., container handling, transport, and storage) as well as terminal administration (e.g., customs clearance, creating invoices or damage notifications, or processing bills of lading).

or the terminal railhead), or "organizational restructuring projects" (e.g., the implementation of pooling strategies or dual-cycle operations for horizontal transport at quayside). In the "re-planning case," planning work must not necessarily start "at the bottom," but infrastructure frequently remains unchanged and suprastructure planning in the terminal area affected is the first step (or even only operation re-planning needs to be done).

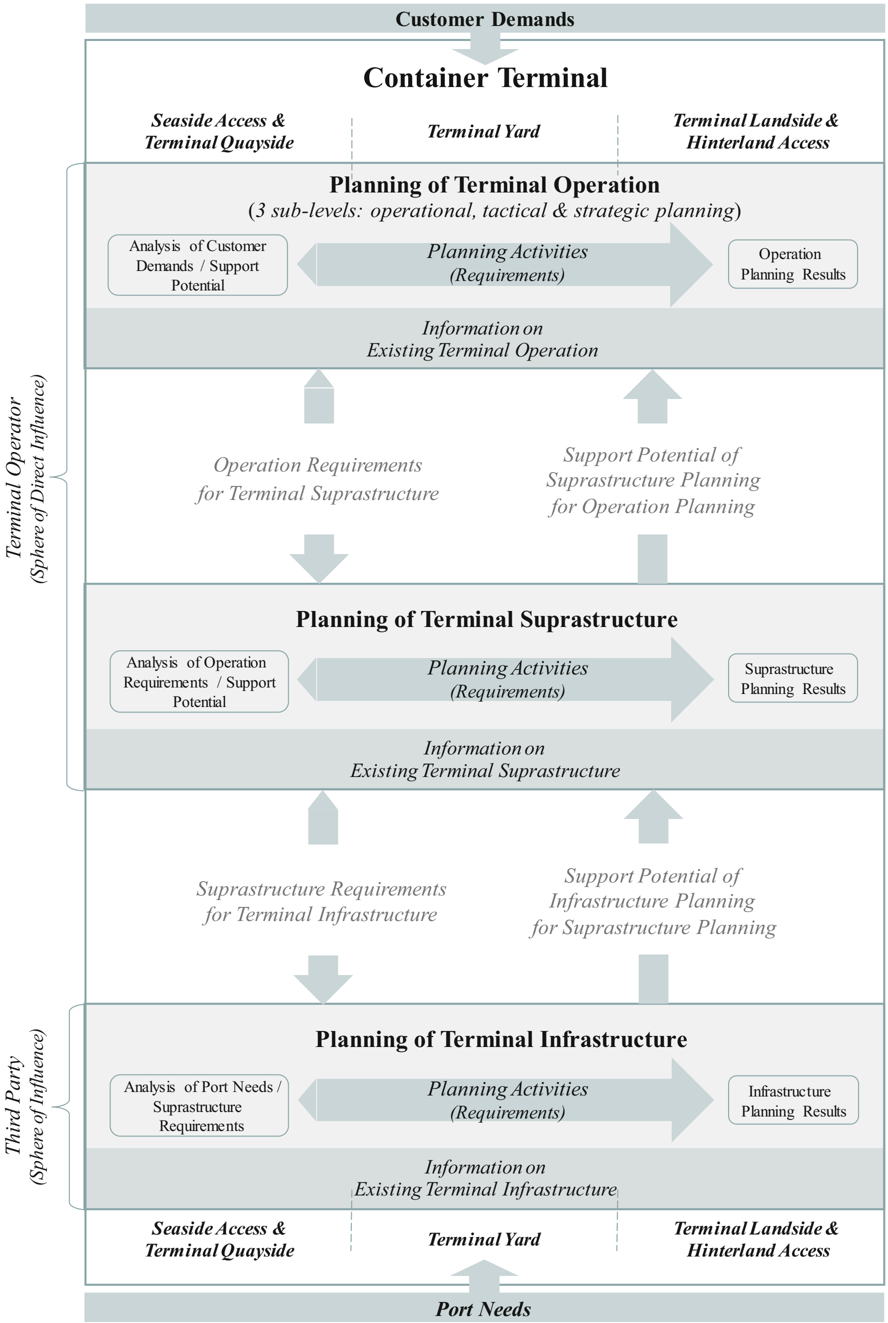

Fig. 1.2 3-level-model of terminal planning

- *Medium-term Planning*
  Tactical planning work focuses on more “durable” operational structures (up to a few years), among others, in the field of outsourcing activities (e.g., IT support), the basic use of terminal resources (e.g., shift system or strategies for equipment control) or intercompany co-operations (e.g., labor pooling with other terminals).
- *Long-term Planning*
  Strategic planning work relates to the basic orientation of terminal operation over many years such as the range of terminal services (e.g., maximum vessel size considered for processing or vessel size-related commitments to berth productivity) or long-term partnerships (e.g., establishment of dedicated berths based on strategic co-operation agreements between terminal operators and shipping companies).

- **Planning of Terminal Suprastructure**
  Terminal planning on this level deals with the analysis of requirements (from the planning level of “terminal operation”) and the support potential of (planned) infrastructure as well as with the planning of terminal suprastructure. Among others, planning activities have impact on the layout design, handling equipment, manning requirements, terminal buildings and pavement as well as the supply & disposal network. Elaborated planning results form the basis for the production and procurement of terminal suprastructure. In the context of suprastructure planning, it is being determined what kinds of resources are used (e.g., equipment type) in which quantity (e.g., fleet size) for the provision of terminal services. Typically, planning needs on the suprastructure level arise in connection with *greenfield projects*, the evaluation of strategies for *terminal expansion* or the development of implementation concepts for the *conversion of handling technologies*.

- **Planning of Terminal Infrastructure**
  In a first step, terminal planning on this level also includes the analysis of requirements for the infrastructure. For this purpose, the needs of the respective port and the requirements of (planned) suprastructure are to be analyzed. Based on the analysis results appropriate planning of infrastructure resources is carried out. Planning decisions especially relate to the preparation of the terminal area (e.g., area size, shape, and altitude or quay wall length) and the connection of the handling facility to external networks (e.g., traffic, energy, and supply & disposal). Among others, this requires planning activities in the fields of land reclamation, sand dredging, and civil engineering (e.g., related to quay wall, (external) supply & disposal pipes or cables as well as traffic access routes).

As regards planning activities on the *level of terminal operation* and *suprastructure*, these are usually the responsibility of terminal operators. This is due to the fact that they must also finance the implementation of planning results and cover the costs for the following operational use and maintenance. That is, terminal operators have a direct influence on processing of planning tasks belonging to these levels and thus on the elaborated planning results. In most cases, planning of *terminal infrastructure* is in the duty of local communities and authorities and accordingly is supported by them financially. Thus, terminal operators usually cannot (or only indirectly) enforce planning decisions regarding the terminal infrastructure (see Fig. 1.2).

In summary, the planning work on the different planning levels may not be seen independently. There are interdependencies between them, resulting in a natural (hierarchical) order of the levels. The 3-level-model of terminal planning considers the existing relationships in two ways – for one thing by the order of planning levels (see Fig. 1.2)[9] and for another by the nature and direction of dependencies.[10]
Keeping in mind the various *levels of terminal planning* it shall be emphasized that the Handbook with its contributions primarily focuses on planning tasks and activities on the *suprastructure level* of container terminals (see Fig. 1.2). In this regard, special attention is particularly given to problems and problem solving in the areas of *equipment dimensioning*, *layout design*, *sea- and landside terminal access* as well as *developing hinterland connections* of container terminals.

1.3 Innovation Causes and Challenges

Looking at the development of container terminals over the past years, the need to innovate is high for many facilities to stay competitive. Before the GEF crisis, scarce capacities and coping with “bottleneck problems” just like new opportunities in the field of automation drove the introduction of innovations in terminal practice. Today, the causes for innovations are more complex and attributed here to changes in three areas (see Fig. 1.3):

- **Changes in terminal technologies**
  Container terminals are facing new technologies which promise to improve their competitiveness and – in some cases – also reduce (negative) effects of handling operations on the environment. Accordingly, a certain pressure develops to integrate related innovations in the own terminal processes. That is, they need to be customized according to the specific conditions of the terminal and smoothly put into terminal practice (ideally) without hampering day-to-day operation. In this regard, a further distinction should be made between technology changes in the field of *container handling systems* and technology changes in the field of *Information & Communication systems* (I&C systems)

[9] *Planning of Terminal Operation* on top, *Planning of Terminal Suprastructure* in the middle, and *Planning of Terminal Infrastructure* at the bottom.

[10] *Requirements* from “quayside to landside” and from “top to down”; *Support Potential* from “bottom to top.”

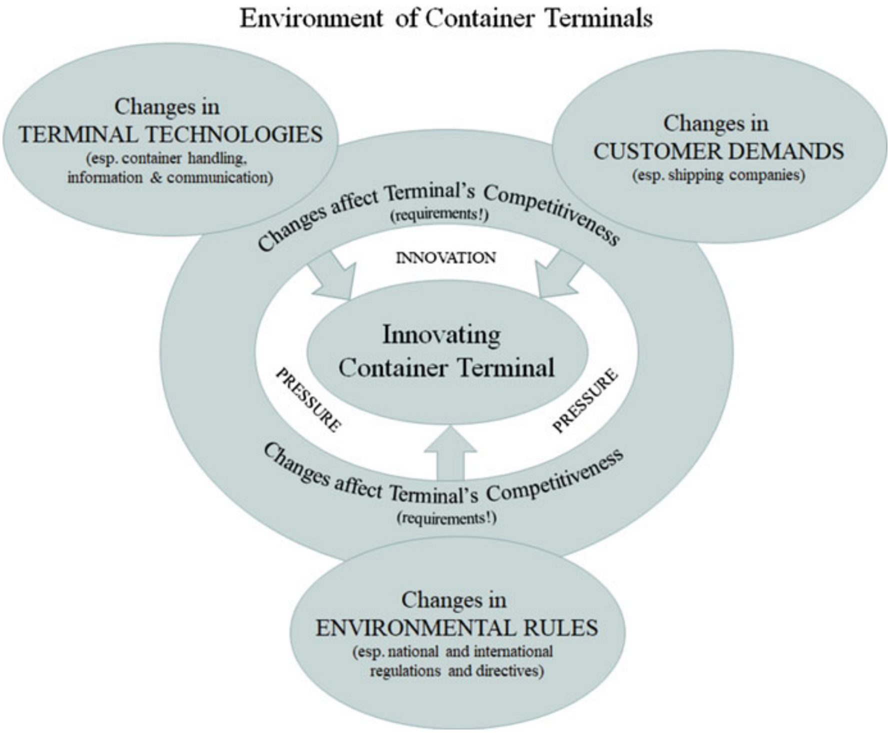

Fig. 1.3 Main causes for innovation pressure on container terminals

- **Changes in customer demands**
  In this area, changing demands of the main customers – the shipping companies – are of particular importance. The satisfaction of their needs determines the market success (or failure) of a terminal, and at the end of the day, its economic survival. Relevant changes in demand relate in particular to increasing efficiency and performance requirements for vessel processing at terminals due to the technical and logistic dimensions of loading and discharging processes of ever larger ships. Shipping companies use more and more *U*ltra *L*arge *C*ontainer *V*essels (ULCV)[11] for providing mainliner services (see Merk 2018) on the intercontinental sea routes. In recent years, the competitive situation in container shipping has been extreme for various reasons. The time- and cost-related improvement of port stays during a vessel round trip is one way for shipping companies to strengthen their competitiveness on the market.

[11]To the best knowledge of the author, the term *ultra large vessel* is not officially defined. The HVCC Hamburg Vessel Coordination Center, for example, classifies ULV as vessels with a length of more than 330 m and/or a width of over 45 m (see HVCC 2019).

- **Changes in environmental rules**
  Driven by societal interest and taken up by politics, a growing importance is attributed to environmental protection in container transport. Related changes are especially manifested in new (stricter) environmental regulations and directives[12] for pollutant emissions on national level as well as on the level of community of nations (e.g., the European Union). These also apply to container logistics in ports and have led to increasing environmental requirements for the operation of container terminals as well as for the inflow and outflow of containers from/to the sea and hinterland. The set of "restrictions" to be observed in this area is often not the same in different regions of the world and depends on the respective legislation or the implementation of international law by the national legislations, respectively. Accordingly, it can even differ between ports of the same region. All in all, the impact on the competitiveness of container terminals should not be underestimated, in particular, if there are imbalances in the legal conditions (for environmental protection) between ports or regions.

Whenever *changes* in the environment of a container terminal affect the competitiveness of the terminal and with it its economic result they represent *requirements* for the facility. In these cases, *innovation pressure* emerges, i.e., there is a certain need for own innovation so that existing and/or upcoming requirements can be better met (see Fig. 1.3).

Innovation activities are usually associated with challenges for the innovating company and thus for container terminals as well. In many cases, the required knowledge/experience is missing (especially with high level of innovation), operational core processes are impacted or more time, budget and/or manpower are needed, etc. to smoothly perform the related innovation process, i.e., (ideally) in the same way as a standard process of the company.

Conversely, this means that challenges associated with an innovation are comparatively "high" if a company has major difficulties to create the aforesaid prerequisites for carrying out innovation activities. Challenges, on the other hand, are rather "low" if the company is economically and technologically strong, and besides is highly effective in implementing innovations. As a consequence, the scale of challenges is always to be evaluated individually based on the respective conditions of each case. Against the background of this insight it becomes clear that the attempt of classifying terminal challenges of recent years can only be of general nature and does not apply to each individual container terminal. Comparing the challenges associated with innovations since the GEF crisis with those emerging in the 10–15 years before the following should be pointed out:

Challenges due to Changes in Technology

In the past years, apart from a few exceptions, the extent of technological changes in container handling has (by far) not reached the level before the crisis. Considering,

[12] A *directive* issued by the European Union is a legal act that formally requests the member states to achieve a particular result without determining the means of achieving this result. It is to be distinguished from a *regulation*, which is self-executing and does not require any specification for implementation.

e.g., the automation of horizontal transport (by AGV) and yard crane operations (by RMG) in the 1990s or the automation of straddle carriers and use of semi-automated double-trolley or tandem-lift quay cranes in the early 2000s, the recent technological changes (and resulting terminal innovations) have been less radical in most cases. Today, the abovementioned terminal equipment is more or less regarded as a "standard product" (see PEMA 2016). During the last years, the innovation focus was more on the further development of terminal technologies (e.g., implementing Lift AGV technology or using hybrid drive engines for straddle carriers.)[13] or the transfer of proven technologies (especially in the field of I&C) to new application areas within the terminals. Examples in this regard are the use of *O*ptical *C*haracter *R*ecognition (OCR) systems in the portal of quay cranes and the entrance of terminal railheads for automatically reading container numbers or the application of remote control systems to remotely operate cranes at quay wall from a control center (see Holmgren 2011).[14] Accordingly, challenges for container terminals originating from these kinds of technology changes are more likely to be classified as moderate compared to those before 2008.

Nevertheless there are exceptions in the more recent development of terminal technologies where the transfer into operation practice is associated with considerable challenges for the terminal. In the field of handling technologies, this concerns, e.g., the greenfield implementation of automated *R*ubber-*T*yred *G*antry (RTG) cranes or the conversion of a yard area with manually operated RTG to automated RTG operation, just like converting a fleet of traditionally driven transport vehicles (with diesel-hydraulic or diesel-electric engines) to electric drive technology. In the former case, especially the "clash" of automated terminal equipment and manually operated road trucks in the yard area leads to challenges for terminals.[15] In the latter case, new transport equipment has to be procured or vehicles in operation need to be refitted (if possible) and, among others, new strategies for vehicle control are to be implemented (e.g., due to battery recharging times to be observed).[16] In both previously discussed examples, processing of vessels at quay wall is directly affected (and with it the interests of the terminals' main customers), if any problems emerge with the use of new technologies. Considering the level of innovation and

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[13] A first Lift AGV prototype has been built and tested in the year 2008. At the port of Hamburg, first straddle carriers with hybrid drive technology came into operation at the beginning of 2019.

[14] The original application area of OCR systems at container terminals is the truck gate. Since the early 2000s related systems have spread widely throughout the world and are today standard in truck processing procedures of truck gates. Furthermore, remote-controlled crane operation was part of automated RMG yard systems from the very beginning. Due to safety reasons (instructions), it is necessary to manually control the container handover process between automated RMG cranes and manually operated road trucks (or internal tractor-trailer-units) at the landside end of RMG blocks.

[15] Currently available automated RTG systems (e.g., in use at the Terminal Petikemas Semarang in Semarang, Indonesia) carry out fully automated container stacking and use remote control technology for lifting/lowering containers from/on trucks in the RTG portal.

[16] Electric drivetrains are now available for all widespread equipment types of horizontal container transport, i.e., for AGV and straddle carriers and terminal tractors.

the possible (negative) customer impact the challenges for terminals implementing related technologies are accordingly high.

In the field of I&C technologies, it should be pointed out that besides the transfer of I&C technologies to other application areas within container terminals (see above), the systems[17] in use for many years are continuously developed further in terms of their functionalities, decision support methods, application of advanced I&C technologies, etc. Due to many years of experiences with these systems the challenges for terminals have been rather moderate in recent times compared to the 1990s when, e.g., automated positioning systems were initially implemented on the terminals (frequently based on GPS technology). An exception in this area represents innovative concepts[18] and I&C technologies (e.g., internet of things, cloud computing or advanced sensors, and mobile system technologies) which form the basis for the present process of digitalization or use its potentials for recent years. The level of digitalization was always high at container terminals. Nevertheless, the abovementioned concepts and technologies represent novelties for the terminals and thus they are comparatively challenging from their perspective. From the perspective of the author, the first appreciable challenge for many terminals will be to find the "right" (competent) staff for analyzing the requirements and opportunities of the current phase of digitalization and to prepare the way for implementing the related tools and/or system solutions in the own terminal processes during the next years.

Challenges due to Changes in Customer Demands

Due to economic reasons (explained in Sect. 1.2), the shipping companies are the most important customers for container terminals. Driven by their dominant position in international container transport, especially the "big ones" have always had quite high handling requirements for the terminals (costs and time) called by their mainliner services. It is important to comprehend that this is all the more the case if several terminals are located in the same region serving the same (or similar) hinterland. Accordingly, challenging requirements of their customers (at seaside) are not new for the terminals, but based on several years of experience they know to deal with it. A successful strategy was and is (so far) to continuously initiate technology- or organization-related innovation processes in defined terminal areas, so that the processes affected remain limited and possible risk manageable.[19] Analogues to the cost and time requirements mentioned above, container terminals have always had to cope with requirements resulting from the growth in vessel size.[20]

[17] For example, terminal operating systems, positioning systems or administrative systems for customer, and freight data storage and processing.

[18] In many cases subsumed under the buzzwords "big data technologies" or "big data analytics."

[19] For example, by using pooling strategies for horizontal transport vehicles exclusively serving the quay cranes of a (single) berth or procuring new (more advanced) quay cranes to "upgrade" a specific berth.

[20] Considering the largest container vessels of their time, the capacity has risen 2.2-fold from about 4,500 TEU to about 10,000 TEU between 1990 (President Truman, a C-10-class vessel) and 2005

But in contrast to former times (i.e., before constructing and commissioning the Maersk E-class vessels between 2006 and 2008), for some years, more and more container ports and terminals reach the limit of their abilities in vessel processing, due to the considerable size of container vessels put into service.[21] Predictions on the development of vessel dimensions show that a further capacity increase (beyond 24,000 TEU) will also lead to further (appreciable) increase in vessel dimensions (see, e.g. Park and Suh 2019). If both occurs (increase in vessel capacity and dimensions), quite a few container ports will have serious difficulties to meet the upcoming requirements as not only the terminal suprastructure will show inefficiencies (e.g., quay cranes) but also the port infrastructure. Possibly, the water depth is too low to enable calls of such *E*xtra ULCV (EULCV) at full capacity utilization and/or the quay wall construction is too weak to take the load of larger quay cranes or other significant bottlenecks occur. With regard to the complex (and partly uncertain) influences impacting the development of container vessels in their size and dimensions, only the next few years will show where the development is going and which challenges container terminals actually have to overcome in future.

Besides the issues of vessel size and dimension, the risen number of ULCV in the fleets of shipping companies imposes additional challenges for container terminals. If you look at the development of average size of container vessels in this context, between 1995 and 2005, it increased by about 45 %. Due to the growing number of ULCV, in the following 10 years the increase significantly accelerated and, in 2015, the average vessel size was about 168% compared to the level of 2005 (see Murray 2016; Tran and Haasis 2015). This dynamic development has lasted until today and will further continue to do so most likely. In the last three years, the absolute number of ULCV has more than doubled and increased from 40 vessels at the end of 2015 to about 100 vessels at the end of 2018. The ULCV coming into operation in 2017 and 2018 alone account for a third of new vessel capacity in these years. For the year 2025, Merk (2018) assumes that around 10% of all container vessels have a capacity of 14,000 TEUs and more. To meet the high ULCV processing requirements in terms of "berthing time" and "handling volume," the general operational approach applied by (actually all) terminals is of organizational nature. In other words, they schedule *more resources*[22] and try to use these resources *more efficiently*.[23] At terminal landside, the approach is the same

(Gjertrud Maersk, a Maersk D-class vessel) and has risen again 2.2 fold to about 22,000 TEU in 2019 (nine CMA CGM LNG vessels are scheduled to come into service from the end of 2019).

[21]Vessel length of up to 400 m, maximum width between 61 m and 62 m, maximum draught of about 16 m and between 22 and 24 container rows across deck.

[22]This means, more cranes at quay wall, more vehicles for horizontal container transport, and more cranes for storing and retrieving containers in the yard area.

[23]For example, by using advanced pooling strategies at terminal quayside or implementing more powerful methods for vehicle scheduling and dispatching and — in case of automated container transport — for vehicle routing. Furthermore, effective methods for control of container stacking and rehandling within the yard area are of interest for improving resource efficiency as well.

but (so far) the focus is primarily on more operation efficiency (e.g., by application of slot management systems to control the arrival process of road trucks or the use of OCR systems at the truck gate and railway station). To the best knowledge of the author, so far, there is no terminal worldwide that has implemented a radical new technology for more effective handling of ULCV volumes at terminal quayside and/or landside.

Against the background of this situation, there may emerge considerable operational difficulties for terminals if several ULCV calls overlap each other. In such cases, the peak loads induced by individual ULCV add up and may lead to operational conditions which are no longer manageable for a terminal as, e.g., not enough quay cranes (and space for further ones) are available on the quay wall or yard cranes are missing and cannot be added without significant extra expenditure (especially in case of RMG cranes) or the peak situation at quayside is aggravated by peak requirements simultaneously emerging at landside. This means, if technological innovation is out of question for a terminal in this situation, at short-term, there only remains the attempt to come to an agreement with the shipping companies to reschedule the vessel call pattern. In the medium- and long-term, the extension (if possible) of the traditional terminal suprastructure will become necessary associated with high costs and low utilization. To sum up the impact of drastic growth in vessel size: The terminals will be facing with further increasing challenges also in future, but today it is not yet clear to what extent this will happen and where the limit is.

Challenges due to Changes in Environmental Rules
Considering the development of environmental requirements for container terminals in the past, it can be basically stated that regulations and directions in this area have continuously increased in their number and restrictive effects over time (especially since the 1990s). Accordingly, a distinction of time periods (before and after the GEF crisis) makes little sense to classify challenges induced by changes in regulatory rules for environmental protection. More and higher legal requirements relate to all major areas of environmental pollution, i.e., pollutant emissions to *air* (including noise), *soil*, and *water*. Due to the kind of service provision at container terminals, air emissions and legislative measures associated with their reduction usually have most relevance for container terminals. The handling processes of terminals are typically based on the use of large-scale equipment which is still driven by diesel or diesel-hydraulic engines in many cases polluting the air by hazardous gases as well as greenhouse gases. Additionally, there are the terminals' customers which deploy large-scale equipment as well and in case of shipping companies even ultra large-scale equipment, namely deep-sea and feeder vessels.

Against this background, two levels of action are to be distinguished from the perspective of container terminals – for one thing, the reduction of air and noise emissions by own operation activities and for another, the limitation of emissions generated by their customers. Regarding the former, there are regulatory rules that define limit values for air emissions of terminal equipment which have to be observed when new equipment is put into operation. These rules are usually becoming stricter in several stages over time.[24] For container terminals, emerging challenges are manageable if they include changes in legal provisions in their long-term equipment procurement process. This allows them to smoothly retrofit (or replace) "insufficient" equipment step by step and avoids an "overnight" exchange of all drivetrains or replacement of all equipment units. The latter is challenging as modified (new) control strategies and/or organizational concepts may be required just like "other" know-how in terms of equipment maintenance & repair (see above).

Similar to gas emissions, challenges induced by (too) high noise emission can be considered as comparatively moderate (if included in terminal strategy in the long run). "Air pollution" by terminal noise usually "only" leads to difficulties in the proximity of urban areas and besides that, there are a variety of effective measures – on different levels – to reduce such emissions.[25]

In summary, new (stricter) environmental regulations and directives continuously have led (and will continue to lead) to the need for innovation on container terminals. Nevertheless, from today's perspective, related innovations appear manageable if container terminals (and ports) pro-actively consider the consequences of regulative changes in their suprastructure (and infrastructure) planning.

For emissions of transport vehicles owned by terminals' customers, the vehicle owner is in charge for complying with the applicable provisions of a port (e.g., since 2010 a ship at berth in EU ports needs to use fuels with a maximum of 0.1% sulfur content). Nonetheless, it is in the interest of terminals and ports (for reasons of competition and environmental protection) to support their customers in this regard. They do so, for example, by providing shore power supply (cold ironing) allowing vessels to shut off their auxiliary engine during port stay, charging lower port dues and tariffs when burning fuels with less pollutants in ports (see Merk 2014) or implementing a slot management system to reduce truck waiting times at gate.[26]

All in all, it can be concluded that the challenges for container terminals continue to be high. In comparison to former times (before 2008), in recent years they have associated less with technological innovations but more with technological enhancements and organizational innovations (e.g., serving an ULCV with 8–9 quay cranes and handling 8000 or 9000 containers per vessel call). Depending on the

[24]In Europe, for example, the EU directive 97/68/EG had to be applied for newly procured "non-road mobile machinery" (including also terminal equipment) between 1999 and 2016. The directive increasingly limited the NO_x emissions (nitrogen oxide) and PM emissions (particular matter) of related equipment by following stages: Stage I (1999), Stage II (2002), Stage IIIa (2006), Stage IIIb (2011), and Stage IV (2014). Since beginning of 2017, the EU regulation 2010/26 determines the NO_x and PM emission requirements for non-road mobile machinery based on emission limits of Stage V.

[25]For example, by direct soundproofing at engine (equipment level), by noise barriers on the terminal area (construction level) or by limiting the number and operating hours of equipment in use (operation level).

[26]Noting that in most cases the implementation of slot management systems is likely more driven by economic and capacity reasons.

development of ULCV in size and number, the current level of innovation could no longer be sufficient in the future to remain competitive in the medium- and long-term.

Accordingly, terminals should increasingly investigate (or even develop) innovative container handling systems[27] that can form the basis for new handling solutions at quay wall and the landside terminal interfaces in future. In this respect, the chapters of the Handbook provide new findings as well as innovative planning approaches and results that can serve planners as a basis and inspiration for their daily work to (better) overcome existing and upcoming challenges for container terminals.

1.4 Contents of the Handbook

This section provides a brief overview of the topics discussed in the different chapters of the Handbook. The book is divided into five parts: Part I with general considerations on terminal planning, innovations and challenges; Part II with basic aspects in the fields of "instruments," "technologies," "management," and "environment"; Parts III–V with innovative approaches and results of terminal planning representing both concepts and solutions which have already been successfully implemented in practice.

1.4.1 Basic Aspects: Instruments, Technologies, Management, and Environment

A fundamental prerequisite for the generation of competitive planning results is the knowledge about relevant basic conditions of planning activities in the respective application domain (here: container terminal), such as available technologies and management concepts or legal regulations in force or to become in force. Furthermore, effective instruments are of interest which can help planners to identify, elaborate, and evaluate appropriate action alternatives. Against this backdrop, the first three chapters of Part II of the Handbook focus on *instruments* that support terminal planning in particular on the operation and suprastructure level. It is worth noting that these instruments can also be helpful for solving specific problems on the level of terminal infrastructure:

Chapters 2 and 3: The contributions of *Schütt* and *Saanen* give a comprehensive overview of the support options simulation models provide and which improve-

[27]New ideas and concepts of innovative handling systems are discussed, e.g., in Chaps. 13, 20, and 24 of the Handbook.

ments can be achieved through their use in solving planning problems on all levels of terminal planning. In this regard, the advantages of using simulation models for planning issues in the different phases of "terminal life cycle" are shown, starting with the (initial) dimensioning of infrastructure and suprastructure going ahead to detailed planning and resource commissioning up to the day-to-day operation of container terminals. Here, not only problems of equipment and layout planning are discussed, but also possibilities for the use of simulation in functional specification and validation of the terminal IT systems and their optimized configuration regarding the day-to-day operation. Based on this, Schütt additionally focuses on the application of simulation for evaluating ecological impacts and Saanen introduces concrete guidelines for using simulation on the various levels of terminal planning. Both authors see a great potential for simulation in operational planning as it allows a comprehensive view into the near future which can lead to significantly better planning decisions.

Chapter 4: Furthermore, the contribution of *Anvari et al.* uses the methods Queuing Theory, Petri Networks, and Discrete Event Simulation to address the fleet sizing problem of horizontal transport vehicles at terminal quayside. The authors compare the three methods regarding their results and effort for application and recommend Queuing Theory for pre-planning issues at the beginning of terminal projects, while Discrete Event Simulation should rather be used subsequently to support detailed planning of terminal resources.[28] Regarding the Petri Net method the authors see application options for pre-planning issues as well, but first further development is required to make the method more applicable for practitioners.

With respect to issues in the field of *terminal technology* in particular the Chaps. 5–8 provide new findings and solutions for planners on both the suprastructure and the infrastructure level. The first three chapters relate to terminal suprastructure and discuss aspects of terminal automation in conjunction with eco-friendly drive technologies, pavement options for container terminals considering the requirements of operational use, and the digital change in ports and resulting opportunities for improved data-driven decision-making. The latter deals with the infrastructure resource "quay wall" and presents technical options for its design.

Chapter 5: Against the background of the changes in the environment of container ports and terminals and resulting challenges for their operation (see Sect. 1.3), more and more container terminals (have) recognize(d) automation as an effective approach for cost control and performance improvement. The contribution of

[28]Differentiating between *pre-planning* and *detailed planning* activities on the infra- and suprastructure level, the former end up with a prioritization of elaborated resource alternatives and finally lead to type-related resource decisions (e.g., use of AGV instead of straddle carriers or vice versa) including a rough estimate on the number of resource units required for day-to-day operation. The latter especially includes the specification of functional, technical, and process-related requirements for the resource type favored before by pre-planning. Results of detailed planning form, e.g., the basis for tendering processes bringing out the equipment supplier(s) and construction firm(s) chosen for a project.

Rijsenbrij & Wieschemann provides an overview of the state-of-the-art of terminal automation and besides, describe short-term developments in this area along with an approach for successful implementation of automation projects at terminals. Furthermore, the authors discuss economic and technical aspects of different electric drive technologies and outline the opportunities for container terminals associated with the use of electrical powered transport vehicles.

Chapter 6: In the context of I&C systems and their use for information processing and decision support, the contribution of *Heilig et al.* introduces the concept of business analytics and points out its support potential for terminal planning and management. The contribution specifically focuses on data mining approaches and provides a comprehensive overview of applications at container terminals and related research. Considering the area of decision-making and decision support, the authors establish a data-driven perspective on terminal planning and management, complementing the traditional optimization perspective.

Chapter 7: As regards the pavement of container terminals, the contribution of *Schnabel* provides experiences and findings on the technical options available for terminals today. After a compilation of terminal equipment loads, the author gives an overview of practical proven pavement solutions for different operational areas of container terminals. Both advantages and disadvantages of available pavement types are summarized and suitable wearing courses for the different operational areas are proposed.

Chapter 8: The infrastructure decision on the quay wall construction type has long-term character and is comparatively complex as many different aspects need to be considered for decision-making. The contribution of *Meyer* presents different quay wall construction types being relevant for container terminal operation. Furthermore, the author elaborates the most important criteria in the process of finding a preferred quay wall type.

The last two chapters of Part II of the Handbook primarily provide new findings for strategic planning of terminal operation. That is, the aspects discussed by the authors are more management-related. For one thing, they refer to the value of a cluster- and network-orientation for container terminals including opportunities to improve this orientation and for another, the focus is on environmental rules for vessel operation and the impact on container ports and terminals requiring new answers from strategic planning as well.

Chapter 9: Many container terminals are focused today on operational excellence and put their "own processes" into the center of attention. *de Langen* argues in his contribution that in addition to this inward-looking view, container terminals may benefit from an orientation on the overall supply chain of which they are a part as well as an orientation on the port cluster of which they are a component. For this reason, the author discusses the embeddedness of container terminals in international supply chains, among others, with examples in the areas of information exchange and extended gates. These show the advantages for container terminals resulting from a supply chain orientation. Furthermore, the author questions the role of container terminals in port clusters with examples of how a cluster orientation is valuable for terminals. In this regard, relevant issues include, e.g., education and training, intra-port container flows, and port marketing.

Chapter 10: The contribution of *Schinas* aims to examine the fundamental connections of ship-related emission regulations to container port and terminal issues. For this purpose, the author outlines the applicable international and regional regulations on air emissions from vessel operation and analyzes their impact on port and terminal decision-making and functioning. The analysis also focuses on effective solutions, especially those promoted by the port or terminal management.

1.4.2 Main Planning Areas

Based on the well-known terminal operation areas (quayside, yard, and landside) the Handbook differentiates three main planning areas for the handling facility "container terminal:" *Seaside Access and Terminal Quayside*, *Terminal Yard*, *Terminal Landside and Hinterland Access*. In a broader understanding of the boundaries of a container terminal, the seaside and hinterland access of the facility are considered as part of the Terminal Quayside/Landside planning area and thus as scope of activities for terminal planning. All topics (chapters) belonging to one planning area are provided in a separate part of the Handbook.

This means in detail, planning contents of the Seaside Access and Terminal Quayside area are summarized in Part III, contents of the Terminal Yard area in Part IV, and contents of the Terminal Landside and Hinterland Access area in Part V. For each planning area, the related part of the Handbook discusses innovative approaches and results of terminal planning representing both concepts and solutions which have already been successfully implemented in practice. Analogues to Part II of the Handbook, the focus is again on terminal planning on the suprastructure level.

Planning Area: *Seaside Access and Terminal Quayside*

Chapter 11: Being aware of the continuous development in size of container vessels, the contribution of *Schönknecht* presents a method for analyzing costs and performance of related vessels as means of transport in global transport chains for ISO containers. The rational is the continuous growth of container vessels, the infrastructure development to cater for them and the strong variations in bunker prices over the past years. The use of the method makes clear that the factors for success or lack of success for large container vessels can be found almost exclusively in the container ports and their hinterland infrastructure in combination with the general loop design.

Chapter 12: Safety of vessels is of major importance when approaching a port and berthing at a terminal. Continuously increasing vessel sizes raise the pressure on proper design of new waterborne infrastructure, but also on safety and risk assessment methodologies when applied to vessels for existing infrastructure. The contribution of *Burmeister* introduces international accepted approaches how to design waterborne infrastructure (especially port approaches and related maneuvering areas) for ensuring safe vessel navigation and maneuvering. Moreover, basic methods and guidelines of safety and risk assessment used for this purpose in the maritime world are presented.

Chapter 13: Ultra Large Container Vessels with high trade volumes per port are making fewer calls per round trip with more transshipment cargo and more port times at higher costs. Innovations which increase handling productivity and streamline handling operations of feeder vessels are required to avoid inefficient long stays in ports as well as to reduce the costs resulting from processing of such mainliner vessels. The contribution of *March* presents a solution (referred to as "Integrated Terminal Ship System") that satisfies these requirements by the innovation of direct container handling between mainliner and feeder vessels. Basically, there are two technical solutions possible: Transshipment containers are simultaneously handled on both sides of the mainliner using two finger piers (first alternative) and im-/export containers are un-/loaded at the mainliner quayside while transshipment containers are directly handled between mainliner and feeder vessels at the mainliner waterside using one finger pier (second alternative).

Chapter 14: Besides quantitative dimensioning of terminal equipment another major task of suprastructure planning on the quayside is the layout design of the operation area. In this regard, the contribution of *Ranau* compares the space requirements of two operation systems for horizontal container transport and derives planning assumptions for dimensioning their terminal layout: The focus is, on the one hand, on AGV systems which perform quayside container transport, e.g., at several terminals on the Maasvlakte (Rotterdam) and, on the other hand, on automated straddle carrier systems being in operation, e.g., at container terminals in Brisbane and Los Angeles. Both system alternatives are investigated in combination with semi-automated quay cranes and automated RMG yard cranes working perpendicular to quay. Main areas for analyzing planning assumptions are the quay crane portal and backreach as well as the traffic area in front of the yard blocks. Based on the findings gained by the analysis, for both systems, the author provides a viable quayside layout and an investment comparison of the equipment required for operating a mainliner berth.

Chapter 15: Within the last 15 years the capacity of the largest container vessels has more than doubled, bringing more containers to terminals within each single call. Among the strategies to increase quayside productivity are, e.g., pooling of carrying equipment as well as dual-cycle and twin lift operation of quay cranes. The latter may be implemented with least impact on spatial and process change requirements and include the joint vertical movement of two 20 foot containers. But only if applied to operations of both lifting and carrying equipment container terminals will fully benefit from each twin move. *Eisenberg et al.* see a gap regarding the assessment of the potential productivity gain by twin carry operations. Their contribution wants to fill this gap by the example of the implementation of twin carry operation for straddle carriers at the HHLA Container Terminal Tollerort (Hamburg, Germany).

Planning Area: *Terminal Yard*

The first three chapters of this part of the Handbook highlight methods to support the short-term scheduling of yard resources. From the perspective of suprastructure planning, knowledge about related methods and their impact on yard operation is essential for an adequate evaluation of logistics capabilities and economic viability of yard equipment. Appropriate knowledge in this regard represents an indispensable prerequisite for planning of yard suprastructure that wants to meet emerging requirements.

Chapter 16: The contribution of *Caserta et al.* provides an updated survey on rehandling of containers at maritime container terminals. In particular, the authors review contributions with a particular focus on post-stacking situations, i.e., problems arising after the stacking area has already been arranged. Three types of post-stacking problems have been identified, namely (1) the remarshalling problem, (2) the premarshalling problem, and (3) the relocation problem. This research area has received an increasing attention since the first version of this contribution appeared in the first edition of the Handbook. Within this update, we discuss recent developments presented in literature. In particular, available solution approaches from the fields of exact and (meta-)heuristic methods are given and benchmark datasets are summarized. Moreover, an overview on extensions of post-stacking problems and according solution methods are discussed.

Chapter 17: As the interface between waterside and landside transport chains, the container yard plays a vital role for the performance and competitiveness of container terminals as a whole. Most terminals of relevant size nowadays deploy gantry cranes for container stacking operations, which are therefore key elements of modern terminal planning. The creation of an efficient terminal design therefore requires a profound understanding of the capabilities and performance of gantry cranes, which is in turn largely determined by the rules and strategies defining the way these machines are deployed in operation. Against the background of this basic conditions, the contribution of *Kemme* reviews academic works on container stacking and yard crane scheduling and besides, critically discusses their practical relevance. Finally, the autor explains the strategical implications of these strategies for terminal planning.

Chapter 18: The contribution of *Speer & Fischer* compares four different automated RMG yard crane systems with respect to their characteristics and performance. Furthermore, different approaches for their scheduling are presented: On the one hand, a branch-and-bound procedure for single yard block optimization, and on the other hand, an integrated scheduling approach which optimizes the equipment at terminal yard and waterside simultaneously. Moreover, a combination of the two approaches is studied. Using a specifically designed simulation model, both the crane systems and the different scheduling approaches are extensively examined with respect to their performance and practical use, e.g., in case of disturbances. It turns out that both approaches are advantageous compared to simple priority rules, and that the crane systems with overtaking possibility are well-adaptable, optimizable, flexible, and productive. Moreover, it can be concluded that optimization aspects should already be taken into account in the terminal planning phase, in order to reach optimal productivity levels later on.

Chapter 19: A well-designed stack layout is crucial for container terminals to maximize both the internal efficiency and the responsiveness to customers (such as vessels, trucks, and trains). One key performance indicator, influencing both efficiency and responsiveness is the container seaside lead time for unloading a container from the vessel, transporting it to the stack area, and storing it in a stack block, or vice versa, loading it in a vessel. The terminal performance depends not only on operational variables such as the location of the container in the stack, but also on design decisions, such as the type and the number of stacking cranes per stack, the type and number of internal transport vehicles, the layout of the stack (parallel or perpendicular to the quay), and the dimensions of the stack. In this chapter, *Roy & de Koster* present an overview of analytical models that rely on queueing network theory, for analyzing stack layout decisions in automated container terminals and summarize the design and operational insights.

Planning Area: *Terminal Landside and Hinterland Access*

Chapter 20: The contribution of *Malchow* presents the *P*ort *F*eeder *B*arge (PFB) as "green logistic innovation" for container ports and besides that, the author describes different application areas for this particular type of barge. The PFB is a self-propelled and self-sustained container pontoon of double-ended configuration (capacity: 168 TEU). It can release the terminal gates from queuing trucks and the terminal ship-to-shore gantry cranes from inefficiently serving small inland barges. Three application areas are seen for the PFB: Shifting container haulage within ports from road to waterway, supporting feeder operation and loading and discharging inland barges. The PFB can be easily integrated in the container logistics within a port. In congested ports or ports with limited water depth and/or insufficient container handling capability even deep-sea vessels can be directly served midstream by the PFB. Hence, the barge can also be used as an emergency response vessel to quickly lighter grounded container vessels. The green potential of the PFB can be further exploited by using LNG as fuel.

Chapter 21: Ports close to cities or even embedded within a city increasingly suffer from truck traffic to and from the terminals. Especially container drayage causes high traffic peaks to serve ultra large container vessels. Citizens complain about traffic jams, hazardous emissions and noise, forcing politicians to think about restricting rules and regulations having an impact on port productivity. Sustainable mobility is not at all a new idea, however, applicable technologies to make heavy port traffic more environmentally-friendly without losing efficiency are just emerging. The contribution of *Froese* discusses several promising solutions in this area, noting that they are either in their early phase of introduction or currently under consideration. This explains the fact that the topic is a very dynamic one and there is a lack of references to proven applications.

Chapter 22: The aim of the contribution of *Wilmsmeier & Monios* is to revisit in the context of more recent work in the field the work of Cullinane & Wilmsmeier on the contribution of the dry port concept to the extension of the port life cycle (first edition of the Handbook). This extension relied on the use of vertically integrated corridors between the port and the dry port to move containers quickly and smoothly from the port to the hinterland for processing and stripping. The authors bring another layer to this conceptualization by adding the inland context, applying the intermodal terminal life cycle published by Monios & Bergqvist in 2016, in order to discuss synchronicities between the port and inland terminal (or dry port) life cycle. Both seaport and dry port in the hinterland have their own institutional governance structures, national and local policy and planning regimes etc., and these change over time according to the different life cycles. Yet the demand for improved quality of port hinterland access means that the two nodes must increasingly work together, which is already demonstrated in increasingly integrated ownership and operational models. However, for port hinterland transport to function smoothly, it is essential to understand both potential synergies and conflicts between various stages of the port and dry port life cycles.

Chapter 23: The contribution of *Arendt* describes the characteristics of European intermodal transport in seaport hinterland and pure inland relations (terminal-to-terminal). The market situation in these fields is assessed as well as existing problems of current intermodal services. Based on the apparent limitations of intermodal transport systems, the author describes the requirements of the market and possible factors for a more consumer-oriented intermodal service. Finally, he proposes an innovative concept for a prime service as a means of increasing the competitiveness of intermodal hinterland transports in a sustainable way.

Chapter 24: In recent decades, the intermodal container transport has emerged more and more as the basis for a globalized economy. This results in appropriate seaport container terminal requirements with terminals serving as transshipment nodes and as an important interface between different transport modes. However, the operational performance in such network nodes is only one fundamental aspect. Especially the capacities of inbound and outbound flows, i.e., the deep-sea and the hinterland transport, play an essential role, in particular because hinterland transport is a typical bottleneck. To solve these problems, the contribution of *Daduna & Stahlbock* presents different concepts including a dislocation of the terminal structures as well as an increased involvement of rail freight transport. However, some crucial problems and questions should be investigated. Although after the economic crisis in 2009 the international container transport increased again, it is much lower than predicted in previous years.

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Part II
Basic Aspects: Instruments, Technologies, Management, and Environment

Chapter 2
Advanced Simulation Technology in Planning, Implementation, and Operation of Container Terminals to Cope with the Varying Challenges Caused by the Shipping Industry

Holger Schütt

Abstract The container terminal industry is meant to be quite conservative. However, ever faster changes in global container transport (e.g., increasing vessel and package sizes or concentration in the hand of fewer global consortiums) lead to continuously growing productivity and efficiency requirements in recent years. As a result, container terminals have to become more and more flexible to adapt their processes to the changing conditions. Thus, during the last 60 years simulation technology found its way from technical applications to the world of logistics and specific software tools for simulation and emulation have been developed for container terminals. Nowadays, change and innovation processes (e.g., regarding terminal dimensioning and configuration or process and equipment automation) just like daily operations may be accompanied by means of simulation and emulation to secure the efficiency of the operation. A holistic approach of using means of simulation or emulation in the field of planning, implementation, and operation of container terminals is introduced in the following to explain the possible range of application from global to detailed analysis, testing of control systems, new ways of training as well as terminal process optimization and shift and personnel planning. In this respect, it will be emphasized that the terminal operator himself will be enabled to use these technologies as tools without being a simulation specialist.

2.1 Simulation in Logistics

In the last century, simulation has found its way into the automotive industry, where nearly each investment is verified by simulation means (see, e.g., Burges and Mayer 2006). Nowadays, this approach becomes more and more accepted in the analysis

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of logistic processes, especially in the field of container terminals. Early examples for terminal simulation are presented by Khoshnevis and Asef-Vaziri (2000), and an overview of various simulation projects is given, e.g., by Stahlbock and Voß (2008), Angeloudis and Bell (2011), and Dragovic et al. (2017).

The challenge to be managed with this technology is: logisticians normally are not able to handle simulation systems. Therefore, special simulation tools are developed to close this gap between application knowledge and the theory of simulation. First examples and a base for such tools which uses terminal operator's vocabulary were already published by Boll (1992).

A new field of application of simulation models is coming up this century: The use of simulation for forecasting the operation of the coming shifts and days. These results will support terminal operators in the personal planning for the next days. Additionally, it will start a paradigm change in the short-term planning on the terminal: Instead of waiting for bottlenecks to occur during operation and then to react, terminal operator's staff in the control room will be able to locate bottlenecks in advance and thus they are in the position to work pro-actively.

2.2 The Planning Phase of a Container Terminal

As a result of the strong competition between ports and terminals, it is essential to improve service quality as well as to reduce the costs. To satisfy customers' demand, like short lead times and high quality products, it is nowadays necessary to carry out all operations fast and efficiently. To meet these demands, terminals are looking for new technologies, such as automated transportation systems and process automation. Furthermore, there are many significant industry changes that influence the development of terminals, e.g., ever increasing vessel sizes[1] in all services and regions, space limitations as well as labor agreements and labor costs. These constraints raise the question whether the terminals will optimize operations to increase the throughput of existing terminals or if new facilities will replace or expand existing capabilities.

However, the more complex and automated the operation at the container terminal becomes, the more rises the importance of a highly sophisticated IT-system to cope with the demands (see Schütt 2015). Nowadays, handling volumes between 6000 and 8000 containers per vessel call are not uncommon in case of mainliner services. Furthermore, some of the influencing quantities have a random character, e.g., arrival times, daily no. of boxes, loading and discharging times of vessels, container movement time of cranes, etc. Last but not least, most decisions have

[1] In 2017, the shipping company CMA CGM ordered a group of nine container vessels each with a capacity of 22,000 TEU. The first two vessels of this group are expected to be delivered in 2019 (see Ziyan 2018). In April 2020 twelve vessels with nearly 24,000 TEU are already sailing for MSC and HMM respectively.

to be made based on uncertainty, as still not all information required is available at the time of the decision making.

With the use of simulation technology, it is possible to reproduce the system "container terminal" as a virtual system in order to analyze an existing or planned terminal in detail. As simulation of logistic processes normally uses IT components as means of representation, the real system "container terminal" has to be represented by a software model that is executable on related (hardware) components and reproduces terminal processes – including fortuitous events – in an equivalent or adequate way, respectively. Thus, a simulation system is a powerful tool by which the user can "play through" and subsequently analyze the processes of a terminal in order to get a transparent basis for the decision-making process.

The planning phases of a container terminal may be supported by means of simulation. For each of these phases, distinct simulation tools have been designed in such a way that users can, even without availing themselves on a software engineer's specialized expertise, "play through" several scenarios with input parameters chosen by themselves.

As shown in Fig. 2.1, various tasks have to be taken into account during the planning phase. While in the beginning of the planning (pre-planning) the amount of information about the terminal is very small (low level of detail) it increases with time until the implementation of the operation starts at the end of the planning phase. Due to the amount of information available, different simulation tools may be used for the analysis and decision support. In the pre-planning phase, the planner

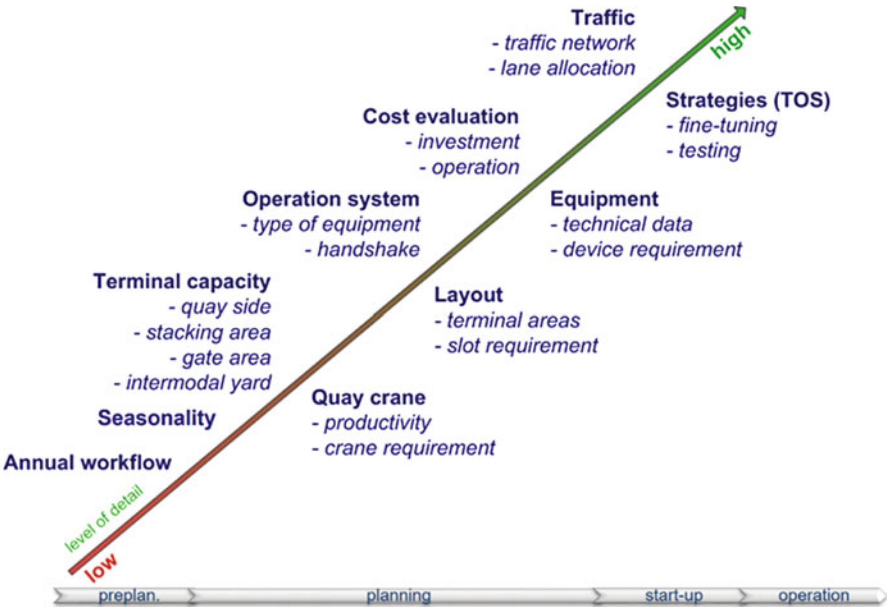

Fig. 2.1 Tasks during the planning phase of container terminal operation

has to think about the annual workflow of the terminal, typically spreadsheets are used in this phase. Knowing more about the seasonality of the container flow and the planning basics of the terminal (area size and quay length) a first calculation of the capacity of the terminal can be done. By getting more information about the operations system, the layout and the technical data of the equipment, detailed planning of the productivity, and the amount of terminal devices needed may be carried out. At the end of this main planning phase and during terminal start-up, the fine-tuning of the (operations) strategies can be supported. Examples for such kind of tools supporting these tasks are discussed in the following sections.

2.2.1 Terminal Capacity

The first question while planning a terminal is calculating terminal's capacity. A tool working on the lowest level of detail of available information does not consider the operations system the terminal uses (beyond the quay wall). The capacity of a container terminal is limited by the capacity of the container stacking area or the quay. The latter is limited by its length and the capacity of the *S*hip-*T*o-*S*hore (STS) cranes available. The aim of such a tool is to identify the current bottleneck of a terminal. With this, the user can determine how much throughput a terminal handles with the existing facilities, as well as the possible capacity of a planned terminal, i.e., how much throughput does the terminal handle in maximum. Such kind of a simulation tool requires a multitude of input data for simulation, e.g.,

- information about the yearly throughput,
- its distribution over the year in order to simulate peak times,
- the number of container slots available in the yard area,
- the container dwell times regarding individual container types,
- several vessel types for automated generation of vessel schedules,
- the apron shape to model the quay in any desired configuration,
- the distribution of the STS cranes along the quay,
- a shift plan determining the available work power (if requested).

Figure 2.2 shows a screenshot of the capacity planning tool called CHESS-CON Capacity (see ISL 2018) based on Boll (2004). The terminal processes in the yard and other subareas are not regarded in the simulation.

After the simulation runs, the tool evaluates the quay as well as the stacking area and provides information about the utilization of the quay and the crane performance. The user is informed, e.g., if the quay length fits to handle a definite container volume and how many STS cranes are necessary to serve the arriving vessels. For the area evaluation, the tool ideally distinguishes various area types (e.g., areas to stack standard, reefer, dangerous, and empty containers) and provides an indication of the sufficient number of stacking slots.

Fig. 2.2 Screenshot of the capacity planning tool CHESSCON Capacity

The terminal operations system responsible for stacking and transporting the incoming and outgoing containers is not examined. This is part of a further step of terminal planning going into details.

2.2.2 Simulation and Analysis of Container Terminal's Operations System

The simulation of the operations system used supports the user in investigating planning alternatives or elaborated designs of container terminals. The design comprises the layout and the deployment of equipment. The interdependence of these two factors of terminal superstructure is a focal point of the model, i.e., it investigates which areas are available and which equipment types and operations system should be deployed best.

The evaluation of the simulated container terminal is carried out with regard to economic and technical aspects. The output of the target variables, measured against each other and interpreted, are in particular the costs incurred and the handling volumes achieved. This strategic level covers the planning of new terminals, the expansion of existing ones, and changes in organizational structures. Simulation tools applied for this purpose do not track each single container but the behavior of the whole system "container terminal." With regard to the simulation analysis of terminal's operations system, a separate module is usually applied for drawing up appropriate simulation scenarios. The scenario module combines all input data needed by the respective simulation tool and builds a frame for each analysis. In this regard, Hartmann (2004) describes how to generate consistent data.

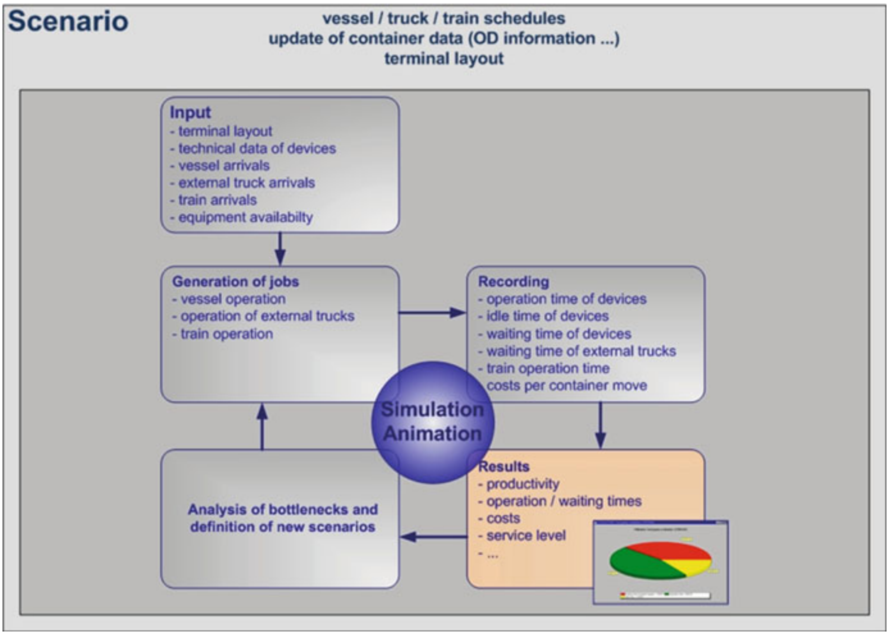

Fig. 2.3 General procedure for simulation of container terminals. OD Information: Information about the origin or the planned destination of the container

The simulation approach shown in Fig. 2.3 includes a scenario module (input) and provides the necessary flexibility for taking new concepts of the system interfaces *quayside*, *gate*, and *railway* into consideration. After entering the information about the terminal layout (typically using a graphical editor), the terminal equipment (amount and technical data), and the workload at terminal quayside, gate, and railway station, the tool will generate job lists which have to be processed by the simulation. An animation is used to let the user understand, what happens within the "black-box simulation." All steps of the operation are recorded into a database to get information, e.g., about waiting and idle times as well as the productivity achieved. With the results of the simulation, the user can calculate the operating costs for each terminal operations system. In the end, a technical and economical evaluation of all analyzed systems will be executed.

In this way, the whole terminal operation can be analyzed and optimized. Different operations systems (e.g., straddle carriers, *R*a*il*- *M*ounted *G*antry (RMG) cranes combined with *A*utomated *G*uided *V*ehicles (AGV) or shuttle carriers,[2] *R*ubber-*T*yred *G*antry (RTG) cranes combined with tractor-trailer units or multi-trailers) may be compared by *K*ey *P*roduction *I*ndicators (KPI) or costs per container move. Similarly, the layout may be optimized regarding the size of the stacking blocks

[2]Straddle carrier with stacking capability of 1-over-1-high.

(length, width, and height) and the traffic control (e.g., one way tracks and priority handling). Furthermore, operations strategies (e.g., for pooling transport equipment, twin, and tandem operation or block allocation) may be analyzed and optimized with tools of this level of detail. The latter delivers valuable insights into organization principles for economic use of terminal resources assuming typical operations cases (see Sect. 2.3).

2.3 Terminal Start-up, Optimization, and Operational Planning

Additionally to the simulation tools and purposes described at the strategic level (see Sect. 2.2), today, simulation is also used to support commissioning activities as well as the day-to-day operation of container terminals. Both areas of application are discussed in the following subsections mentioning various examples for using simulation in this manner.

2.3.1 Equipment Emulation

Applying simulation for emulation of terminal equipment has proved to be promising when analyzing (and solving) problems at the operational level. Emulation is defined as "a model that accepts the same inputs and produces the same outputs as a given system" (see IEEE 1989). The emulation is directly coupled to the real *T*erminal *O*perating *S*ystem (TOS). With these attributes, emulation can be used among others for:

- **Evaluation and optimization of strategies used in the TOS**
  While in typical simulation tools the control strategies for terminal operations are usually modeled within the tool, in the case of emulation the implemented strategies in the real TOS are used. Thus, a more realistic model may be built using this available level of detail. In this way, the strategies may be optimized by finding the values of their parameters, which fits best to the container flow and equipment used.
- **Test bed for the real TOS**
  While the device emulators are reacting in the same manner as the real devices do, the TOS may be tested against a software system instead of the real terminal. Setting up of new releases of the TOS will be much smoother after testing it against software emulators. Furthermore, the tests are more time, maintenance, and fuel saving than testing with the real equipment. This test bed may be used by software engineers as well as by terminal operators.

- **Visualization of new terminals**
  Using the 3D-animation component of an emulation tool, the planned operation of new terminals as well as new processes at existing terminals can be demonstrated visually. The animation can be used to explain the changes in operation and to show their benefits.
- **Test bed for acceptance tests of equipment**
  Within the start-up phase of a terminal, the acceptance test of devices needs trouble free surroundings. Typically this is not given within this start-up phase. The failures of neighboring subsystems (e.g., STS cranes, horizontal transport, or stacking equipment) will disturb the acceptance test. By using the emulators for related subsystems, these failures can be omitted and the acceptance test may concentrate on the behavior of the device to be tested.
- **Training purposes of terminal operators**
  With means of emulation, the crew of the control tower can be trained without impacts on the real operation. They use the real TOS within their training and use the 3D animation as their "looking out of the window." The evaluation tool shows the results of their work in terms of KPI, e.g., quay crane and vessel productivity or waiting and idle times of the handling equipment. In this way also extreme situations (e.g., breakdown of equipment or delay of vessel arrivals) may be trained without impacts on the real live.

Thus, in contrast to simulation an emulator clones the functionality of the target system. The emulated system receives identical data, works in the same manner, and produces identical results like the original system, i.e., the emulated system imitates the original one (see Rintanen and Allen 2016). Considering terminal simulation elaborated models reproduce, among other things, the behavior of devices applied for container handling. These representations may be used as base for drawing up device emulators. Note, however, that emulation typically represents dynamic aspects of the real system in a more detailed way and that an interface between the emulation model and the TOS has to be built, additionally.

Within simulation tools of container terminals the behavior of the transport and handling devices is modeled. The respective modeling of equipment may be used as a base for drawing up device emulators. Note, however, that emulation typically represents dynamic aspects of the real system in a more detailed way and that an interface between the emulation model(s) and the TOS has to be built, additionally. The core system of the CHESSCON Virtual Terminal tool (see Fig. 2.4) is based on the simulation tool SCUSY (see Boll 1992). The layout definition as well as the evaluation and operation database is re-used. While in the case of simulation the information flow and in particular the control strategies are part of the model (depending on the level of detail available), the real TOS or the implemented TOS algorithms, respectively, cover control tasks in the emulation case.

The behavior of the equipment has to be simulated in both cases. While in the simulation tool typically all devices are included in one model, the Virtual Terminal tool provides the *D*evice-*e*mulator *Co*mmunication *Net*work (DeCoNet) for conducting emulation studies, for details see Kassl et al. (2008). In this way,

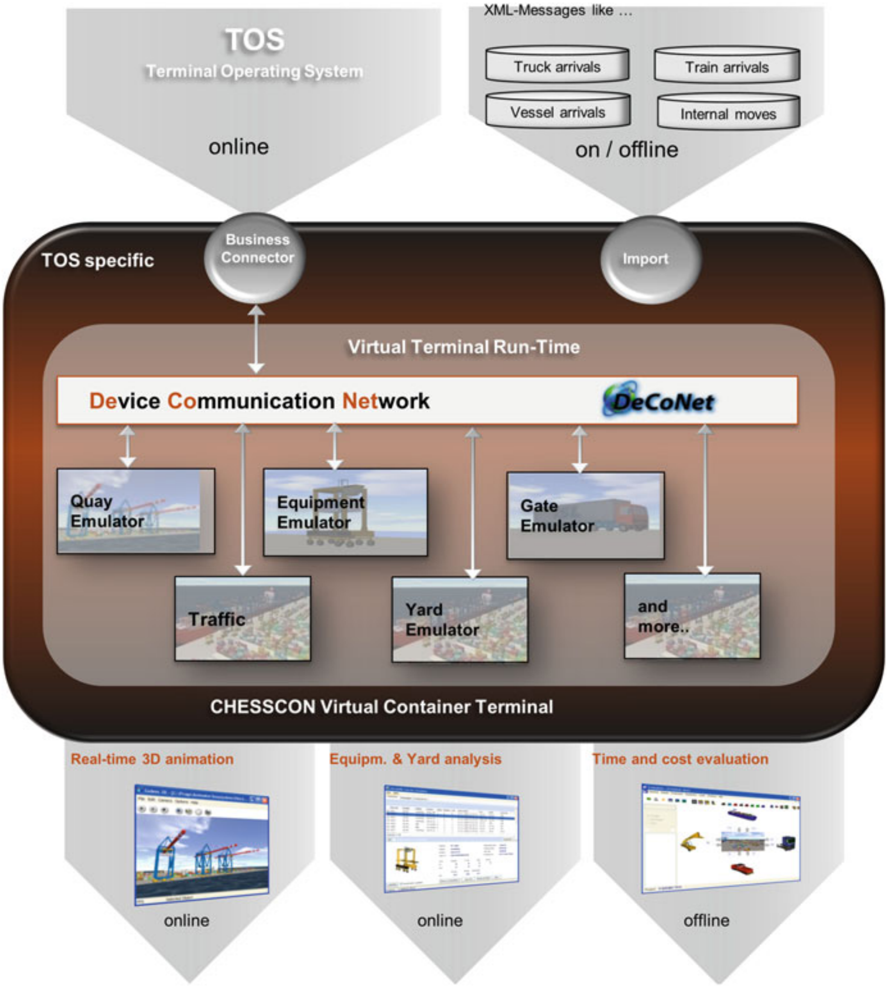

Fig. 2.4 Architecture of CHESSCON Virtual Terminal combining the simulation and the emulation (using the TOS as control module) functionality within one tool

the (device) emulators may use different computers in a network. Furthermore, this open architecture provides the possibility to use emulators of different suppliers. Thus, a terminal operator may connect the emulator of his device supplier (if available). Especially for the use of complex routing algorithms within the horizontal transport this functionality will be helpful.

Since various modules of the Virtual Terminal tool required for simulation form also the basis for its emulation functionality, the latter may be used as a logical additional function after simulation-based terminal planning. Of course, the level of detail may require some more data concerning the layout or scenario description,

Fig. 2.5 Screenshot of the emulation of Eurogate's container terminal Bremerhaven (Germany)

but the main input data may be re-used out of the planning phase. In this way, the terminal operator may use the Virtual Terminal tool in a similar way as he applies tools in the field of simulation. Only the interface to the TOS (called business connector) has to be configured by simulation specialists. In the case of emulation, the scenario generator may be substituted by a replay function of historical data, which have been logged during real terminal operation.

The methodology described has been used for the planning, start-up, and is still in operation at the fully automated Container Terminal Altenwerder in Hamburg (Germany). Each software release is still tested against the emulators before "going live" at the terminal. Saanen (2004) and Ha (2007) describe similar approaches as well. While the huge greenfield projects – especially the automated ones – are using this technology as a standard, nowadays also smaller and existing terminals count on emulation for securing new TOS releases and/or training issues. For example, Eurogate IT Services GmbH uses it for optimizing and emulating the terminals of the Eurogate group (see Fig. 2.5 as well as Sect. 2.3.2).

2.3.2 Pro-Active Operational Planning – Using Simulation to Have a Look into the Future

Most terminals today use a re-active approach within their terminal operation: Terminal planners on the operational level (yard, vessel, berth, and process planners) are using their experience to pre-plan the operation of the next shift/the next days. Sometimes this experience is increased by trainings using the means of simulation as mentioned before.

Once the planning is finished, the staff in the control room is monitoring the operation and is re-acting on bottlenecks that may occur during the operation. Some of these obstacles are generated randomly by breakdowns of equipment, these may not been foreseen at all. But others are a result of the planning parameters, set by the planners. In this case, simulation of the coming shift (or longer periods) may detect them before they occur in reality. The reason for these bottlenecks (e.g., overload of a block with one RTG or congestion due to high traffic in a specific area) may be deleted by changing the planning parameters. This pro-active planning will avoid bottlenecks, which are to be foreseen. With two examples this new and advanced approach will be discussed.

2.3.2.1 Shift Preview – the Look into the Crystal Ball

The Bremerhaven terminal operator North Sea Terminal Bremerhaven, a joint venture of APM Terminals and Eurogate, uses emulation technology mainly for TOS functionality and strategy testing. But they complained about the time to build scenarios and to run the simulation, as they wanted to use the technology to check the current shift planning. The idea of *Shift Preview* was born. It includes the following steps (see Fig. 2.6):

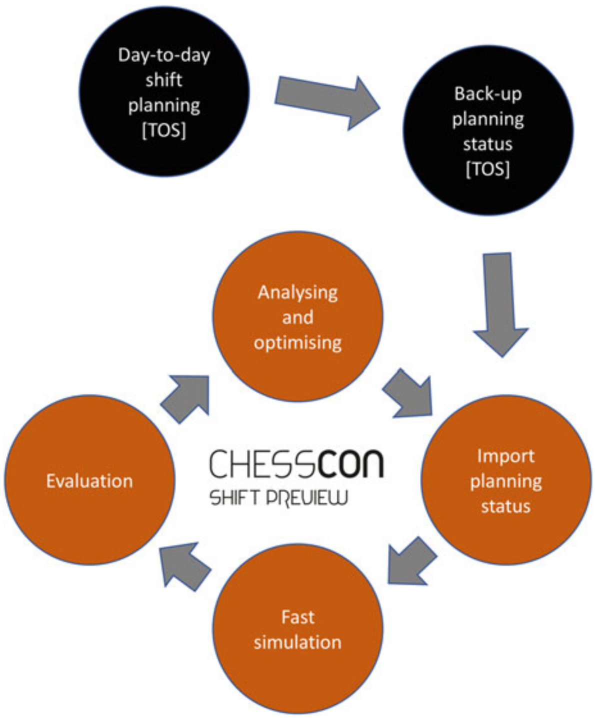

Fig. 2.6 Stepwise optimization of the planning with *Shift Preview*

- Terminal's shift planner plans the next shift (his day-to-day task).
- After finishing his planning, he starts the *Shift Preview* by pressing the backup button of the TOS (in this case NAVIS).
- The current planning state including the yard inventory, the work queues defined, and all planning parameters (e.g., allocation filters) are imported to the simulation model.
- A fast simulation starts.
- After a short time, the result of the forecast for the next shift is presented in a compact format, the *O*verall *E*quipment *E*ffectiveness (OEE) evaluation. The OEE combines information about the productivity, the utilization of the used equipment, and the quality of the process within one KPI. Thus, the control staff detects potential bottlenecks or underutilization in one view on the dashboard and may go into deeper in the hierarchical structure of the evaluation to understand the reasons. A similar approach has been used by Pinto et al. (2017).
- The planner may – after analyzing the results – change some planning parameters and run the simulation again (steps 1–4).

In this way, the shift planner will be set into the position to plan in a pro-active way instead of waiting for bottlenecks during the operation and re-act accordingly. This approach combines the following benefits:

- All data is directly imported by using the interfaces to the Navis TOS, which are provided by the Virtual Terminal technology. This results in a very fast scenario generation and guarantees a very accurate modelling of the next shift.
- Instead of asking the TOS for each decision, a model of the TOS is rebuild within the simulation system, which is able to depict the strategies of the real TOS by reading their parameters (e.g., yard planning's allocation filters). Thus, a very accurate modeling of the strategies has been achieved.
- The speed of the simulation has been increased by changing from time-based to event-based mode. In this mode, the computer is no longer speeding up by a defined factor (e.g., 5-times real-time), but it jumps from event to event and actualizes the clock in each step. In emulation mode, the interface between TOS and the Virtual Terminal model typically uses asynchronous communication which requires the time-based mode. By using the detailed TOS model, as described before, the faster event-based mode is available.

The system is installed at North Sea Terminal Bremerhaven and the result may be summarized by the statement of the operations manager *Marc Dieterich*: "Why do we use *Shift Preview*? ... Terminals, which today are not in the position to analyze their operation predictively, are living yesterday!"

2.3.2.2 SimTOS – Simulation-Based Online Evaluation Engine for Container Terminal Operating System

The SimTOS[3] approach also combines the TOS with an emulator, but is looking further into the future than the Shift Preview. The approach is being developed in conjunction with a South Korean control system supplier *T*otal *S*oft *B*ank (TSB), the University of Bremen (Germany), and the Pusan National University (Korea).

With the help of Big Data, a forecast for expected workload on different areas of the terminal beyond the current shift plan and beyond the current detailed planning schedule can be generated. Historical data, taken from a customer's terminal, has been analyzed (see Riaventin et al. 2015). Based on these results, the workload as well as container parameters of the future period is forecasted (see Nam et al. 2016).

The resulting scenario may be simulated directly using the configuration shown in Fig. 2.7 (emulation system integrated into the TOS) and again the OEE evaluation supports the planner in finding the optimal planning parameters. This includes the number of equipment and gangs required for the next shifts as well as their allocation to the working queues on the terminal. In this way, the terminal planner is provided with a decision-making support in the field of equipment and staff scheduling for the next days.

Fig. 2.7 Emulation system integrated as a tool into the control system (here TSB's CATOS – *C*omputer *A*utomated *T*erminal *O*perating *S*ystem)

[3] The project is funded by the German Government (BMWi – the *B*undes*M*inisterium für *W*irtschaft und Energie, Germany) and the Korean Government (MOTIE – the *M*inistry *O*f *T*rade, *I*ndustry, and *E*nergy, Korea). The BMWi is represented by the AIF Projekt GmbH as body project executing organization.

2.4 Evaluating Ecological Impacts

More and more ecological impacts become important for container terminal planners. Therefore, the integration of these aspects into simulation tools is state of the art. As an example, the inclusion of an acoustical analysis into the tool CHESSCON Simulation will be shown in this section. The aim is to provide the planner of a container terminal with noise-relating evaluations. It shall be mentioned that the planner still works within the same environment using his well-known tools and that any noise-relating facts are reduced to a minimum. The implementation needs the following three steps (see Fig. 2.8):

- **Generating sound emission in the simulation model**
  Inside simulation tool, all devices used from the available terminal equipment are included with their technical parameters (device type definition), as far as they are required for the task of productivity and cost evaluation. Additionally, a database was created containing known types of devices and their noise values for different states of operation (device noise parameters). Afterwards, these values will be used to calculate the emissions of the terminal by allocating the devices saved in the database with the states of operation measured in the simulation. Noise emissions are created in each active operating state, i.e., when a device moves around, receives/delivers a container or even when it is standing still with running engine. Each action generated by the simulation will be recorded in a given time pattern (1 h) and assigned to the corresponding sector(s). After the simulation finished, there will be information for each sector which device has worked (in each time slot) how long in which operating state (state/time).

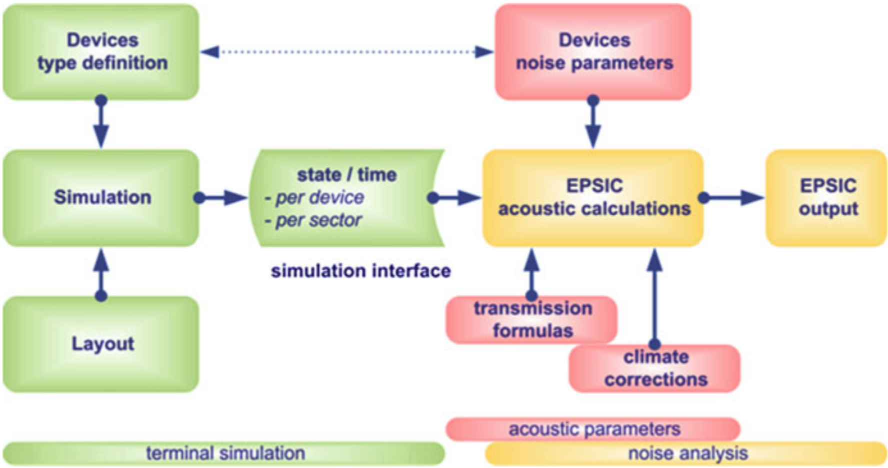

Fig. 2.8 Modules of the noise evaluation enhancement called EPSIC (see Hünerberg et al. 2009)

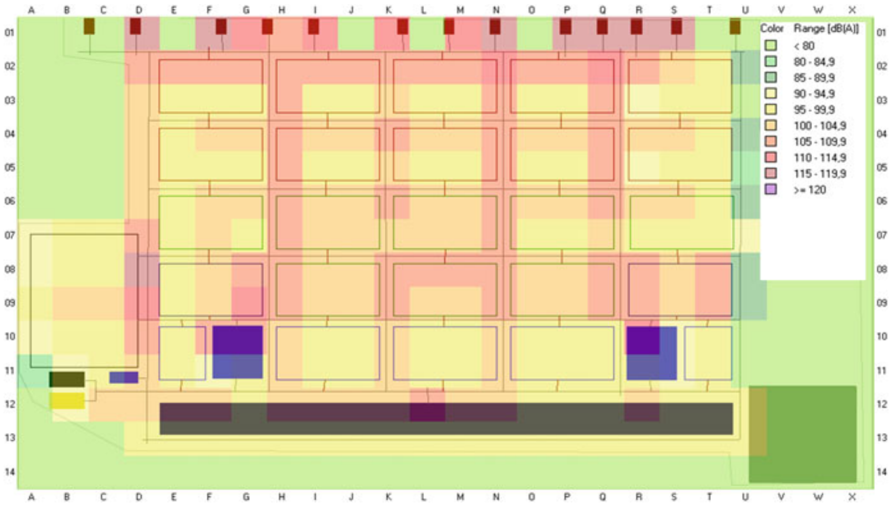

Fig. 2.9 Noise emission of each sector of the terminal (color regarding the amount of noise emissions)

- **Noise transmission**
  While generating device related emission values is part of the main module of the simulation tool, the noise propagation calculation is realized by means of an additional module. The (transmission) formulas using climate correction parameters correspond to the norm DIN ISO 9613-211 (see DIN 1999). The calculated emission results can be provided as one overall value and/or as value for each sector of the terminal area. Figure 2.9 illustrates the graphical output which allows a fast overview of emission distribution. Each sector of the emission diagram is dyed regarding the amount of noise emissions.

A planner using related emission diagrams can identify noise sources that have a great impact on the target locations and he is able to modify the planning (at short notice). Relocating areas with a strong noise impact or implementing noise protection packages may help to reduce the noise impact at the target location. This tool gives the planner the possibility to make noise-relating decisions at a point in time long before the beginning of the licensing procedure for envisaged (terminal) construction measures, which may avoid protracted, and therefore, expensive amendments.

2.5 Conclusion

Nowadays, there is a large range of simulation tools which are mostly used for analyzing and solving (planning) problems at the strategic level. This concerns, e.g., the planning phase of new (greenfield) terminals or the reorganization and optimization of existing terminals structures. In recent years, more and more simulation technology was also applied to operational issues within the start-up phase of new terminals using the principle of equipment emulation (see Sect. 2.3.1). In the emulation case, an interface between the simulation tool and the TOS is necessary to combine the material flows of the emulation model with the information flows of the TOS (induced by the implemented strategies for resource control).

Additionally, the tool examples presented in Sect. 2.3.2 show that simulation technology is already taking place in the day-to-day operation of container terminals. The main idea of these tools is that the terminal operator is not required to define extra scenarios to start simulation or emulation runs, respectively. Instead, operational planning and forecasting results are used for scenario definition. They will just be a (further) component part within the TOS and can be used for a look into the "crystal ball" (at any time). This way terminal operators have an effective instrument for meeting the tremendous operational challenges of today, such as the processing of mega container vessels (with thousands of containers) in comparatively short berthing times.

Furthermore, ecological impacts may be analyzed in the field of noise emissions by combining the simulation of terminal operations with appropriate emission parameters. Using transmission formulas, the noise impact of a terminal at any point in the surrounding area may be calculated. As a result, the terminal planner is able to evaluate related impacts in a very early planning phase, long before the licensing procedure forces him to do. At this stage, a re-planning is much cheaper than it will be later on. In a similar way, the carbon footprint of the terminal may be calculated by assigning emission parameters to the device types in use.

By making simulation technology accessible to logisticians and management, numerous software solutions have helped simulation to find its way into the logistics and provide support, e.g., for planning "greenfield" projects, optimizing processes, and implementing new control strategies, thus contributing to major cost savings and quality improvements in the industry.

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Chapter 3
Modeling Techniques in Planning of Terminals: The Quantitative Approach

Ensuring Planning Becomes Reality – Even in Challenging Times

Yvo A. Saanen

Abstract The use of models in the process of planning a container terminal, or optimizing day-to-day operations, as well as to ensure the quality and configuration of the control software at a terminal, has proven to be of great value in practice. Simulation models, as one kind of models, are particularly well applicable due to the variable and interdependent nature of processes at a container terminal. For the various stages in terminal planning and expansion, various types of models are needed. At the early stages, more abstract models are applicable, and in later stages this can lead to very detailed models, capable of answering very detailed questions, such as about ways to control the terminal and about the exact kinematic specifications of equipment. A crucial part in the process of applying models is validation – making sure the models are representing reality for the scope of the analysis, as well as accreditation – making sure that the users of the results the models provide are actually trusting, and therefore also use them. We have seen that the lifespan of simulation models, in particular, has been extended from early design-engineering questions to final commissioning of control software and day-to-day operations, where models serve as a means for answering questions in a quantitative way, as well as project memory. In the near future, we expect more advanced models to play a role in the decision-making during operation by taking the data off-line and advancing the operation in an accelerated way to see where problems might arise.

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3.1 Introduction

Terminal planning involves high capital investments, and therefore needs to be conducted in a systematic, thorough manner. This to oversee the planning tasks and all available options which allow for a holistic design, and to ensure that all system components – civil, equipment, labor, IT, and layout – are well aligned. This necessity increases with the growth of terminal complexity due to scale, and more advanced technology in the form of automated processes, which are both administrative and physical.

This chapter is about the application of advanced models to support the terminal planning process. The aim is to realize the terminals as planned, also with regard to performance. A long list of cases[1] has provided a wealth of experiences of applying simulation models in container terminal planning – e.g., APM Terminals Portsmouth (2007),[2] DP World Antwerp Gateway (2007), Hutchison's Euromax terminal (2008), DP World Brisbane (2013), DP World London Gateway (2013), GCT New Jersey (2014), APMT Maasvlakte 2 (2015), Rotterdam World Gateway (2015), and Long Beach Container Terminal (2016) – and taught us that such is feasible. Although not all terminals have reached their planned levels of performance yet, the "older" ones do, and are among the best performing terminals in the world.

This chapter outlines as follows. First we will deal with the question about why to apply models, followed (see Sect. 3.2) by when it is appropriate and useful (see Sect. 3.3). In Sects. 3.3.1–3.3.4, we discuss the various steps in the terminal design-engineering process and the type of models that we typically apply. We also mention some other types of application, such as how to optimize day-to-day operations (see Sect. 3.3.5). Subsequently, we go through a number of guidelines to be observed when using a modeling approach (see Sect. 3.4) and finally, we end the chapter with concluding remarks, as well as a look into the future.

3.2 A Modeling Approach – Why?

Before discussing the details of modeling in the context of container terminal design, we first need to ask ourselves why modeling? According to Holbaek-Hanssen et al. (1975) *…it is necessary to have suitable tools for system description in order to be able to understand, design implement or control complex systems. By writing a system description, the inquirer forces himself to consider relevant aspects of a system, and a system description language should be so constructed that it assists him in this process. By writing a description, the inquirer makes it possible to convey his conception of the system to other people. Thereby he may contribute to their*

[1]The go-live date of the respective facilities is mentioned in brackets.

[2]Due to the change of ownership in 2010, the name of the terminal today is *Virginia International Gateway* (VIG).

knowledge, and make it possible for them to correct his views and to improve his understanding.

Basically, a simulation-based modeling approach – also addressed as a simulation approach (see Rozenblit 2003) – is a *problem-solving* driven approach using models to define the problem more clearly, to avoid solving the wrong problem, to prototype and assess various ways of solving the problem in a *quantitative* way. The essence of simulation is to make a *valid* model of the (future) reality within the scope of the objectives. Validity is determined by the *scope* of the analysis. For specific questions, a rather abstract, aggregated model can be well suited, whereas for other questions a detailed model may be required. It is the task of the modeler to capture the real system in such a way that the model is able to answer in a valid way. The purposes of the use of models are the following (see Booch et al. 1998, p. 13):

- To capture and precisely state requirements and domain knowledge so that all stakeholders may understand and agree upon them. The interesting thing here is the assumption that all stakeholders could possibly understand or even agree on the models. In practice this is not always possible, because modeling always contains an element of subjectivity, albeit the modeler's way of representing and depicting a real thing.
- To think about the design of the system. In principle, a model is a simplified representation of reality or future-reality that enables an analyst, a designer, or a constructor to investigate the subject in a cost-efficient way. Here, for instance, performance optimization is one of the key objectives.
- To generate usable work products. Because models can be made in an early stage, they function as source of inspiration for new alternatives, as well as way of analyzing possible consequences of the choices that have been made or are being made.
- To organize, find, retrieve, examine, and edit information about large systems. As systems become more and more automated as well as more complex due to their scale, intelligence, etc., the need for tools (i.e., models) rises, which enable the stakeholders to define views or aspects of the system, and model them individually as well as coherently.
- To explore multiple solutions economically. Especially if there are hardly any similar systems in existence that can serve as calibration (i.e., the best practice), the need arises for models as means for analyzing and evaluating alternatives. With those models, we are able to provide insight into the consequences of possible alternatives, before implementing them in reality.
- In order to be convincing, the insight a model provides must be of a high quality. Especially in this area, where the processes are of a complex nature (dynamic, uncertain, and mutually dependent), where conventional systems are about to be replaced with new, automated systems, and where the decision-makers tend to be very risk-averse, it is a challenge to obtain the required level of quality.

Quality aspects are the validity of the insight based on the results from analyses and their resemblance with reality, and the credibility of the insight: as important and indicative for the degree to which the results will be applied in the decision-making. The situation is even more complicated when completely new concepts are introduced, because validation cannot take place by comparing the results with current practice.

In the light of the design of new (automated) container terminals, in which new technology is typically applied, the following key objectives of a modeling approach may be emphasized:

- Enclosing the (new) specific properties of processes at a maritime automated container terminal into the modeling environment that we use to gain insight from and to perform the analyses.
- Ensuring that the insight we provide by applying the models is reliable and valid. How can we validate results when we do not have similar examples that are already operational?

Although simulation-based modeling approaches and resulting models of processes and sub-systems are increasingly used at container terminals, it is not as commonly applied as it is, for example, in the automotive industry, where no investment above hundred fifty thousand Euros is made without thorough prove by means of simulation. This is not strange at all when knowing that the rule of thumb is that for every Euro spent on simulation, ten are saved (see Saanen 2015).

In addition, a modeling approach is only common in the early stages of the design process (here the typical "what-if" questions arise). In the later stages, i.e., when the terminal is actually under construction, the emphasis on using models is (much) less in our experience, although in the aforementioned examples we have experienced that the continued application of models during implementation can be highly beneficial. Models provide a "project memory" during the entire duration of the project, they can give answers to questions at various levels of detail at any time, and are able to recapture reasons for earlier decisions.

That being said, the problem setting at container terminals is one that has triggered many modeling efforts to tackle specific problems at terminals. An overview of Stahlbock and Voß (2008) shows many model supported approaches in the field of Operations Research focusing in particular on the optimization of day-to-day operations – e.g., berth planning, crane allocation, stack planning, equipment dispatching, and equipment routing – and find better ways of organizing these (see Stahlbock and Voß 2008).

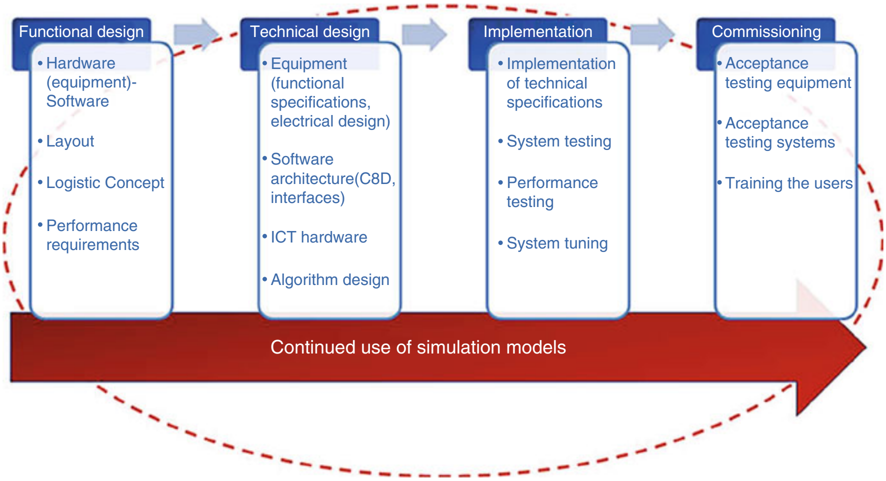


Fig. 3.1 Continued use of simulation models throughout the design and engineering of a container terminal

3.3 When to Apply Models?

The design-engineering process of a new container terminal, terminal extension, or conversion can typically be divided into four types of activities (see Saanen et al. 2000)[3]:

1. Conceptual (or functional) design
2. Technical design
3. Implementation and realization
4. Commissioning and operation.

Figure 3.1 provides an overview of the design and engineering activities which can be supported by the use of simulation models.

Considering the (four) activity types of terminal design-engineering processes, the related development work is not necessarily executed sequentially. In practice, there will probably be significant overlap and iterative feedback loops. Nevertheless, the type of problems that have to be solved differs between the phases. The differences can be categorized into three categories:

- Contents of problems to be solved (aggregation level, type of questions).
- Information available (problem space, solution space).
- Type of people involved (from managers to technical and operational people).

[3]In system design literature (see, e.g., Roozenburg and Eekels 1998 or Pahl and Beitz 1999) the same activities are divided over different phases, but can all be covered by the following activities.

In the next sections, we will discuss various key steps in the design-engineering process of a container terminal where models can (and should) be applied. The following steps will be discussed:

- Determination of the dimensions of the terminal (especially quay length and yard size).
- Determination of the type of handling system (i.e., layout and equipment and operation).
- Design of the logistic concept manifesting itself in specification and testing of the *T*erminal *O*perating *S*ystem (TOS).
- Optimization of the operation after go-live.

First, we elaborate on the typical modeling cycle, which is applied in all these steps.

3.3.1 The Modeling Cycle

Models can be aimed at decision-support for various questions and subjects. In the consecutive sections, we will discuss the key topics for modeling in the context of container terminals. In general, a modeling project consists of the following steps:

- Analysis of the problem or situation.
- Specification of the problem and development of the model.
- Validation of the model.
- Experimentation with the model base configuration or actual situation.
- Analysis of the actual situation: definition of bottlenecks.
- Design of alternative solutions.
- Modeling of alternative solutions.
- Experimentation with the alternative solutions.
- Analysis of the results and drawing conclusions, which leads to the decisions regarding the design.

This process is iterative in principle, until one has reached a satisfying solution, which meets the design criteria, or improvement objectives. The aforementioned cyclic approach can be applied in each of the activities described below, however by using different models.

3.3.2 Dimensioning the Container Terminal

In a design process of a container terminal, a typical first step is to determine the main dimensions[4] of the terminal, given the objectives with regard to volume, cargo

[4] Quay length, terminal depth, and total storage area.

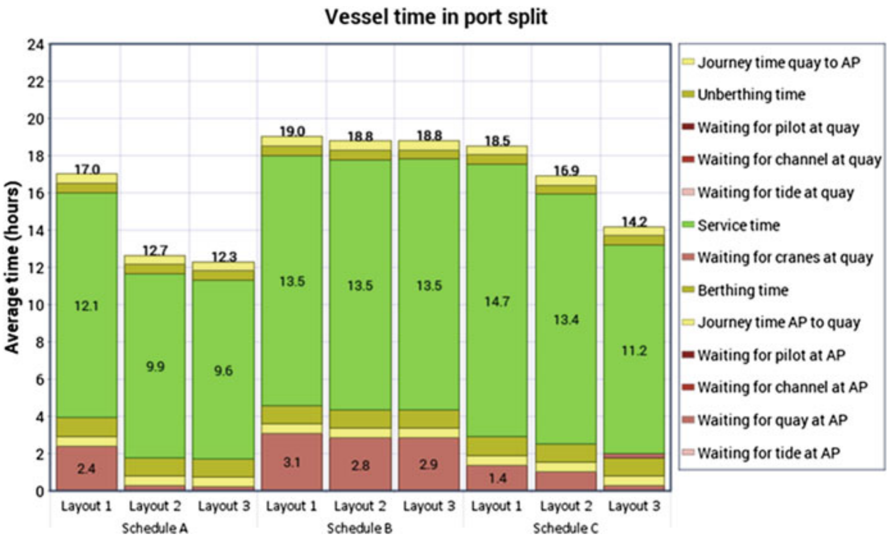


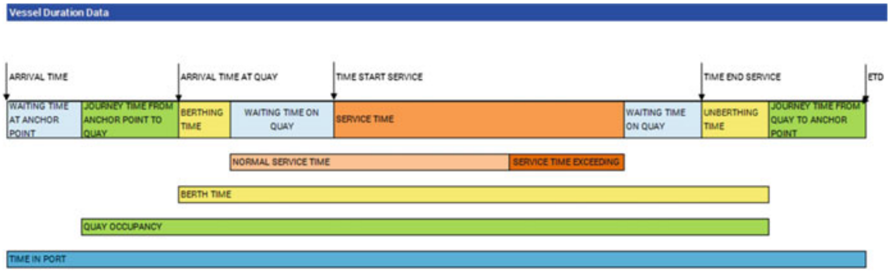
Fig. 3.2 Example port stay depending on the quay length (indicated as layout) and the pro forma berth schedule

mix, service levels, and taking the characteristics of the cargo flow (type of carriers, type of cargo, transhipment ratio, modal split, seasonal variation, peak factors, dwell times, etc.) that goes through the terminal as starting point. As these characteristics are usually surrounded with quite some uncertainty, it is of eminent importance to analyze the consequences of variations by means of sensitivity analysis (Fig. 3.2).

In order to arrive at the terminal's dimensions, which fit service level objectives and assumed cargo flow characteristics, we need to analyze the service level (vessel service time, gross berth productivities, and crane density on vessels) under varying terminal configurations (quay length, number of *Q*uay *C*ranes (QC), and gross QC productivity). For this purpose, the principal focus of investigation is first the terminal quayside, and a typical type of model is being applied, called a *berth simulation* (see Fig. 3.3). This type of model is referred to in many studies (e.g., Henesey et al. 2004; Sheikholeslami et al. 2013, or Esmer et al. 2013).

Typically, per configuration, 1 year of operation is simulated, creating a picture of the service over the year. During the year, the variation in storage requirements (seasonal effects, peaks during the peak, and even hourly peaks due to large discharge calls), the variation in berth occupancy (due to vessel delays and variation in the call size), the port stay (including all types of waiting times, see Fig. 3.2), and the occupation of QCs can be observed, giving a rich picture of the service the terminal provides.

In order to determine the quay length and required number of QCs the time in port (see Fig. 3.2) is the most important *K*ey *P*erformance *I*ndicators (KPI). We tend to measure it from the moment the vessel arrives at the *A*nchorage *P*oint (AP), till



Activity	Unit	Time	Explanation
Waiting time at Anchor Point	(hh:mm)	Result from simulation	Waiting for available berth
Journey time from Anchor Point to Quay	(hh:mm)	1:00	From anchor point to quay when berth becomes available
Berthing time	(hh:mm)	1:00	Approach to berth
Waiting time on Quay	(hh:mm)	Result from simulation	Waiting for available quay cranes
Service time	(hh:mm)	Result from simulation	Handling of vessels by quay cranes
Waiting time on Quay	(hh:mm)	Result from simulation	Waiting for tide, channel or pilot
Unberthing time	(hh:mm)	1:00	Departure from berth till berth is given free for next vessel

Fig. 3.3 The processes a vessel goes through in the berth simulation model *Trafalquar*

it leaves the berth, enabling another vessel to come in from anchorage. In between, several process times can be observed, as visualized in the figure.

Applying a simulation-based modeling approach here replaces an approach where merely rules of thumb (TEU/m quay, for instance) are used. Notwithstanding the fact that these benchmark numbers remain relevant and useful, a (simulation-based) modeling approach allows for consideration of the dynamics in the system, such as the arrival time of vessels, as well as the impact of various variables (e.g., the type of ships, call sizes, crane densities, and crane productivities) in relation to one another. Furthermore, it allows for easy sensitivity analysis of factors such as the gross vessel productivity, the duration of berthing and un-berthing, and possible tidal variations. Finally, it combines the local factors and specifics the arrival patterns with the feasible productivity levels, which benchmark figures typically do not.

The simulation model we have created to support this process is called *Trafalquar* (see de Waal and Saanen 2016), which stands for traffic analysis of quay, rail, and road (see Fig. 3.3). Besides the elements mentioned above, it contains berth assignment rules ("where to berth a vessel?") and crane assignment rules ("how many cranes on which vessel?"). The latter, in relation to the stowage of the vessel, are very much determining how cranes are being deployed. In many cases, it appears that starting with high crane densities does not per se lead to shorter vessel turn times, as the longest hook – the area in the vessel that must be handled by a single crane – determines the vessel turn time.

As an important input for the next step (determination of the handling system), the model creates a picture of the operational variation (including the peaks) in handling (quayside, but also railside and truckside). These peaks are important to determine how much equipment is required to supply the QCs with enough boxes during peak circumstances. Based on the outcome, decisions can be made concerning the quay length, the number of QCs, the gross productivity that the

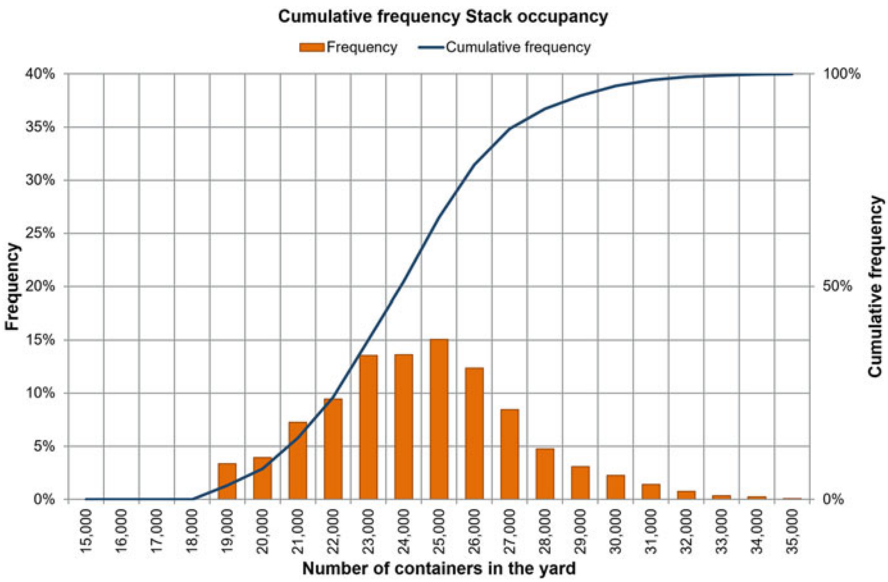


Fig. 3.4 Example of a storage demand distribution over a year

quay have to achieve in order to accommodate a certain terminal throughput, the requirements for storage capacity (see Fig. 3.4), and the peak handling conditions.

3.3.3 Handling System Design

When the outer boundaries are set, one can dive into the more detailed design of the facility. This second step is more comprehensive, in the sense that there are many variables involved, however less uncertainty is typically associated with these variables. The objective of the handling system design is to arrive at a layout, type of equipment for the various operations[5] as well as a logistic concept, which includes the way containers are handled through the terminal, where they are stored (stacking strategy), and by which equipment.

As more and more tasks are handled by computers, the logistic concept, which is basically the way a terminal is operated and controlled, becomes more important. Especially in (semi-)automated terminals, the terminal relies on its logistical control concept as laid down in the TOS. But also at manually operated terminals, the emphasis is put on efficient operation – for instance, the implementation of truck or *S*traddle *C*arrier (SC) pooling. In close relation, the TOS should be considered as

[5]For example, think of the number of prime movers (like trucks, straddle carriers, or automated guided vehicles, see Saanen 2016), yard cranes (like rail-mounted or rubber-tyred gantry cranes), and rail cranes as well as the number of gate lanes, and so forth.

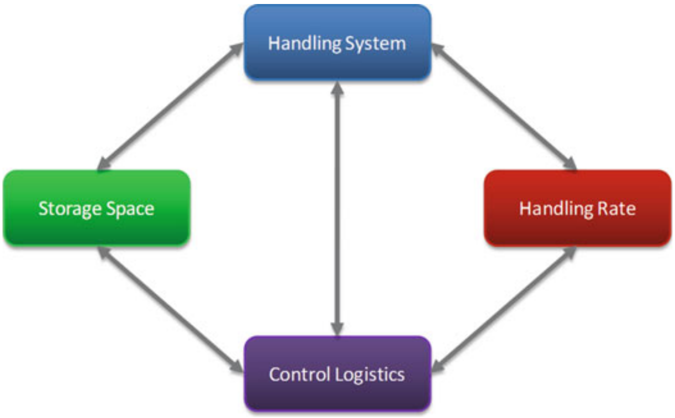


Fig. 3.5 Interdependencies in terminal design

only a TOS that has been configured for a specific operation will create a performing operation.

Also the availability of space is one of the factors influencing the handling system. As different handling systems (e.g., SCs, *R*ubber-*T*yred *G*antries (RTG) with *T*ractor-*T*railers (TT), wheeled operations,[6] *R*ail-*M*ounted *G*antries (RMG) with TTs, *A*utomated *G*uided *V*ehicles (AGV), or shuttle carriers) have different stacking densities and requirements for horizontal transportation, the throughput ability of a defined yard area varies from ca. 240 TEU/ha for wheeled operation to ca. 1400 TEU/ha for a 1-over-5 *A*utomated *S*tacking *C*rane (ASC) system with RMGs.

Finally, the selection of a handling system is determined by the peak handling rates (see Fig. 3.5) that need to be delivered in order to meet the service level demands resulting from simultaneous peaks at quayside and landside. There are terminals that have three peak operations per week, and little or nothing during the rest of the week. There are also terminals that have almost continuous operation, with relatively small variations between average and peak. Not only the pattern of operation but also the required speed of operation determines what kind of handling system is most appropriate. For instance, based on our experience we can say that SC operations are flexible, high-speed, and low-density, whereas RTG + TT operations are middle-high-density, less flexible, and less performing on a machine by machine basis, and RMG + AGV operations are high-density, least flexible, and require the highest upfront investment.

Therefore, when considering a handling system, the logistic concept (implemented mainly within the TOS), the available space, and the required handling rate

[6]Storage of containers on road chassis which can be picked-up by trucks without interference of container handling equipment. This mode of operation is quite popular in North America.

have to be considered on a holistic point of view in order to avoid sub-optimization in a particular area, since the four variables are clearly intertwined (see Fig. 3.5). A (simulation-based) modeling approach lends itself very well for an integrated approach, in case the processes on the terminal are well represented in the model. Modeling equipment is the least complicated part here, as equipment kinematics (speed, acceleration, deceleration, dead times, and load dependency) are typically well defined. It is more difficult to model the drivers of the machines, who may behave quite differently. Skill levels, motivation, safety provisions, and training highly impact their productivity. Also their interaction on the terminal, especially in high-density operation with much traffic, may vary from case to case. To illustrate the importance of modeling this correctly, one only needs to look at the technical capabilities of an RTG, for example (easily able to handle 20–25 moves per hour, and its realized performance in practice, typically less than 12 moves per hour, with peaks up to 16 moves per hour). Similar effects can be observed with TTs and even with SCs, producing respectively less than 4 and less than 8 moves per hour, where simple "distance/speed-calculations" would lead to twice those numbers.

Not only the driver's impact on equipment productivity but also the logistic concept – in terms of stacking strategy, equipment deployment, and dispatching – is of a large influence. In many cases, equipment is waiting for each other – trucks queuing in the yard and at the QC, and yard machines waiting for trucks to arrive – as well as machines have not been allocated by a single job. This may seem to be easily solvable, but so far no breakthroughs have been achieved, especially not from a holistic perspective, optimizing the operation in an integrated way. In order to reflect these imperfections, the TOS also needs to be modeled to a sufficient level. Aspects as vessel stowage (where containers are placed inside the vessel), loading sequence (in which sequence containers are discharged from and loaded onto the vessel), container characteristics (like service, "Port of Discharge," weight, length, and type), grounding rules (where containers can be placed in the yard, such that driving distances and unproductive work are minimized), and dispatching rules (which equipment unit should do which move) all have a high impact on productivity. If the modeling is not performed correctly, one can easily overestimate a system's performance by 50%. Moreover, it typically means that by improving the way a terminal is operated, more can be done with less, which can be shown in a quantitative way using a modeling approach. Own studies have shown opportunities to reduce costs and increase service levels by 20% and 15%, respectively, *at the same time*!

The model we use for these kinds of exercises is called *T*IME*SQ*UARE (TSQ), which models all processes inside the terminal to a detailed level. TSQ not only contains a detailed model of the equipment and its drivers (or control software in case of automated equipment) but also of the logistic concept (and therefore the TOS). The *validation* of such models is an extensive process, consisting of time and motion studies, analysis of driver's behavior, analysis of the TOS and its configured rules, and interviews with the terminal's staff to get the tangible but not less important behaviors specified. Although validation is necessary for every model built for a terminal, a model with a well-defined architecture contains components

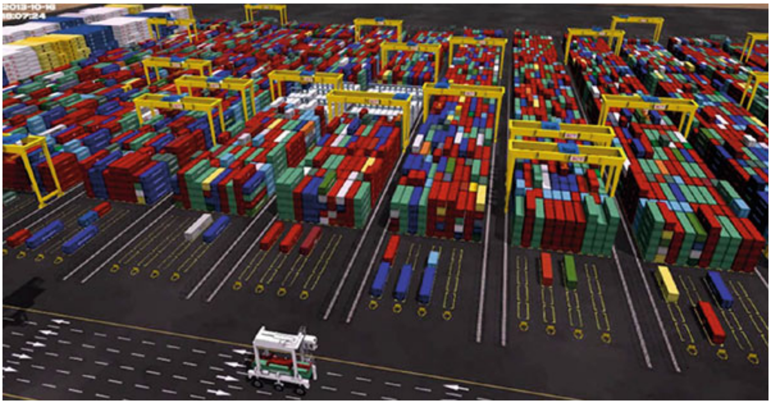


Fig. 3.6 Examples of a three-dimensional visualization of a terminal model

that can be re-used between models. This saves time and effort when building and validating a new model.

Not only validation is critical, but also accreditation of a model is essential for achieving full use out of a modeling approach. In some cases, valid models are still not trusted (accredited) by the decision-makers, and therefore may lead to diminishing the impact of the results. Even more dangerous is the use of invalid but accredited models: this means decision-makers trust the outcome, although they should not! This sometimes happens when the three-dimensional visualization that comes with the model – being a powerful support tool when doing validation – is too convincing (see Fig. 3.6 in which the operation of an ASC system with RMGs is shown combined with shuttle carriers).

From the visualization not only the movements of equipment should become apparent, but also their interaction (especially at crossings) as well as the yard strategy (location of containers, way of stacking, and shuffling) can be observed. Therefore, statistical validation based on the outcome of the model is at least as important as expert validation, for which the visualization is typically used. Models today can be developed in such a way that the accuracy with which they represent reality is very high, leading to deviations from real results limited to $\pm 5\%$.

What are typical results of models in this step of the terminal planning process? The most obvious is the amount of equipment required to meet the service level demand, as we discussed earlier. Related requirements depend on, e.g., the kinematic specifications of the terminal equipment (see Fig. 3.7 in which the impact of an RMG crane's acceleration is shown on the achievable productivity of the crane for an ASC system). Also the "optimal" yard layout can be determined in an iterative way, comparing the effect of changes in the arrangement of yard blocks, roadways, and exchange points between equipment (see Fig. 3.8). Furthermore, the utilization of equipment and its energy consumption and driving distances can be determined, which is subsequently input into financial analyses. In addition, optional control

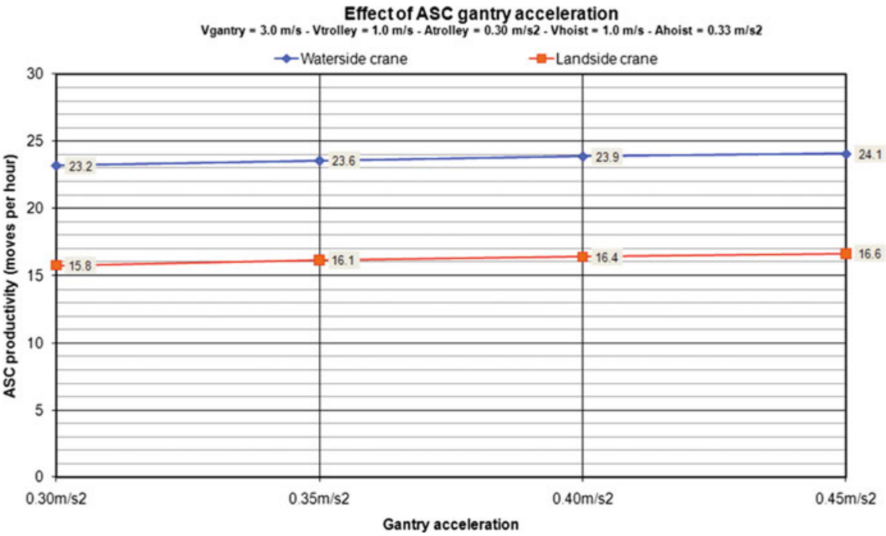


Fig. 3.7 Result from a comparison of kinematic specifications of an automated RMG crane (see Saanen 2004)

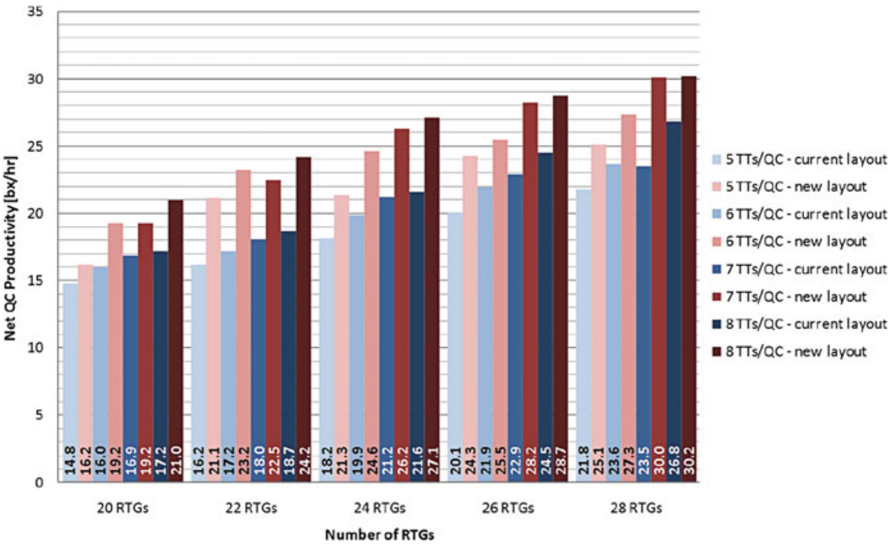


Fig. 3.8 Results comparing the effect of two different layouts

strategies of the envisaged logistic concept (e.g., pooling, stacking strategies, and dual cycling) can be compared.

Finally, the impact of changes of external factors (e.g., the percentage of renominations – changes to container destination or vessel after arrival at the terminal, the accuracy and timeliness of loading information, or simply the percentage of transhipment or the dwell time) can be analyzed. The latter we address as sensitivity analysis, which is very important in case of high uncertainty ("Greenfield" terminals) to obtain a terminal design that is robust to changed assumptions.

3.3.4 Design of the Logistic Concept

We already argued about the importance of the logistic concept and the way a terminal is controlled (see Sect. 3.3.3). In practice, this is reflected by the TOS and its users. As it plays a central role in terminal operation (see Acciaro and Serra 2014), sufficient attention should also be given during the terminal planning process.

As shipping lines are requesting higher service levels, terminal systems need to be designed striving for various – mostly contradictory – objectives. QC productivity has to go up, stack density has to increase, operating costs have to go down, and the landside service times have to be shortened. The TOS brings it all together in the form of allocations of space and dispatching decisions for all equipment. In case the business rules and parameter settings are not well configured in the TOS, it may result in major (20–50%) performance losses compared to the design values.

In order to create handling systems that comply with those requirements, the use of (simulation-based) modeling as problem-solving approach has proved to be beneficial to separate good from bad solutions, to prioritize functionalities in the TOS, since not all features can always be implemented, and – last but not least – create a relatively inexpensive and safe trial and error environment for both prototyping and testing new solutions for hardware and software.

Thus, a simulation-based modeling approach is applied here in a different way, as the models provide a test bed with which the real software can be tested and tweaked (long) before going live (see Auinger et al. 1999; Boer and Saanen 2012a; Mueller 2001 as well as Boer and Saanen 2012b). This approach is also termed as *emulation*. Compared to the previous stages of the terminal planning process, the real software is in the loop (see Fig. 3.9) and the emulation models provide the representation of the physical reality (equipment, drivers, clerks in the operation, and external systems). Important aspects in this step are the high granularity of the models and their completeness. Since software testing should not only cover the "good weather" cases but also exceptions, the models need to comprehend these events, requiring extensive modeling.

But not only for test purposes, modeling by means of emulation models is useful, it also separates feasible solutions from non-feasible ones; it assesses the contribution of solutions to the overall goals, always putting the entire system performance – rather than the individual performance of components – as key indicator. Moreover, it provides an environment where one can evaluate under varying, but manageable, conditions, e.g., busy and quiet operation, breakdowns, and so forth. In the end, this will result in less start-up problems, solutions that

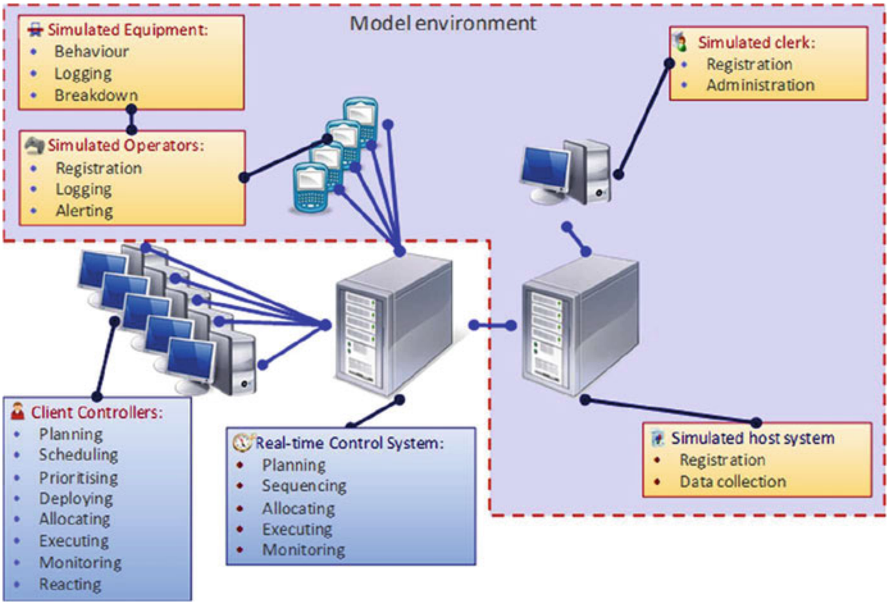


Fig. 3.9 System architecture with real TOS tested in a model environment consisting of the physical reality

are better thought through, increased software robustness, all leading to a reduction of risk.

3.3.5 *Optimize Day-to-Day Operations Using Emulation*

Terminals are dynamic systems with a high degree of interaction with their environment, and limited influence on the external "world". Every day the operation is different from that of the day before. Still, it is worthwhile to explore the possibilities of using models to improve day-to-day operations. As the TOS plays a key role in this decision-making (in preparation of the terminal, as well as during execution), the fine-tuning of these decisions is the key to high performance.

In prior work (see Saanen 2011), we referred to fine-tuning using simulation, actually creating a model of the decision rules and algorithms in the simulation to optimize them, and then implement those in the real (TOS) software. Meanwhile, we have found a way that avoids the complicated modeling of the TOS, and avoids the cumbersome process of translating the findings into the changes of the TOS. The approach uses the emulation approach (see Boer and Saanen 2012a as well as Boer and Saanen 2012b) where the actual TOS to be fine-tuned is in the loop, and is tested under laboratory circumstances, and hence reproducible circumstances.

This enables fine-tuning without the “noise” and disturbances always encountered in live operations. Typically, the following decisions are analyzed, and the related algorithms and associated parameters are fine-tuned:

- Manning and equipment deployment given a certain operation at quay, rail, gate, and housekeeping.
- Strategies and patterns of strategies for yard operation in order to increase yard density, and reduce travel distance and false moves (shuffles).
- Decisions concerning the in-advance preparation of the yard (so-called housekeeping).
- Changes regarding operational procedures, such as equipment pooling, sharing part of the equipment, real-time re-allocation of equipment, and sizing the gangs.

The outcome of these analyses (typically the operational strategy and the associated parameter mix) can be fed back into the TOS, and into the minds of the managers, planners, dispatchers, and operators running the terminal. It can overcome the often contradictory perceptions about the bottlenecks in the current operation, and prioritize improvement measures. By using real data and the real TOS, the outcome of the emulation experiments will be very close (within 5%) of the outcomes in live operations, and therefore a solid predictor of the impact on the operation (see Boer and Saanen 2014 as well as Magnúsdóttir 2014).

Examples of findings in this regard are provided in Fig. 3.10. Here, two different strategies for TT use at terminal waterside are analyzed regarding their impact on QC productivity. The right three columns show the net QC productivity achieved with TTs pooled to the QCs and the left two columns are the result with dedicated transport equipment.

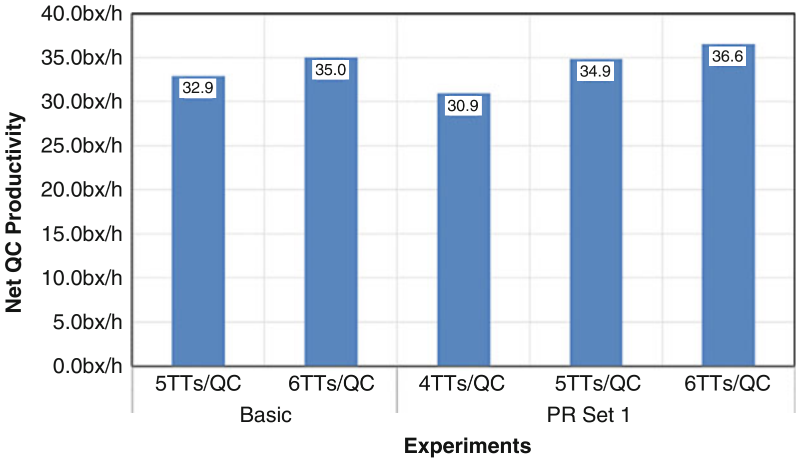


Fig. 3.10 Comparison of two operational strategies for horizontal transport; in this case a TT pooling algorithm (“Prime Route”) is tested against dedicated equipment use (“Basic”)

3.4 How to Apply a Modeling Approach (Successfully)?

Before we start developing models to design and improve our terminal, we should first deal with the modeling approach itself. And to avoid any confusion: modeling requires skills, experience, and tools, just like any other profession or trade. Although there are several tools available on the market, it does not mean that purchasing these leads to high quality analyses or results. There is a little more to it than that. Therefore, step 1 is to ensure the right modeling team, then to ensure that the right questions are asked, and then to ensure that the modeling environment (the tools) are also adequate to answer these questions.

When these conditions are met, the basis is laid for successfully applying models. Moreover, we would state that it is recommended to deploy models throughout the entire design-engineering process of a terminal, from the initial conceptual design to the detailed design, and even during commissioning and software testing. In addition, we suggest the following guidelines (see Saanen 2004).

3.4.1 Holistic, But Layered View on the Terminal Processes

We propose to analyze the container terminal from a holistic perspective, taking all processes between the terminal boundaries into consideration. Of course, some processes require more attention than others, but due to many changes, some processes, which may at first seem unimportant, could influence the system as a whole. In order to keep the design process manageable, we also apply different hierarchical abstraction levels in our analyses and models – see, for example, the various types of (simulation) models already discussed in Sect. 14.3 to 3.3.4. Depending on the design activity, we focus on a specific terminal process or component.

3.4.2 Object-Oriented View on the Real World

We propose to use the object-oriented modeling paradigm, which means that the entities that execute actions are leading. The object-oriented modeling paradigm has a number of advantages (see Rumbaugh et al. 1999), which make this way of viewing the world suitable for a terminal design process. When the object-oriented way of modeling is compared with the flow-oriented way of modeling, the advantage appears in the fact that there are many different processes (flows) throughout the terminal depending on internal and external conditions, not known at the time of ship arrival. However, the actions that can be performed by the entities (equipment, terminal personnel, and customers) are known and defined. These two aspects make it easier to conceptualize a terminal in an object-oriented way, rather than in a flow-oriented way. Moreover, in the case of robotized container terminals, the use of an object-oriented view of reality eases the conceptualization of the control software, because most control software is object-oriented and, therefore the conceptual description is much closer to the implementation in software.

3.4.3 Explicitly Taking Uncertainty and Process Variability into Account

A dominant property of a container terminal is the lack of deterministic elements, which has already been argued. The influence of external processes is high, the information presented is of a poor quality or missing, and the variation in behavior of terminal processes is relatively high due to unreliable manual operation or equipment failure. In order to create a design that also works in practice, the design has to address the dynamic system behavior of the real system. Therefore, our guideline is to take the variation explicitly into account when modeling and analyzing the system. We prefer this approach above an approach in which the variability is averaged and the outcome is increased with a certain safety margin to cover peaks. Explicitly modeling the variation of process behavior requires more sound knowledge of the range of outcomes of each process, because not only the (estimated) average is required but also the minimum, maximum, and relative frequency of all outcomes. The choice to model the variation in an explicit way has consequences for the solutions that can be applied, especially in the area of optimization and control algorithms (see Stahlbock and Voß 2008). Usually optimization algorithms (such as the Hungarian algorithm) treat information as certain. Therefore, in order to be able to use these optimization algorithms, continuous re-planning, based on the actual available information, is required. Only then, the information used as input for the optimization can be considered as relatively certain.

3.4.4 Identifying the Impact of Manual Interventions

At most terminals, many processes are still dependent on human operators. This heavily impacts the outcome of operation, and therefore it should be considered in the modeling process. In the modeling environment, there should be room for varying skills and various unpredictable decision-making. Also the interaction between man and machine at execution and control level is a key issue in a terminal's design. In Fig. 3.11, an example of the impact of the operator's experience on a terminal's service levels is given. In this particular case, the terminal start-up was planned with (experienced) expat labor, with a step-wise transition to local labor.

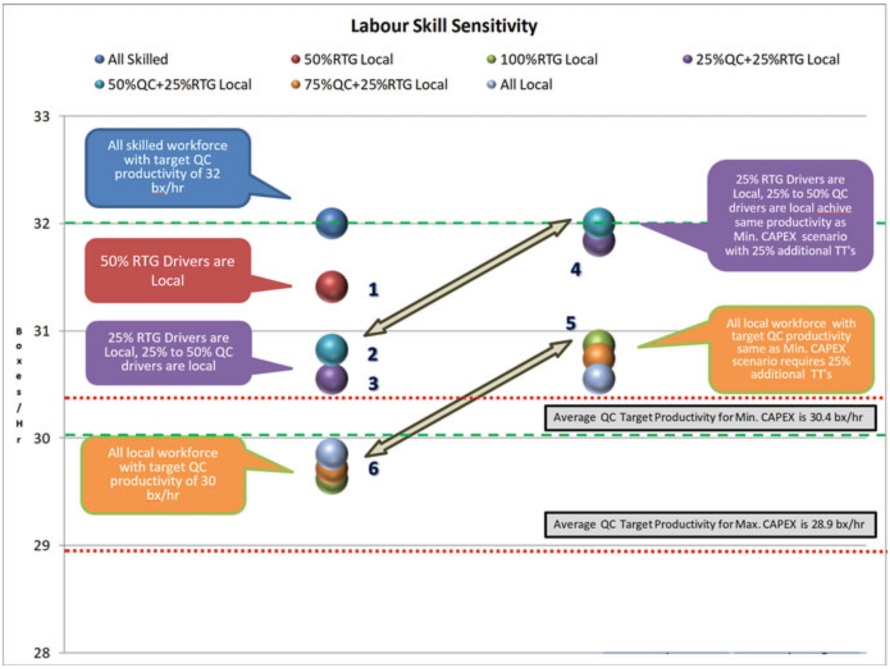


Fig. 3.11 Example of impact of operator skills on QC performance (see Saanen 2009)

3.4.5 *Basing the Decisions within the Design Process on Performance Measurements*

In order to understand the behavior of the process that is carried out at a container terminal, adequate measurement criteria (so-called KPIs) have to be developed, because only then can relationships between events or actions and the output of the system be laid. In addition, operational data has to be collected in order to determine whether the criteria have been met. The designers can analyze the processes and define the bottlenecks with actual operational information. Therefore, the performance indication instruments should not be limited to the indicators that measure the performance towards the customer. van Rhijn (2015) showed in an in-depth study how to decompose the high level KPIs (such as "QC productivity" and "truck turn time") down to internal KPIs such as "waiting time at yard crane." She made apparent that this decomposition of KPIs (whether from live operations or from simulation results) is necessary to define where the root cause of the problem is situated.

Moreover, improvements should always be instituted when there is a lack of performance in accordance with the measurement criteria. When these criteria do not converge with both the terminal goals and customer goals, then the criteria have not been well defined. Subsequently, the priority of improvements should be determined based on the potential performance increase of the improvement. In the modeling environment, these KPIs should be measured and presented as a result.

3.4.6 The Design Process Should be an Ongoing Process in Order to Keep the Terminal Up-to-Date with Continuous Changes

The environment of a container terminal is ever-changing. For instance, the handled volume increases, the size of vessels changes, the modal split changes, and the labor cost changes; in most design-engineering processes, the design team is dissolved after commissioning. However, in an environment with ongoing changes, the design process should be continued in order to keep the terminal fulfilling its requirements. In the inductive cases, we have learnt that many terminals do not remain up-to-date, which leads to a decreasing service level or a less competitive position because internal and external factors such as labor costs, dwell times, and the vessel call pattern change.

The (re-)design effort might be at a less intensive level after commissioning, however, the evaluation and improvement process should be continued in order to know whether changes are required or improvements can be made. This also means that a model environment, meant to support questions in relation to the changing terminal environment, should be kept up-to-date; this is to avoid long periods of model updates when urgent questions arise.

3.4.7 The Architecture of the Modeling Environment Should Mirror the System Architecture, Including the TOS

It is common to model in accordance with the scope and purpose of the analysis for which the simulation is used. Often, this results in models that are more or less different from the system that will be implemented in reality in terms of structure and processes. That is not a problem in itself; it can even reduce costs of model development, because the representation of reality in the model is easier to realize and still valid for the purpose for which the model was developed. However, it does not contribute to the reusability of models within a design project where the same system components are redesigned multiple times. Nor does it support the use of the same models throughout an entire design-engineering process, because there are multiple purposes inherent to the various activities in the design process. Finally, yet importantly, creating a model whose architecture is similar to the real system is beneficial during the implementation process, where it can serve as system environment for function and technical testing. Therefore, we propose developing simulation models that have an architecture, which is similar to the real system, both hardware and software.

3.5 Concluding Remarks

Operations at container terminals are highly complex. Automation makes them even more complex. The current trend of ever-growing vessels – forcing terminals to upgrade and at the same time handle larger volumes per time unit – adds onto the complexity of terminal operations (see, e.g., Saanen 2014). In addition, overcapacity in many regions decreases operating margins and induces pressure on terminals to improve their cost-efficiency. Hence, the need to invest only what is really needed, and to operate as efficiently as possible. All speak for data-driven decision-making, in which advanced models form an indispensable tool.

The use of models – enabling especially the representation of dynamic and uncertain real-world aspects – is an effective methodology to facilitate terminal planning processes by providing quantitative data to decide upon, and allowing comparison for all kinds of alternatives and ideas in an inexpensive way. As a result, more balanced and leaner terminals are being realized, which also meet the performance objectives in reality.

The type of models that we consider most suitable for container terminal planning – in terms of recognizability, and dealing explicitly with stochastic effects for representing terminal operation – are dynamic simulation models. Optimization tools treating the operation as a deterministic process are difficult to apply, because in real-time the operation differs highly from the planned situation. Therefore, tools that explicitly consider the dynamics of life operation should be favored above others. In addition, most simulation models are also able to represent and visualize container terminal operation.

Applying a related modeling approach makes the decisions concerning the investment in the quay and QCs, the choice of handling system, and the configuration of a terminal's control system better founded, better to understand, and more transparent. It enables a terminal operator to reduce the risks of the terminal development and extensions. Additionally, we have seen that it justifies itself as testing and tuning tool when implementing a new TOS, by means of linking the TOS directly to a simulation model of the terminal. That allows for testing and tuning the TOS under laboratory circumstances (*emulation approach*).

Finally, the way of applying similar models as during the design phase in later life-cycle phases enables a terminal operator to improve the terminal on a continuous basis. Especially when it concerns robotized container terminals, such a use of models has become common practice. In recent projects (e.g., Maasvlakte 2 and Long Beach Container Terminal), advanced, stochastic models have been used throughout the life cycle of the terminals. All being highly automated, the design-engineering phase has relied heavily on the decision-support function of simulation models, as well as the implementation phase of the complex control software running the facility. Just before go-live, the models were then used to provide a "near-to-live" training environment (see Saanen and Koekoek 2015 as well as Boer et al. 2014) for the control room operators, and finally after go-live the models are still in use for parameter tuning in the control software, as the volume is growing. We expect that this trend will continue, and further grow as terminals get more automated.

Last but not least, one should always keep in mind that models need to be a valid representation of the systems being analyzed (*validation*). Moreover, decision-makers should have confidence in the models (*accreditation*) to avoid that valid models and their results are not used in the actual decision-making.

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Chapter 4
Comparison of Fleet Size Determination Models for Horizontal Transportation of Shipping Containers Using Automated Straddle Carriers

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Abstract Planning of horizontal transport is a significant problem with material impact on the development budget and productivity of a container terminal. This contribution uses Queuing Theory, Petri Networks and Discrete Event Simulation to address the fleet size determination problem for tactical planning. Considering the different information and modelling effort required for the three methods, it is recommended that Queuing Theory be applied in the preliminary planning stage as it is conservative, while Discrete Event Simulation which can yield significantly more cost-efficient results is applied for the detailed planning stage. Further development would be still required towards an easily applicable tool based on Petri Nets for practitioners to use in current planning problems, but the methodology itself can provide reasonable yet conservative results at a preliminary planning stage.

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4.1 Introduction

The maritime sector is responsible for the transportation of a significant share of the freight volumes generated as a result of increasing consumer demand and global supply chains. This was estimated in 2015 to account for over 80% of total world merchandise trade and between 55 and 67% in value terms (see UNCTAD 2016). With the introduction of containerization in the 1950s, freight movements became standardized, more efficient and less expensive (see Rodrigue et al. 2017). Annually, there are about 5000 container vessels ferrying over 580 million *T*wenty-foot *E*quivalent *U*nits (TEU) of containers between ports in 200 countries worldwide (see AL 2018). These container ships use dedicated areas in ports called container terminals to handle their cargo. Due to fierce regional and international competition, terminal operators seek ways to maximize throughput and productivity (see Saanen and Valkengoed 2005). The three groups of operations in a terminal which have the greatest influence on quay-side productivity are: (un-)loading containers to/from the vessel (quay-side operations), storing/retrieving containers at/from the stacking yard-side (yard-side stacking operations), and transporting containers between the quay-side and the yard-side (horizontal transport operations), see Chen et al. (2003) and Park et al. (2011). The stored containers are usually either loaded to another vessel (transhipment containers) or carried out by rail, truck, or barge (domestic containers). The operational performance of container terminals has been studied and optimized at length by academic research that can be broadly categorized into three distinct areas for which recent literature surveys can be found: Quay-side operations (see Carlo et al. 2015; Meisel 2009, pp. 31–46), storage yard operations (see Carlo et al. 2014a), and horizontal transport operations (see Carlo et al. 2014b).

Because of costs, area requirements, and operational and staffing consequences, a thorough feasibility and fleet sizing analysis should be performed before choosing equipment for horizontal transport and container stacking activities. On the choice of horizontal transport, there are mainly three decisions that have to be made (see Carlo et al. 2014b):

1. Which type of equipment or vehicle is the most appropriate,
2. how many are needed, and
3. how can we optimally deploy (assign, route, and dispatch) this equipment?

With regards to the sizing decision (how many?), optimization methods (Integer Programming), Queuing Theory, and Discrete Event Simulation are commonly used for tactical and strategic planning of container terminals (see Cai et al. 2013; Carlo et al. 2014b; Carteni and de Luca 2012; Mrnjavac and Zenzerović 2000; Zehendner et al. 2013). In practice, and based on one author's industrial experience, due to the time it takes to implement, test, and commission new algorithms, fleet size determination for tactical purposes is performed by empirical ratios (see e.g. PIANC-135 2014) and verified by Discrete Event Simulation at the final design stage. Empirical ratios reflect a standard geometry, which although it has been implemented and studied before, would be hazardous to apply in radically different geometries.

Another developed graphical and mathematical modelling method is *P*etri *N*etworks (Petri Net or PN), see e.g. Murata (1989), Lenka and Das (2012), Li and Zhou (2009), and Kumanan and Raja (2008), a modelling approach originally developed for the study of qualitative properties of systems exhibiting concurrency and synchronization. PNs have been used in the past to represent complex dynamic systems through the block-based representation of continuous and discrete processes into subsystems that host a series of sequential logical operations. PNs have been used in the past in manufacturing, transport networks, rail operations, and communication systems to describe, analyse, and verify systems characterized by precedence relations, concurrent activities asynchronous events, and resource sharing conflicts. To our knowledge, there are few applications of PNs on container terminals and none on the fleet size determination problem for horizontal transport via *A*utomated *St*raddle *C*arriers (AStC). Liu and Ioannou (2002a) introduced a timed-place PN to model the lower level control systems of *A*utomated *G*uided *V*ehicles (AGV) (such as collision avoidance, intersection priority, and direction control) and yard and quay cranes (such as status, movement direction for crane and spreader, and hoisting/lowering control) in an automated container terminal. Perhaps the previous work closest to the problem at hand is Liu and Ioannou (2002b), where the same authors present a PN model for scheduling and fleet size determination of AGVs serving a sequence of machines in a manufacturing workshop. PNs, in this case, are used to schedule the minimum number of AGVs possible so that the machines have zero idle time. The fleet size is found as the minimum number of AGVs for which such a schedule can be found. More recently, Kim et al. (2010) use a deterministic PNs for estimating the cycle time of an unloading vessel in a vessel-to-vessel transfer concept called *the Mobile Harbour*. Kezić et al. (2007) use Discrete Dynamic Theory and Petri Nets for the design of a collision prevention supervisor between automated and non-automated vehicles in a mixed terminal.

The objective of this paper is to introduce and illustrate the application of PNs to the fleet size determination problem for tactical purposes and provide a comparative analysis of Queuing Theory, PNs, and Discrete Event Simulation methods by applying them to the same problem. The proposed offshore terminal in Venice (Italy) is used for modelling the complex processes of horizontal transport in a container terminal and determining the optimal number of horizontal transport equipment required for efficient and cost-efficient operations at the quay- and yard-side. Through the comparative study presented herein, the different types of insights afforded by different methods can be appreciated.

The paper is organized as follows: Sect. 4.2 presents an introduction to AStC. In Sect. 4.3, the details of the deployment of AStCs in the proposed new offshore terminal in Venice (Italy) are described. Different Queuing Theory formulations, PNs, and Discrete Event Simulation are used to determine the optimal fleet size of AStCs in a container terminal in Sects. 4.4.1, 4.4.2, 4.4.3, and 4.4.4. The performance analysis using the three methods are compared in Sect. 4.5, while Sect. 4.6 summarizes the general conclusions of this paper.

4.2 Automated Straddle Carrier Operations

Frequently used container handling equipment at the yard are *R*ubber-Tyred Gantry (RTG) cranes, *R*ail-*M*ounted *G*antry (RMG) cranes, and *St*raddle *C*arriers (StC). Based on a survey by Wiese et al. (2009) as well as Wiese et al. (2011) of 114 container terminals, however, 63.2% of container terminals use RTG cranes, 6.1% use RMG cranes (mainly in Europe) and 20.2% use StCs as their main horizontal transport and stacking equipment. This makes StCs the second most used container handling equipment in storage yards despite the fact that the stacking density of the yard when using a gantry crane can be double that compared to a StC (see Saanen and Valkengoed 2005). The reason for their popularity is the versatility of use since the same equipment can be picking containers up from the ground, transporting the containers horizontally to the storage area and stacking them nowadays up to one over 3-high (see e.g. Kalmar 2018b; Konecranes 2018c; Liebherr 2018). Additionally, they can make significant differences in its productivity (see Cai et al. 2013), while keeping the operational and capital expenditures in a terminal low. The latter is because they do not require fixed infrastructure such as runways or crane rails.

AStCs (see Kalmar 2018b; Konecranes 2017) have operational characteristics that closely correspond to those of conventional StCs with the added benefit of not requiring the presence of a driver. Hence the operating costs can be considerably reduced, while the operational flexibility is fully maintained. In contrast to other types of automated horizontal transport equipment, they can drop a container on the *S*hip-*T*o-*S*hore (STS) crane back reach, and they do not require a lifting equipment to be loaded or unloaded. Therefore, they enable the decoupling of the horizontal transport from the STS crane operations by the existence of a buffer zone at the quay apron. This increases the efficiency of STS cranes and vessel turnaround times. Their productivity is dependent on a number of geometric, mechanical, or operational factors, including operating and lifting speeds, travelling distance, restacking strategies, assigned workloads and waiting times and the layout of buffer (interchange) zones under STS cranes, and between the yard and the gates, etc. (see Vis and Harika 2004). For example, the size of buffer zones is critical since spill-overs caused by lack of space disrupt the coupled operations (such as STS crane loading and unloading and gate truck service).

Automated horizontal transport vehicles in container terminals can be classified into two categories:

– *AGVs* (see Konecranes 2018a; VDL 2018; Gaussin 2018) including *Lift AGVs* (see Konecranes 2018b), and
– *Automated Lifting V*ehicles (ALV), i.e., unmanned vehicles for horizontal transport (see Kalmar 2018a; Konecranes 2017) with own lifting abilities.

Accordingly, AStCs belong to the class of ALV that can independently lift and set down containers while AGVs require direct assistance by other yard cranes to load and unload containers on their platforms. An intermediate solution is the Lift AGV,

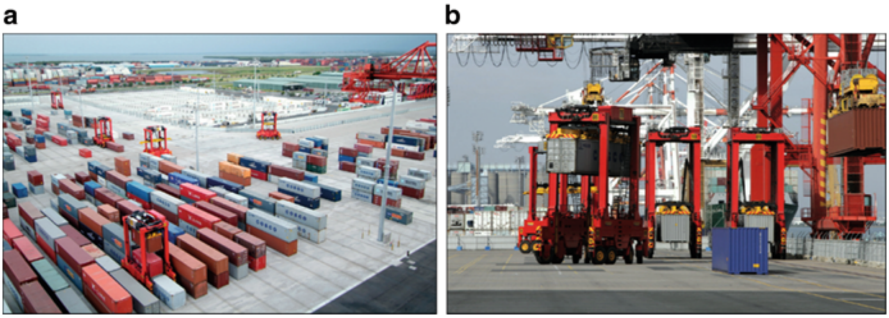


Fig. 4.1 AStC at the Fisherman's Island Terminal in Brisbane: (**a**) Operating at the yard-side and (**b**) serving the hook under a STS crane (see Durrant-Whyte et al. 2007)

which on the one hand gets loaded by the STS crane at the quay, but on the other can self-unload the container on a platform at the yard, offering partial decoupling. The advantage of the decoupling has been demonstrated in a number of studies, summarized in Carlo et al. (2014b), where it is indicated that roughly twice as many single-load AGVs than single-load ALVs would be required to perform the same transport operations at a similar service level. The large difference in the number of vehicles is related to the AGVs dependence (coupling) on an external crane for loading and unloading.

The first implementation of AStCs, seen in Fig. 4.1, allows the stacking of up to three containers high and enables operations in a completely automated fashion. In more recent implementations, such as the TraPac Terminal in the Port of Los Angeles (see Di Meglio and Sisson 2013), a shorter (one over one) and faster vehicle, called *AutoShuttle* (see Kalmar 2018a), or *A-Sprinter* (see Konecranes 2017) is deployed for only horizontal transport between the quay and the (automated) stacking yard. The manned version of this equipment has different names under different manufacturers, such as *Shuttle Carrier* (see Kalmar 2018c) or *Boxrunner* (see Konecranes 2018c).

4.3 Case Study of AStCs for Venice Port

The Venice Onshore Offshore Port, a system of two container terminals linked with a seaway connection, was considered for the port of Venice by the Venice Port Authority (see Haskoning 2014 as well as Pachakis et al. 2017). The new system aims not only at serving mainland northern Italy but also several customers in central Europe such as Austria, Switzerland, south Germany, Hungary, Slovenia, and Croatia.

As shown in Fig. 4.2a, the Venice Onshore Offshore Port consists of 3-parts: an offshore terminal for (un-)loading containers from ocean going vessels, a

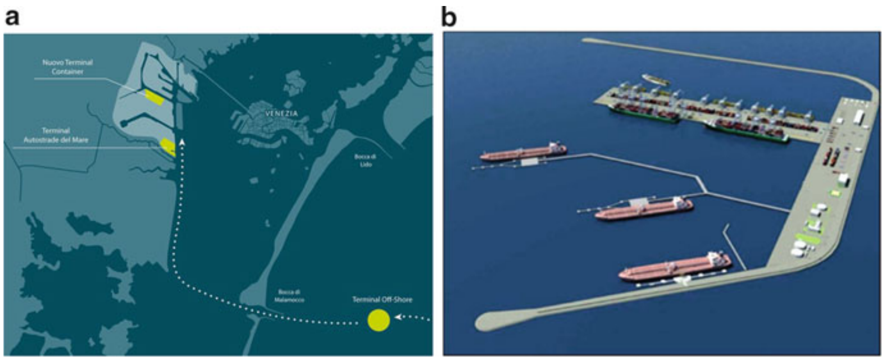


Fig. 4.2 The new port of Venice: (**a**) The onshore and offshore terminal locations and (**b**) the offshore container and liquid bulk terminal structure (rendering), see Pachakis et al. (2017)

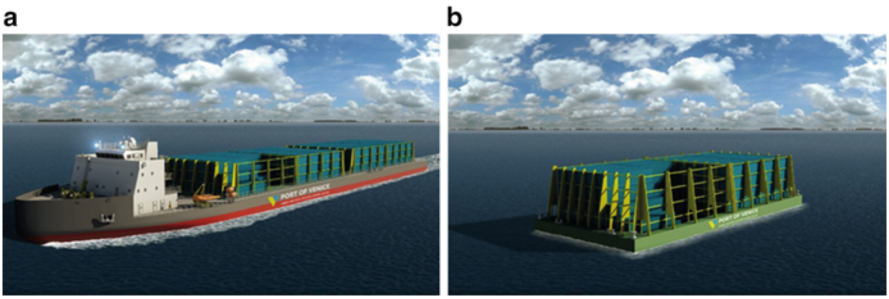


Fig. 4.3 Renderings of (**a**) the semi-submersible barge transporter vessel and (**b**) the container carrying barge. Concepts developed for the Port of Venice by BMT TITRON (see Causer 2014)

barge-based container transfer system, and an onshore terminal (called *MonteSyndial*). An overview of the offshore terminal of the new port of Venice is shown in Fig. 4.2b. The barges and barge carrier vessels are shown in Fig. 4.3.

Given the available area and productivity demands, AStCs are proposed as the system for stacking and horizontal transport of the offshore terminal, after an evaluation of four different systems concerning capital and operating costs (see Pachakis et al. 2017). This paper considers the fleet sizing of AStCs for the horizontal transportation and stacking of containers at the offshore container terminal. As shown in Fig. 4.4, eight STS cranes (maroon colour) and ten barge cranes (blue colour) are assigned for (un-)loading containers to/from the vessels on the deep-sea side and the barge side, respectively, of this terminal. The areas coloured orange in Fig. 4.4 are for turning into and out of the stacking yard but can also be used for waiting of the AStCs. The stacking yard is divided into three stacks with travelling lanes between them.

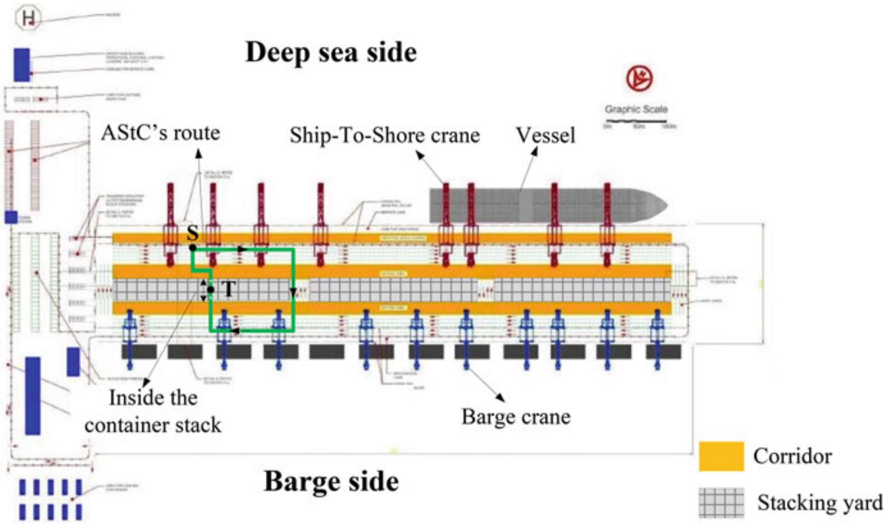


Fig. 4.4 The offshore container terminal layout of Venice's port at the planning stage (see Pachakis et al. 2017) and the route (green line) that each AStC travels to finish one cycle. The orange area near the stacking yard is the turning and waiting area for the AStCs. The out of gauge cargo loading area is under the STS cranes, also shown in orange

4.4 Modelling the AStCs Movements

4.4.1 Operational Assumptions

For the comparative analysis of modelling techniques, the following target STS crane productivities are assumed: 34 moves/h on the deep-sea side and (ambitiously) 30 moves/h on the barge side.[1] The cycle times are thus 2.00 min and 1.76 min, respectively.

To estimate the number of AStCs required to operate the offshore terminal at the target throughput, some of the technical and operational assumptions are summarized in Table 4.1. These assumptions are applied in the calculations of the average cycle time of the StC. These average cycle times are then used in the queuing model and the PN model. For Discrete Event Simulation modelling, the equipment travel is modelled on a certain path from random locations in the stack with the equipment speeds and the various times apply as deterministic delays. The software has a collision avoidance routing, so the corresponding delays are accounted.

[1] PIANC-135 (2014) reports the range of low, medium, and high productivity per STS crane in large container terminals to be between 20–25 moves/h, 25–30 moves/h, and 30–35 moves/h, respectively. For the case study the assumption is met that one crane move corresponds to one container move.

Table 4.1 Operational assumptions for the AStC operation (see Kalmar 2018c) and common industry assumptions

AStC specification	Unit	Value
Average travel speed outside the block (85% of max. speed)	[m/s]	5.90
Average travel speed within the block	[m/s]	1.39
Time for 90° turn	[s]	2
Housekeeping moves of total	[%]	10
Acceleration adjustments	[s]	40
Traffic and safety adjustments	[s]	20
Miscellaneous manoeuvring time	[s]	20
Maximum stacking height	[Boxes]	3
Maximum lifting speed for unloading	[m/s]	0.33
Maximum lifting speed for loading	[m/s]	0.27
Maximum lowering speed for unloading	[m/s]	0.30
Maximum lowering speed for loading	[m/s]	0.25

The average travel route of the AStCs is marked green with indicators along its entire length in Fig. 4.4, and with the starting point and destination location symbolized with "S" and "T", respectively. The average travelling length of the AStCs for the Queuing Theory and PN models applications is calculated from the centre of each stack (point "T") to the centre of the berth opposite to the stack (point "S"). This geometry is consistent with the container locations being uniformly distributed anywhere in the stack and uniformly anywhere along the berth corresponding to that stack. All AStCs have higher speeds on the travel lanes than inside the container stacks. To minimize the in-block travel time, the travel lane between stacks is used at least once in the route of the AStCs. The travel distances outside and inside the stack are 581 m and 39 m, respectively. Considering the horizontal and vertical movements and including 25% delay allowance, the final AStC cycle time is about 600 s for the route in Fig. 4.4. Thus, each AStC can finish approximately 10 moves/h in the stacking yard, which is close to observed productivities in the industry.

The maximum stacking height is set to up to 3 containers high. For the calculation of the lifting and lowering time, the working height considered is the maximum times the average utilization factor of the stack. The housekeeping operations are accounted in the cycle time of an AStC by adding 10% of the vertical movement time to the cycle time. The acceleration (deceleration) time of an AStC (i.e. when turning or stopping) is accounted for in the cycle time by adding 40 s to the horizontal movement time. Traffic and safety adjustments are also accounted for in the cycle time of AStC by adding 20 s to the horizontal movement time. Miscellaneous manoeuvres (i.e. positioning by STS crane) are also covered by adding 20 s to the horizontal cycle time. Delay is added as 25% of the sum of horizontal and vertical movement times, which is added to the total cycle time of an AStC.

4.4.2 Queuing Theory

Queuing Theory (see Gross et al. 2017) is commonly used by consultants in the preliminary stages of a project, during tactical planning, because of its solid theoretical basis, its ability to provide quick and indicative results. Queuing Theory also provides a sanity check to the results of other methods such as simulations, by comparing the corresponding long term (steady-state) averages. The standard notation established by Kendall (1953) for defining every queue in its most basic form is $A/B/c/K/m$, where A denotes the stochastic arrival time distribution, B represents the stochastic service time distribution, c is the number of operating servers in the system, K denotes the capacity of the queue, and m represents the maximum number of customers. A and B are commonly defined as a Poisson (or Exponential) distribution (M), a deterministic value (D), or a General distribution (G). K and m are infinite when they are not defined. For instance, in the $M/M/1$ queuing system, both arrival and service distributions are a Poisson distribution, and one server is operating in the system. Table 4.2 summarizes the parameters used in the queuing systems based on the case study. In the models described herein, the customers are the containers that are (un-)loaded from a single STS crane at an *average arrival rate* λ of 34 moves/h and 30 moves/h on the deep-sea and barge cranes, respectively. The servers are the AStCs that are assigned to a single STS crane and operate at an *average service rate* μ of 10 moves/h.

There are several already solved queuing models in the literature, each with their advantages and limitations. None of the available models will capture exactly the STS-AStC operations. The objective of this section and the modelling exercise is to

1. highlight how the existing models can be used to approximate as best as possible these operations,
2. indicate any insight that can be gained through applying them, such as a rough first estimate for the quantity of AStCs required for the terminal, and
3. explore how the readily available performance results can be used to support decisions about the fleet sizing of the AStCs.

Seven standard queuing models, $M/M/1$, $M/D/1$, $M/M/c$, $G/M/1$, the Allen–Cunneen [A–C] Approximation for $G/M/1$, $G/M/c$, and $M/M/c/K$ are explored in this chapter, as possible models for the STS-AStC queuing system. The single-server models $M/M/1$, $M/D/1$, and $G/M/1$ were applied under the operating assumption that each AStC acts as a separate server with its queue, which is the traffic lane in the backreach or portal of the STS crane, who drops the containers

Table 4.2 Parameters used in the Queuing Theory models according to the case study

Parameter	Meaning	Deep-sea side			Barge side		
λ [moves/h]	STS crane productivity	34	34	34	30	30	30
c [# AStC]	No. of AStCs in the system	4	5	6	4	5	6
μ [cycles/hour]	AStC service rate	10	10	10	10	10	10

randomly in each of the traffic lanes. The minimum amount of ALVs, $c_{\min}$, required for a stable queue given the parameters λ and μ is calculated as 4 (vehicles). Hence the performance metrics for these systems are calculated for between 4 and 6 AStCs per crane. The multi-server models ($M/M/c$, $G/M/c$) can apply to the situation where the STS crane drops containers sequentially in the next empty position on the traffic lanes, and the AStCs pick the containers from any traffic lane as they come. This way there is one queue (the drop-off/pick-up positions under the crane) and multiple servers. It is noted that the First-Come-First-Serve (FCFS) queue discipline cannot be applied in practice with these operations. Finally, the $M/M/c/K$ model represents the case where the STS crane drops the containers on a finite number of positions on the quay apron and if all these positions are full and no empty AStC is coming to the transfer area, the crane has to wait. The reason that the General interarrival distribution is desired as a model is to see the effect of reducing the variance of crane productivity (say by adding a secondary trolley) in demand for horizontal transport equipment. Here, a coefficient of variation of 5% was used in the $G/M/1$ formulations. The Allen–Cunneen [A–C] Approximation for $G/M/1$ is used because it provides a simple to implement the formula for spreadsheet calculations. An Exponential distribution for the service time is considered appropriate as the distances that the AStC travels from the apron to the stack (and vice versa) vary considerably.

Using the seven Queuing Theory formulations, the performance metrics (*average number of containers in the system*, *queue length*, and *average waiting times*) of the system after assigning 4–6 AStCs per STS crane are calculated for different STS crane productivities (arrival rates). The results are sorted by the *average arrival rate* λ in Figs. 4.5 and 4.6. It is evident from the results that the examined performance metrics follow the same trends of performance improvement as the AStC number increases and the related arrival rate decreases, despite having different values from model to model.

As expected and can be seen in Fig. 4.5a and b as well as in Fig. 4.6b, the performance of the $M/M/c$ (green bars) model is clearly better than the $M/M/1$ (blue bars), with regard to the customers in system (see Fig. 4.5a), as there are

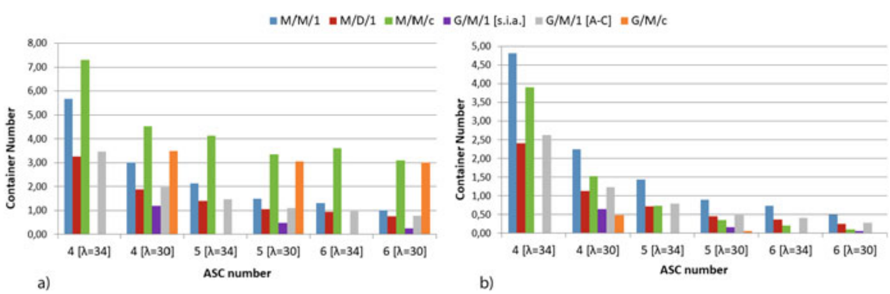


Fig. 4.5 (**a**) Average number of containers in the system per STS crane, (**b**) average number of containers in the queue per STS crane

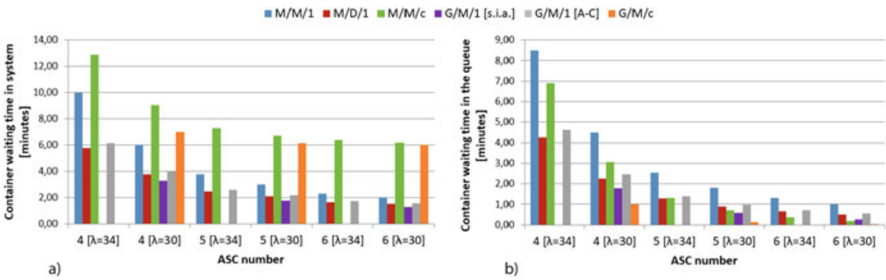


Fig. 4.6 (**a**) Average container waiting time in the system per STS crane and (**b**) average container waiting time in the queue per STS crane

more containers in transit but fewer standing in queue (see Fig. 4.5b) and waiting less time on average (see Fig. 4.6b). Reduction in the variance of the service times (red bars), as expected improves the queuing performance, but it is deemed a less realistic model. The reduction in variance in the arrival distribution as modelled by the $G/M/1$ system (violet and cyan bars) is shown to result in a significant reduction in containers in the queue (see Fig. 4.5b) and their *average waiting time* compared to the $M/M/1$ (see Fig. 4.6b, blue bars). The explicit modelling of the *interarrival time* variability by introducing the General arrival distribution allows the quantification of this effect. In that sense, the $G/M/c$ model probably allows the best flexibility at the expense of some computational complexity. However, solution routines are readily available for its implementation (see Gross et al. 2017).

On the question of decision support, the above-mentioned performance measures provide some insight, but to the authors' knowledge, there is no rigid rule that defines what the minimum acceptable level of service for container terminals is. Obviously, the terminal operator wants to maximize the utilization of their equipment, and given the cost of AStCs, they would try to provide the minimum number that ensures the STS crane productivity is unaffected, which in turn is the level of service that the shipping lines measure and value. Therefore, judgement is necessary to decide the fleet size. Indeed one can see from Figs. 4.5 and 4.6 that the performance is marginally improved for 5 AStCs per quay crane or more.

Perhaps the model closest to the problem at hand is a multi-server queue with limited size ($M/M/c/K$), as it can approximate the situation of the limited number of transfer positions (buffer) under the STS crane and the multiple AStCs (servers) transferring the containers between the yard and the apron. A system size of K corresponds to the situation where every one of the c AStCs is carrying a container, and there is a container laid on each of the K–c transfer positions at the apron. An appropriate level-of-service criterion needs to be defined to evaluate the appropriate fleet size and the number of transfer points required. In this article, the criterion was blocking probability as this would mean that the STS crane would have to wait before laying a container on the apron. Because of the nature of this model (blocked clients have turned away), it is not possible to estimate the average delay on the STS crane, but only approximate the revised container arrival rate as $\lambda' =$

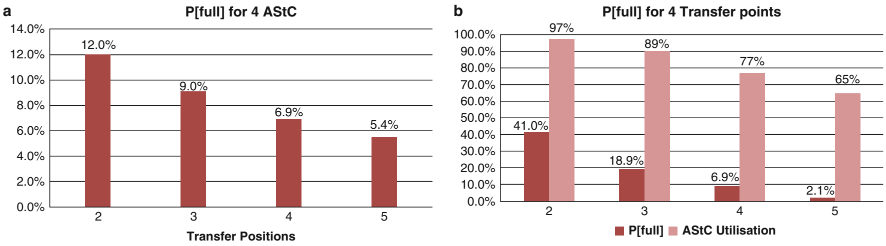


Fig. 4.7 Using the M/M/c/K queuing model, (**a**) blocking probabilities and 2–5 AStCs are assigned to an STS crane and (**b**) blocking probabilities for 2–5 transfer positions for 4 AStCs to an STS crane

(1-P[full])·λ. The crane productivity rate of $\lambda = 33$ moves/h (weighted average productivity between deep-sea and barge cranes) was considered here. If a minimum acceptable productivity is agreed as $\lambda' = 30$ moves/h, then the level-of-service criterion becomes [P[full]]max = 10%. The sizing problem then is a 2-step process:

1. determine the min number of AStCs for which the utilization is high and the blocking probability is acceptable,
2. conduct sensitivity on the number of transfer positions on the apron so that the blocking probability is acceptable.

As a starting value for the number of transfer positions (K–c) we can take the minimum number of traffic lanes required behind the STS crane. In the Venice example, assuming that 4 STS will be put on a deep-sea vessel, 4 traffic lanes and one bypass lane would be needed (see Fig. 4.4). The 4 transfer positions (assumed one container high) are on each of the 4 traffic lanes.

The results of this queuing model indicated that with 4 AStCs assigned to an STS crane, the equipment is sufficiently busy (utilization is 77%) and the probability of blocking is 7% (with four transfer positions) as shown in Fig. 4.7a. Having between three and four transfer points (i.e. traffic lanes at the deep-sea berth and the barge berth) will keep the blocking probability within an acceptable range (9–7% respectively, see Fig. 4.7b).

4.4.3 Petri Nets

A PN is a conceptual and visual-graphical tool particularly suited to represent and analyse the properties of concurrent systems with discrete number functions. Its mathematical features enable systematic analysis and verification, while its modular composition enables the construction of complex systems characterized by precedence relations, concurrent activities, asynchronous events, and resource sharing conflicts (see Liu and Ioannou 2002a). Because of these qualities PNs have been used extensively to model manufacturing, communication, and urban transport systems, as mentioned earlier.

It should be noted that overall, PNs are a means to formalize a model of flow operations, similar to Queuing Theory. For the solution of that model (and hence to get the metrics that help in the performance evaluation of the operations model), various mathematical methods are used, such as analytical techniques for solving (semi-)Markov Processes or Discrete Event Simulation (see Lenka and Das 2012). The available tools for PN solutions have integrated some of these methods in an autonomous capacity. In this sense PNs are not dissimilar from Queuing Theory as the latter also uses concepts from stochastic process modelling (e.g. Birth-Death models, Markov and semi-Markov Chains), and Discrete Event Simulation to get the performance metrics (queue size, waiting times, etc.). Therefore, it is the authors' belief that PNs can be considered a valid candidate for evaluating decision alternatives in container terminal horizontal transport. On one hand they borrow elements from both deterministic and stochastic processes while on the other they present a middle option regarding computational demands and modelling complexity.

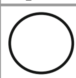
Following the standard definitions (see Murata 1989), PNs consist of four elements: Place, Transition, Arc, and Token, which are summarized in Table 4.3. In PNs, an area, activity, or state of the system can be modelled using a Place, and the number of instances of a Place can be represented with Tokens. Sequential processes are modelled with Tokens progressing through state machines. Arcs between resource Places and Transitions represent the acquisition (return) of some resources by a process. In the end, the process state machines can be merged into a model of the whole system by combining the common resource Places.

In mathematic terms, a PN represents a (bipartite) network graph and consists of five parts (see Murata 1989):

$$PN = (P, T, F, W, M_0) \tag{4.1}$$

where P is a finite set of Places, $P = p_1, p_2, \ldots, p_i$. T is a finite set of Transitions, $T = t_1, t_2, \ldots, t_j$. F is a finite set of Arcs (flow relation) that $F \subseteq (P \times T) \cup (T \times P)$. W is a weight function and M_0 is the initial marking. The essence of the

Table 4.3 Petri Net elements

Element	Function	Traditional representation	Graphical representation
Place	Area, activity, or state of the system	Circle	
Transition	Functions linking places	Rectangular bar	
Arc	Connect places to transitions and vice versa, enforce conditions	Vector (arrow or curved arc)	
Token	Counting/controlling medium, the quantifying aspect of the net	Dot	

mathematic representation of PNs is that a Transition cannot fire until a series of conditions have been fulfilled:

- The destination Place has the capacity for incoming tokens.
- There are enough Tokens available at the input places.
- No other Transition fires simultaneously.
- Other conditions such as time or colour restrictions may apply, depending on the Petri Net type.

One of the most important properties of PNs is that they are memoryless. This is a Markovian property which entails that any state in a PN is only dependent on the immediately previous one and not the ones before that. Commonly computed performance measures in PNs are the

1. probability mass function of the number of Tokens at steady state in a Place,
2. average number of Tokens in a Place, and the
3. frequency of firing a Transition (throughput).

In this article, an indicative *Timed-Place Stochastic Coloured Petri Net* is introduced to illustrate the modelling and analysis of horizontal transport movement in container terminals via PNs for fleet sizing. The definitions and transition rates for modelling a full AStC cycle are summarized in Table 4.4. It is "Timed" because a delay between transitions had been programmed to represent the AStC cycle and it is also "Place" because the Places can hold more than one Token (that are equal and indistinguishable apart from their colours).

Although the transition sequence and times for each AStC (token) (final duration in Table 4.4; net time calculated using the terminal and equipment geometry, and machine parameters in Table 4.1, adding a delay equal to 25% of the net time) are deterministic, the order with which Token transitions occur is random, hence introducing an element of stochastic behaviour. This stochasticity is due to the fact that a PN is required to depict simultaneous events, such as movements of different AStCs operating concurrently, in a realistic manner. In the model, this is achieved by randomizing the transitions between each PN stage. All eligible Transitions (those that are in a "ready to fire state") are placed in a pool and a selection is conducted amongst them, usually via a random number generation process. Thus a semblance of time is created, much like "stop-motion" animation, for the PN and the movements of the entire AStC fleet (than are simultaneous in reality) can be simulated after a satisfactory amount of repetitions. For completeness it is mentioned that in certain PNs there is also the option of introducing logic in firing specific Transitions, a feature which is not used in the current analysis.

Moreover, the PN model used here can be characterized as ordinary, live, persistent, regular; all stages would be reachable and reversible, and 3-, 4-, 5-, or 6-bounded depending on AStC configuration.[2] Here, coloured Tokens represent the movements of AStCs; black Tokens for deep-sea side and red Tokens for barge side.

[2] A PN is called "k-bounded" when all its places contain no more than k Tokens at any given time, including the initial stage.

Table 4.4 AStC transition rates in PIPE (v4.3.0) for the deep-sea side PN segment, similar values were used for the barge side

Origin place ($P_{\#}$)	Transition ($T_{\#}$)	Destination place ($P_{\#}$)	Movement type	Net time [s]	Delay time [s]	Final duration [s]
P_1: STS crane queue	$T_{1,2}$: safety clearance	P_2: crane loading spot	Horizontal	29.24	7.31	36.54
P_2: STS crane loading spot	$T_{2,3}$: start loading	P_3: loaded	Vertical	28.30	7.07	35.37
P_3: loaded	$T_{3,4}$: depart for block	P_4: reach block entrance	Horizontal	88.07	22.02	110.09
P_4: reach block entrance	$T_{4,5}$: slow down	P_5: block destination	Horizontal	8.29	2.07	10.37
P_5: block destination	$T_{5,6}$: start loading	P_6: unloading	Vertical	37.73	9.43	47.17
P_6: unloading	$T_{6,7}$: depart	P_7: reach block exit	Horizontal	8.29	2.07	10.37
P_7: reach block exit	$T_{7,1}$: speed up	P_1: STS crane queue	Horizontal	88.07	22.02	110.09
			Total	287.99	71.99	360.00

Coloured PNs (see Jensen et al. 2007) are utilized here to distinguish between AStCs of the two different sides, commonly operating in the block destination stage at any given moment. Coloured PNs provide the capability of modelling the two sides simultaneously and still keep the option of separating them at a later stage for any reason (equipment incompatibility, geometric separation of the process, etc.). An indicative configuration of the PN model with five deep-sea side AStCs and 4 barge side AStCs at the initial stage and at a random later stage are shown in Figs. 4.8a and 4.9b. Although in the figures the Places before the cranes are indicated as *loading spot* and the Places outside the yard block as *unloading*, the status of the AStCs could be reversed, describing a discharging process, without any change in the model. This is because the loading and discharging time under the crane (final duration at Place $P2$ in Table 4.4) and the lifting and dropping times in the yard block (final duration at Place $P5$ in Table 4.4) are taken as equal. In other words, what is modelled in the PN is the movement of the AStCs irrespective of the flow of containers (inbound or outbound).

For simplicity, the PN models the operations of one STS crane and one barge crane with the assorted AStCs, i.e. gang on each side. Although outside the scope of this illustrative example, the network of Places and Transitions can be expanded without loss of generality to consider all the cranes and all the AStC that serve a deep-sea vessel and set of barges, in a pooled resource set up, similar to Liu and Ioannou (2002b). In such a case, dispatching rules would also be necessary to decide which *STS* crane queue (STSC queue) the AStCs would join.

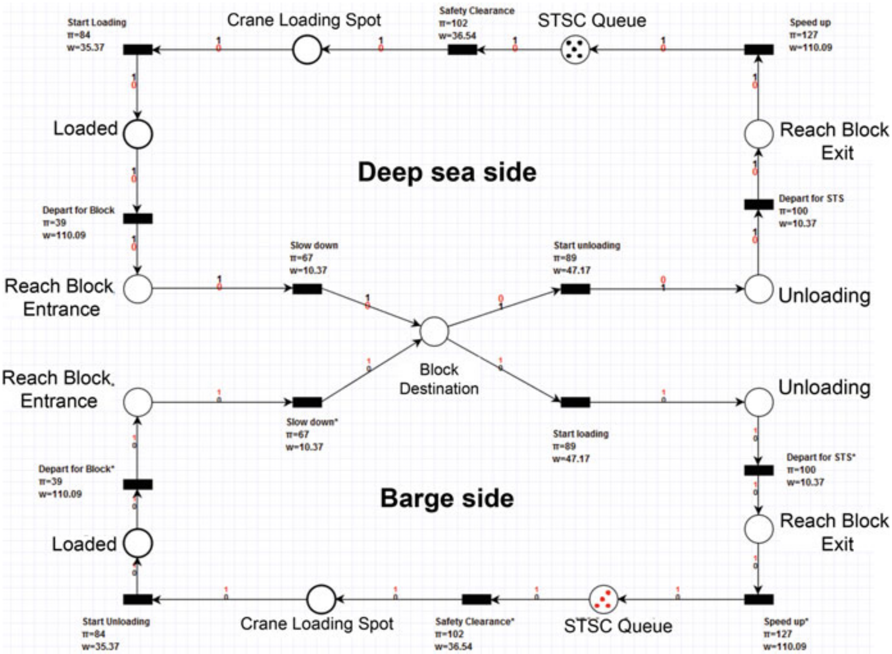


Fig. 4.8 PN model of the terminal with 5 deep-sea side AStCs and 4 barge side AStCs at the *initial stage* (barge side Places are shown with '* ')

The above AStC cycle time of 360 s (rounded) leads to a productivity rate of 10 cycles per hour. To match the STS crane productivity requirements (30 moves/h or 34 moves/h for barge and deep-sea side, respectively), the experiments have a minimum of 3 Tokens. In contrast to Discrete Event Simulation, because of the way the PN is set, there is no link, such as a crane routine that pulls the Tokens from the Place *STSC queue* to the Place *loading spot* at a certain rate, other than the random selection of which Token moves next (Transition firing). In contrast to Queuing Theory, the times that the Tokens spend at the Places *loading* and *unloading* are deterministic. As such, there are no metrics for Tokens in a Place that are directly comparable with these two methods.

The Places *loading spot* and *loaded* are the only ones with capacity restrictions of 1 token (Places appear as bold circles) as it was assumed only one AStC can operate under the crane at a time, like in Queuing Theory. Arc weights, by definition, are integers that are assigned to each Arc. They determine how many Tokens are destroyed from the input Place as they pass towards the Transition and how many Tokens are created from the Transition to the output Place. In traditional PNs, Arc weights can generate or remove Tokens to simulate a production line environment (with parts being split or assembled, for instance). In this case however, due to the nature of the PN designed, no AStC Tokens are generated or lost since the number of AStCs is stable for each analysis. Therefore we used Arc weights of 1 to ensure

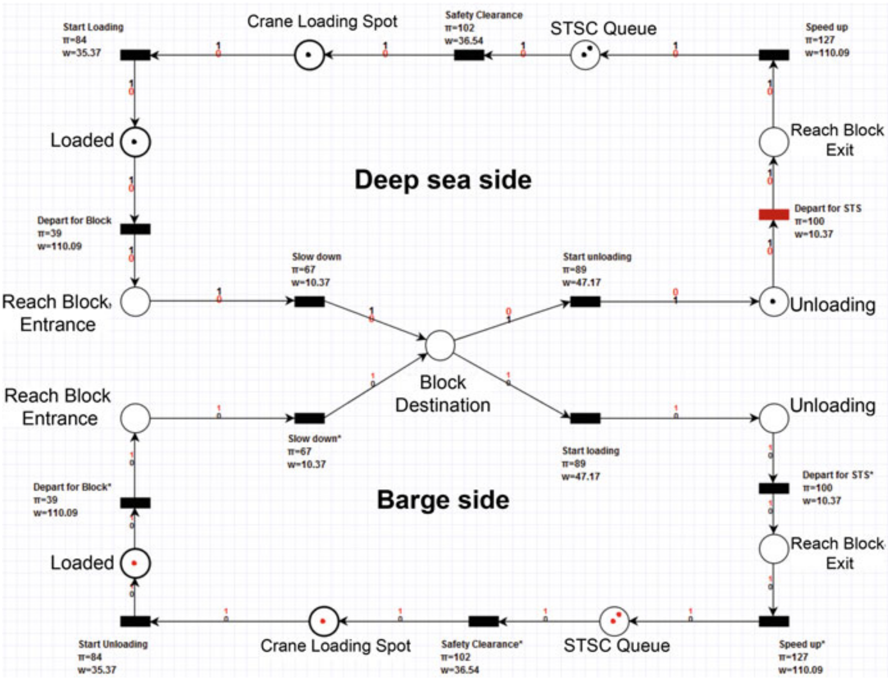


Fig. 4.9 PN model of the terminal with 5 deep-sea side AStCs and 4 barge side AStCs at a *random stage* (barge side places are shown with '* ')

this number remains stable each time the PN is created and loaded for analysis by the software, and when analysis is underway (each time the PN Transitions fire and a new state of the PN is created). In addition to the previous, Arcs include filters of the proper colour to separate AStCs per barge or deep-sea side (so that no barge AStC can enter the deep-sea side of operations and vice versa). Hence, there are two types of Arc weights, utilized here, black and red with values 0 and 1 on each Arc. To simulate the need of at least one AStC to be on standby by the quay crane, so the latter keeps operating, the highest priority, π, has been assigned to the Place *STSC queue*, and others have gradually diminishing ones.

The PIPE2 software (see Bonet et al. 2007; Dingle et al. 2009) is a Java-based, platform-independent, open source tool for the construction and analysis of *G*eneralized *S*tochastic *P*etri *N*et (GSPN) and was used for simulating the PN and extracting results. For each experiment, the PN is loaded with an equal number of Tokens of each colour, for each scenario (3, 4, 5, and 6 Tokens, respectively), to conduct analysis comparable to the other methods. As previously described, the Token movements occur with a fixed sequence and transition times for any individual AStC, but in a random order between different AStCs. Because every firing Transition in PIPE2 is determined from the pool of all eligible ones randomly (via a Java random function), the number of Tokens at each Place at any time

Table 4.5 Terminal PN simulation results for the average AStCs queue length at quay cranes

	Average number of tokens at STSC queue place			
#AStC/STSC	Deep-sea side	95% confidence interval	Barge side	95% confidence interval
3	0.72	±0.025	0.72	±0.025
4	1.73	±0.035	1.70	±0.035
5	2.73	±0.033	2.70	±0.033
6	3.73	±0.026	3.71	±0.026

is a random variable. The random ordering of the individual Token movements simulating the simultaneous AStC movements introduces a stochasticity factor to the PN. The steady-state average and confidence interval of the number of Tokens at each Place are calculated for every experiment, which is the selected performance metric here. Each firing is the process of conducting a discrete transition, thus changing the state of the PN. It was found that 2000 firings are sufficient for the PN to reach a steady state beyond the initial conditions. It was also found that, after 30 replications, there was a satisfactory convergence of the PN analysis, with consolidation at the 4th decimal digit. The average number of Tokens (AStCs) at Place $P1$, i.e. in the *STSC queue*, for both terminal sides (deep-sea side and barge side) and their 95% confidence interval values are shown in Table 4.5.

The criterion for the optimal fleet size is the same as with the other methods, i.e., the smallest size that does not lead to crane underutilization (as measured by the average number of Tokens on the Place *STSC queue* and not by some observed STS crane productivity, as this is not possible in the PN setup). The analysis shows that, given the geometry and cycle times, the best option for the AStC fleet size appears to be 4 vehicles ($1.0<$ average tokens in queue <2.0). If 3 vehicles are assigned, there will be some time periods without any AStC standing by the crane, which might lead waiting for the more expensive equipment (cranes). On the other hand, if 5 or more AStCs are assigned, it appears that they would form an unnecessarily large queue for operations, leading to underutilized equipment (reduced efficiency) for both the deep-sea side and the barge side.

The presented PN model has deterministic times in the different places as shown in Table 4.4. Consequently, from the performance measure results that are used in other equipment sizing methods, only the number of AStCs at Place $P1$ (*STSC queue*) is a comparable random variable. An indication for the vehicle queue length, i.e., the AStCs available to service each quay crane can be given by the average number of Tokens at the Place $P1$, to be read in conjunction with the total number of AStCs operating. While in practice this usually means that one AStC can enter the crane portal at a time, the rest of the vehicles in the queue will be on close standby to fall into position when the crane begins the start of the next loading phase and ensure productivity is not disrupted.

Table 4.6 AStCs utilization and quay crane productivities for two deployment strategies (*gangs* and *pooling*) with two scenarios (1: an average and 2: a contingency vessel schedule)

Scenario	Strategy	AStC utilization [%]	Deep-sea STS crane productivity [moves/h]	Barge crane productivity [moves/h]
Scenario 1	Gang	38	27	20
	Pooling	43	31	24
Scenario 2	Gang	39	27	20
	Pooling	44	28	22

4.4.4 Discrete Event Simulation

In using Discrete Event Simulation, the aim is to determine the number of AStCs needed to operate the offshore terminal at the target throughput and to achieve target quay crane productivities. As with the previous methods, the approach includes oversizing the fleet results to underutilized AStC (i.e. unnecessary costs), while under sizing the fleet results in reduced crane productivity. The criteria used to determine the optimal fleet size were (a) the AStC utilization and (b) the quay crane productivities (see Table 4.6). Again, judgement is required to balance the requirements for AStC utilization with the need for crane productivity. The authors believe that in the preliminary stages this approach is better than an optimization algorithm.

FlexSim (2018) is an advanced Discrete Event Simulation (see Law 2014) platform that is designed for detailed simulation of container terminal operations. A specific model was built for the offshore terminal of Venice and can be seen in Fig. 4.10. The software models both the geometrical attributes of the terminal (e.g. the dimensions of the stack and the lengths of the traffic lanes) and the container handling processes (i.e. the delays in the handling and various rules on quay crane and equipment assignment). The operating design of this terminal is unique in the sense that there are a high number of direct moves for import containers as they are taken directly between the deep-water berth and the barge berth. Considering the very limited storage space available, the barges are used as import storage and the terminal yard as export storage. Several initial validation models were set up to determine rules that apply to the barge and barge carrier system and the container transfer from the barge quay to the deep-sea quay and vice versa. The following rules have been identified through discussions with the project team and analysis of smaller validation runs.

- In the first instance, the loading of export containers to barges has to commence at the onshore terminal approximately 48 h before a mainline vessel arrival, to allow time for transfers into the offshore terminal stacks.
- The barge delivering a main line vessel's export containers is unloaded into the offshore terminal stacking area. Therefore, export container barges must be unloaded before a mainline vessel's arrival.

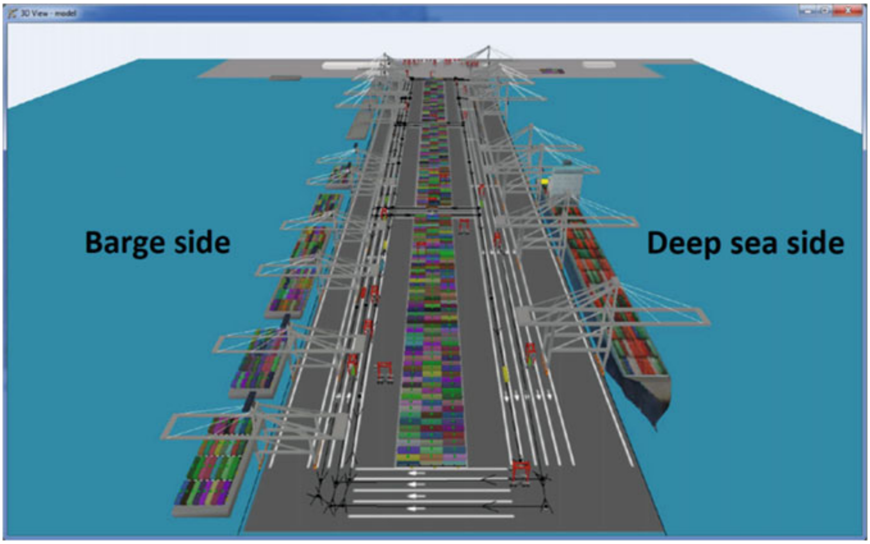


Fig. 4.10 Animation view of the FlexSim simulation model for the Venice offshore container terminal

- The empty barges are then used to take the import containers back to the onshore terminal.
- Up to 5 cranes are used per vessel on the deep-sea berth.
- Up to 6 cranes and six barges are used on the barge berth per main line vessel.
- The barge carrier (Fig. 4.3a) is assumed to take any available barges to and from the offshore terminal on a regular repeating pattern. Taking single barges (Fig. 4.3b) is avoided where possible to maximize efficiency.
- At the offshore terminal, the priority is to permit empty barges to load containers directly transferred from the deep-sea going vessel.
- At the onshore terminal, the priority is to load up barges for transfer to the offshore terminal promptly.
- Unlimited barge lay-up area available at the side of the offshore terminal berths
- Flexible berth allocations are allowed.
- Maintenance routines and breakdowns are not included in the assessment of equipment numbers. Instead, the numbers are assumed to be the number of regular equipment available for operations, and additional equipment (commonly 10%) will be allowed for planned maintenance and breakdowns.
- Housekeeping operations (customs and stack block optimizations) are carried out in AStC idle periods, i.e. outside the busy periods simulated herein.

The model was used to study the fleet sizing problem and test two different AStCs deployment strategies for the terminal, namely running in *gangs* and *pooling*. Simulation allows the planner to apply different operating strategies (such as *pooling*) and see the particular effects on operations, despite the fact that it is not possible to compare the results with the other methods (Petri Nets and Queuing Theory). Although the theoretical results regarding *pooling* are generally known, it was decided to study the effect of *pooling* in this sizing problem, because, it was not clear to the team a priori that *pooling* would yield the best result under all operating circumstances, and how big the difference would be in terms of fleet sizes and resulting quay crane productivities. So it was decided first to compare the two operating strategies and then study the sizing problem on the most efficient deployment strategy.

For the *gangs* strategy, specific AStCs are assigned to specific deep-sea berth STS cranes, ensuring that horizontal transport equipment is always available for berth operations regardless of vessel arrival times or patterns. For the *pooling* strategy, a central pool of AStCs serves all STS and barge cranes, each AStC assigned to different tasks based on a pre-assigned task prioritization.

To best represent the most critical operational cases, two scenarios have been investigated (see Table 4.6). In Scenario 1, a *typical vessel schedule* where vessels arrivals are scheduled and variations come from a Uniform distribution with up to 12 h maximum variance before or after the estimated time of arrival. In Scenario 2, a *contingency vessel schedule*, where two vessels unload or load simultaneously, or one vessel unloads and one vessel loads simultaneously before the vessel schedule returns to a regular weekly pattern. Each model was run to simulate 12 weeks of terminal operations based upon pre-determined schedules for barge and mainline vessels arrivals generated from a setup with two barge carriers and 20 barges. The first 10 weeks are run to make sure that the terminal is correctly populated with containers and to establish the steady-state shipping patterns. The last 10 weeks are then monitored closely on the screen to identify any bottlenecks that may arise during operation and for statistics and data collection. For Scenario 2, because it represents severe events, they were manually simulated in shorter runs after the steady state is reached and then the time taken to recover normal operations (defined as yielding comparable service time results to scenario one runs) was recorded.

Prior analysis for the STS and barge crane fleet size indicated that 8 STS cranes and 11 barge cranes were required to meet the productivity demands of the operations. Four AStCs were initially assigned to each STS and barge crane (i.e. fleet size of 76 AStCs) to compare the deployment strategies. The two deployment strategies, *gangs* and *pooling*, were run with the average and contingency scenarios. The equipment utilization results and the quay crane productivity rates are summarized in Table 4.6).

The initial comparison between the two operating strategies confirms that the *gang* strategy, as set up in the model, is less efficient than a *pooling* strategy. Both the utilization of AStCs and the resulting quay crane productivities while operating in *gangs* are lower compared to the central pool strategy, in both scenarios, despite the equal number of horizontal transport equipment. The improved productivity is primarily because AStCs can be assigned to berth cranes more flexibly with a higher AStC-to-berth crane ratio when additional StCs are available. These results confirm the well-known conclusion that *pooling* of equipment shares the workload more evenly and achieves more uniform equipment utilization. However, there are two observations that may not be obvious:

1 The *gang* strategy has a much more consistent performance. No change in crane productivity between the typical and the contingency scenarios was observed; whereas with *pooling* the productivity drops in the contingency scenario, and
2 The gains in crane productivity with the *pooling* strategy in the contingency scenario are marginal (additional 1–2 moves/h).

Due to the efficiency gains of the *pooling* strategy during the typical schedule (Scenario 1), the central pool option was selected for further analysis. The initial low AStCs utilization (43%) indicates that there may be space for reducing the fleet size.

In the second step of the analysis, simulations were run with the AStCs pool size gradually reducing from 64 to 32, to compare the effect on their utilization, total cycle time (i.e. service and waiting time), and crane productivities (see Table 4.7). It can be seen from the increase in average AStC cycle time that increasing the fleet size beyond 48 (i.e. 2.52 AStCs per crane) will only result in congestion and queuing at the berth, without any increase in quay crane productivity. Therefore, a fleet size of 50 AStCs (48 operating and two spares) was selected as the optimal fleet size for the particular layout, operations, and quay crane arrangement, yielding the maximum crane productivity at the smallest fleet size for both the regular and contingency scenarios.

Table 4.8 shows the simulated average quay crane productivities with an equipment pool of 48 AStCs in operation, compared to the target STS crane productivities for both the deep-sea side and the barge side. Table 4.8 also shows the average crane waiting times. It can be seen that although they are slightly lower than the target, they are within the industry benchmark range PIANC-158 (2014) of 30–35 moves/h for high STS crane productivity. Additionally, it is shown that the average quay

Table 4.7 AStCs utilization and quay crane productivities for a *pooling* strategy with two scenarios (1: typical and 2: contingency vessel schedule)

Scenario	AStC pool size	AStC utilization	AStC average cycle time [min]	Deep-sea STS crane productivity [moves/h]	Barge crane productivity [moves/h]
Scenario 1	32	77	7	29	23
	40	68	9	31	24
	48	63	9	31	24
	56	57	9	31	24
	64	52	9	31	24
Scenario 2	32	78	6	27	20
	40	70	7	27	20
	48	65	9	29	22
	56	58	9	29	22
	64	52	9	29	22

Table 4.8 Simulated quay crane productivities and waiting times (1: an average and 2: a contingency vessel schedule)

Scenario	Berth type	Target crane productivity [moves/h]	Average crane productivity [moves/h]	Difference [%]	Average crane waiting time [%]
Scenario 1	Deep-sea	34	31	−9	3
	Barge	30	29	−4	3
Scenario 2	Deep-sea	34	29	−15	5
	Barge	30	26	−12	3

crane waiting time is consistently low (particularly for the contingency scenario), below 5% of the total. These additional operational indicators provide confidence in the selected fleet size.

Compared to the other fleet sizing methods, Discrete Event Simulation not only yielded a 37% more economical fleet sizing (2.5 AStCs to a quay crane versus 4 vehicles, or 48 total versus 76), it also highlighted different aspects of the operations that would not be possible otherwise. Of course, these results come at the cost of additional time, data, and complexity requirements.

4.5 Comparison of AStC Sizing Models

This section summarizes the advantages and disadvantages of each of the previously considered methods and attempts to provide a recommendation for when they should be used. Queuing Theory formulations and practical examples are widely available, rendering them particularly easy to implement. Most publicly available implementations are approximate and moderately conservative, which makes them good candidates for preliminary fleet sizing. Additionally, they provide intuition regarding the uncertainty of the operations to the practitioner that wants more than first order (average) results. On the other hand, there are many different solutions available, and judgement should be exercised as to which queuing model is most representative of each particular problem. There is a trade-off between the sophistication of arrival and service time probability distributions and the number of servers and buffer positions in the currently available models, i.e. there are single-server, infinite-queue models with complex distributions, or multi-server, finite size models for Exponential arrival and service distributions. All these solutions describe steady-state queuing systems with non-deterministic rules, so more complex operating strategies can be intractable in their solving. Perhaps the model closest to the problem of fleet sizing of AStCs is a multi-server queue with limited size ($M/M/c/K$), as it can approximate the situation of the limited number of transfer positions (buffer) under the quay crane and the multiple AStCs (servers) transferring the containers between the yard and the apron. The results of this queuing model indicate 4 AStCs assigned to an STS crane, and having between three and four transfer points will keep the blocking probability within an acceptable range.

Petri Nets are visual-graphical tools that can be formulated to represent any Markovian (memoryless) System with discrete number functions, simple or complex. Their implementation in this example and in other automated horizontal transport applications (see e.g. Kezić et al. 2007; Kim et al. 2010; Li and Zhou 2009; Liu and Ioannou 2002a,b) promises some cost efficiency and has advantages, such as visualization tools similar to flowcharts, block diagrams, and networks for easy verification of the system examined, with direct display of its parts. An important contrast with Queuing Theory is that while it traditionally uses stochasticity for the arrival, service, and departure stages, certain types of PNs such as the one utilized here have deterministic transition (travel, delay, and service) times but random execution order of the transitions that are then realized during a certain deterministic time margin. In certain cases, such as when highly non-linear relationships are involved in basic system components it appears that PNs may not be the most appropriate tool to tackle planning problems. However, it should be noted that PNs are a conceptual modelling tool first and foremost, and they have value as such.

Overall, PNs appear remarkably flexible and able to describe operation procedures, such as concurrent activities, precedence, priority, and scheduling rules in a simple and graphical manner, something that neither Queuing Theory nor Discrete Event Simulation can do without significant mathematical and programming effort. Hence, their implementation merits consideration as a "middle road" between quickness of results and computational and modelling complexity. Nonetheless, PNs are not as easily accessible and well-understood yet to practitioners as Queuing Theory formulas, while there is still some computational effort required to obtain useful results. Perhaps the biggest hindrance to the more widespread implementation of PNs since the early 2000s is the requirement to adapt the model representation to a Petri Net graph, whereas modern Discrete Event Simulation environments such as FlexSim, with customized application modules, allow a more natural representation. From the results obtained from PNs, 4 AStCs per quay crane appears as the optimum solution for both deep-sea and barge side berths. The authors' recommendation is that further development would be still required in an easily applicable tool for practitioners to use in current planning problems, but the methodology itself as the simple illustration herein demonstrated can provide results at a preliminary planning stage. It also has the capability as shown elsewhere (see Liu and Ioannou 2002a,b) to model system logic and control relationships. It is hoped that openly available PN platforms such as PIPE2 become easy enough for practitioners to use and with sufficient complexity implemented to readily apply in actual container terminal problems.

Discrete Event Simulation models allow realistic investigation of any process in a container terminal, and a full evaluation of the performance of the layout, equipment, and deployment strategy. However, this comes at the cost of additional time, data definition and processing and programming complexity, to the point that in current recommended practice (see e.g. Salt 2008) it is best to tailor simulation solutions to answer specific questions than model a system in full realistic detail.

Nonetheless, the rapid growth in the simulation software platforms and bespoke modules for container terminal applications of the last 10 years has led to significant reduction in the effort required to create, debug, run, and post-process the results of a representative simulation model. Compared to the other fleet size determination methods, Discrete Event Simulation yielded a significantly more economical fleet sizing (2.5 AStCs to a quay crane) but was also able to test and validate the most efficient operating strategy that would result in this sizing (*pooling*). It is, therefore, the authors' recommendation that Discrete Event Simulation can be readily used during the detailed planning phase of the container terminal, when sufficient time, resources, and information from the end user is available to create a sufficiently detailed and validated model that takes advantage of the capabilities of the method. With all methods, their application to the Venice offshore terminal horizontal transport fleet size determination problem showed that judgement is required in setting and evaluating the appropriate performance criteria. For the preliminary fleet size determination, it is recommended to look at different metrics, as provided by each method, to obtain a better insight into which fleet size offers the best trade-off between initial cost, utilization, and crane productivity.

4.6 Conclusions

This paper presented and compared multiple practical methods for addressing the horizontal transport equipment fleet sizing problem in container terminals. An additional contribution of this paper is the application and evaluation for the first time of Petri Nets as a method for horizontal transport planning and fleet sizing. The applicability of methods and their results and insights were compared and demonstrated in the planned Venice offshore container terminal, using AStCs as means of horizontal transport. It is concluded that while Queuing Theory is a mature field that can be applied with some approximation to the preliminary sizing problem, it is rather conservative. Discrete Event Simulation is also a mature method that can yield significantly more cost-efficient results and recommended for detailed design due to its time and information requirements. Further development would be still required in an easily applicable tool based on Petri Nets for practitioners to use in current planning problems, but the methodology itself can provide reasonable yet conservative results at a preliminary planning stage.

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Chapter 5
Automation and Electric Drives

A Powerful Union for Sustainable Container Terminal Design

Joan C. Rijsenbrij and Armin Wieschemann

Abstract Despite a reduced annual growth in trade volumes, major shipping lines continue to invest in ULCVs (*U*ltra *L*arge *C*ontainer *V*essels with 20,000+ TEU). For efficiency reasons shipping lines operate in alliances and joint services, to maintain attractive shipping services to shippers/consignees and to benefit from economies of scale and enlarged buying power. Parallel to this, the complexity of logistics is growing and the society and port authorities put stronger demands on environmental control and sustainable designs. These developments influence terminal designs and terminal operations, which have to deal with much larger vessel call sizes, longer container dwell times, and frequent changes in handling volumes from varying alliance policies and shipping services. A growing amount of container terminals have recognized (partly) automation as an appropriate tool for cost control and performance improvement, required by the powerful shipping alliances. The application of state-of-the-art electric drive technologies will support an increased use of renewable energy and long-term cost reductions.

5.1 Introduction

Over the last years there has been a moderate growth in yearly port handling volumes, reaching towards about 700 million TEU handlings in 2017. A major part of this volume (>34%) is handled by Chinese ports and when looking to the developments in other Asian ports, there is a clear shift in volume towards the Asian region (see Fang et al. 2013). Contrary to the moderate growth in port handlings, the world container vessel fleet capacity has increased considerably to over 20 million

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TEU. An impressive part of the fleet is realized by vessels larger than 10,000 TEU capacity, with already more than 50 vessels in the range of 18,000–21,000 TEU (mid July 2017; see Alphaliner 2017). In order to fully benefit from economies of scale, the shipping lines increasingly operate in global alliances (e.g. 2M, Ocean Alliance, THE Alliance), very helpful to optimize their worldwide shipping services and to increase their buying power not only for supplies and bunkers but for terminal services as well. This has caused noticeable reductions in terminal handling rates and at the same time the enlarged vessels have resulted in larger operational peaks and more idle time for the terminals' waterside operations. In addition, shipping lines and inland transportation companies require terminals to realize increased handling performances and predictable, limited turnaround times (see Merk et al. 2015).

Parallel to this, the complexity of logistics is growing. The dominance from shippers and consignees deteriorate landside stochastics as a result of last-minute changes and unknown (inter-)modal connections. Moreover there is a growing influence from customs regulations and security requirements, larger volumes of container checking with X-ray and recently the demands from the International Convention for *S*afety *O*f *L*ife *A*t *S*ea (SOLAS) that shipping documents must include a *V*erified *G*ross *M*ass (VGM); see IMO Secretary-General (2016).

And finally, governments, port authorities, and the society put stronger demands on environmental control and sustainable designs. Habitats around port developments should not be influenced and pollution from sound and exhaust gases is increasingly restricted and the use of renewable energy from hydro, wind, and solar power is stimulated or even subsidized. The use of casual labor is diminishing and port operators are required to provide good working conditions, appropriate training, and labor contracts with well described regulations.

In this rapidly changing environment terminal operators are challenged to design or modify their terminals for the expected volume growth in the next decades. Many terminals have recognized (partly) automation as an appropriate tool for cost control and performance improvement. The application of state-of-the-art electric drive technologies will help to design sustainable automated terminals that can meet the future demands from a caring society.

5.2 Changed Demands in Terminal Design

After the year 2000 the larger terminals were confronted with the introduction of container vessels carrying more than 10,000 TEU. In the 1990s, an overall berth productivity of 100 moves/hour/vessel served with 4–5 *S*hip-*T*o-*S*hore (STS) cranes used to be a good service to shipping lines. However, after the arrival of 14,000 TEU vessels and nowadays up to 21,000 TEU vessels, the shipping lines require a berth productivity of 175–250 cont. moves/hour/vessel with 6–8 STS cranes, still seldom met by terminals and thus a real challenge for an automated transportation system connecting so many STS cranes per vessel and the (large) stacking yard.

Not only a proper scheduling and dispatch for all the transport vehicles, but also the dynamic logistics, caused by the reversing push (discharge operation) and pull (loading) processes, require an intelligent control system for the horizontal transport system between STS cranes and stacking yard (see Rijsenbrij 2008). Regardless smart interfaces and well-defined priority rules, the required berth performance for *U*ltra *L*arge *C*ontainer *V*essels (ULCV) results in a highly intensified traffic density at the apron. The example elaborated in the below presented case study shows the impact of ULCVs on apron traffic density, labor demand, and idle time for waterside operations (simplified comparison with equal yearly volume) (Table 5.1).

The demand for increased berth performance from large shipping lines and alliances is often combined with guaranteed berthing, which is even worse for the terminal's quay wall utilization. Shipping lines introduced ULCVs to get cost savings in their operations; however, for terminal operators the handling of ULCVs causes inefficiencies and more complex (and thus more costly) logistics.

Other demand changes can be recognized at the landside of the terminal. There the inland transportation operators (road, rail, and barges) demand guaranteed service times and pre-planned service slots. This must be realized independently from the workload at the terminal waterside resulting in additional equipment/systems for the terminals' landside service.

Beside the handling systems at terminal water- and landside, one of the most important terminal design components is the stacking yard, both the size and type (handling equipment, interchange areas, stacking height, and modular design) as well as the possibilities for future expansion. Many years of planning experience show that over the years the dwell time of containers has not been reduced; to the contrary, in many large terminals average dwell times longer than 5 days are rather common. The arrival of very large container vessels has resulted in 1.5–2 times larger call sizes and due to the reduced call frequency and limited inland transportation capacity this has increased the dwell time. Another phenomenon in that respect is the demand for cost reduction in the overall logistic chain, resulting in lowering (or even avoiding) warehousing and regional distribution centers. Shippers and consignees try to avoid warehousing by delivering containers directly after packing and through the collection of import boxes just in time for their logistics. Also the delays from incorrect CSI (*C*ontainer *S*ecurity *I*nitiative from U.S. Customs Service) information or missing VGM documents cause transit elongations. The mentioned changes in container logistics could be detrimental for the container dwell time at terminals and will increase the area demand and even (unpaid!) housekeeping.

Design changes can be triggered as well by the demand to cope with changing annual throughputs due to carrier policy to divert volumes for commercial (cost) reasons. Noticeable volume shifts have been occurred between terminals in Hong Kong, Singapore, Port Klang, North-West European ports, USA East Coast, etc. In those cases terminals want (and have!) to adjust stack capacity, handling capacity, and related labor demand.

Parallel to the above terminal design influences, terminals have to implement many features forthcoming from increased environmental awareness (pollution

Table 5.1 Case study: impact of ULCVs on apron traffic density, berth utilization, and labor demand

The ongoing drive for Economies of Scale has resulted in ULCVs operated by shipping lines. In 2016 more than 25% of the world's container vessel fleet consists of vessels with >10,000 TEU capacity (see Wadey 2016). Unfortunately, the application of ULCVs in an almost stable trade environment influenced terminal operations in a number of areas: berth utilization, labor utilization, more equipment, and more traffic density at the apron. These are the consequences from the shipping lines' requirement for much higher performance figures, when handling their ULCVs. In a case study the impact of ULCVs on the above issues was analyzed and in particular the transportation traffic between the STS cranes and the stacking yard, hence this traffic density is an important topic, when realizing automated transport systems.

For the case study a liner service calling at a terminal was projected; however, with two alternative vessel sizes: one service with 8000 TEU vessels and another with 18,000 TEU vessels. Both services, equal in yearly terminal throughput, realized approx. 1 million TEU and for that volume the terminal guaranteed a 500 meter berth length throughout the year. The service with 8000 TEU vessels resulted in 4 vessel calls per week, each call 3000 cont. moves (equals $3000 \times 1.6 = 4800$ TEU) and the service with ULCVs had 2 calls per week, each 6000 cont. moves. As vessels never arrive exactly on a labor shift change a 15% labor idle time was considered. The results per vessel type are presented in the table: The study showed: when shipping lines apply vessel sizes with capacity ranges of 16,000–20,000 TEU (instead of 6000–9000 TEU), the traffic density of transport vehicles at the apron will increase by 50%–60% and during performance peaks even by 60%–85%.

In addition, the requirement for increased berth performance (to maintain an almost equal time in port for the ULCVs) will decrease berth utilization by 35%. Moreover for the terminal operator, ULCVs cause less demand for waterside labor shifts, however with much higher peaks. This is unattractive when aiming for well-motivated employees with fixed labor contracts and work rosters (casual labor is less attractive for automated operations).

Vessel size (TEU)	8000	18,000
Vessel length (m)	340	400
Required additional berth length for mooring (m)	25	25
Berth length guaranteed for shipping line during the year (m)	500	500
Number of vessel calls per week	4	2
Call size (total moves for discharge and loading)	3000	6000
Yearly throughput (in TEU with TEU-factor = 1.6) realized in this liner service	998,400	998,400
Number of cranes assigned to vessel during vessel operation	4–5	7–8
Average operational crane productivity (cont. moves/hour/crane)	26–29	26–34
Required average berth productivity (cont. moves/hour)	125	225
Assumed extra time at berth for berthing and un-berthing (hour)	3	4

Vessel operating time (hour)	24	26.7
Total vessel berth time during one call (hour)	27	30.7
Average traffic density (transport cycles/hour per required meter berth length during a call)	0.34	0.53
Peak traffic density (all cranes operating at hourly maximum of their operational productivity)	0.40	0.64
Berth occupation from all vessel calls (berth-meter * hours)	2,049,840	1,356,940
Available berth-meter * hours (500 m 8760 h/year)	4,380,000	4,380,000
Berth utilization (%)	47	31
Gross number of crane operating hours required during one call, including 15% idle time	138	246
Required yearly waterside labor shifts (8-h) when all cranes operate simultaneously	718	400
Theoretical available waterside labor shifts during the year (365 days)	1095	1095
Labor utilization (required versus theoretically possible in %)[a]	65.6	36.5
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[a] Assuming that labor is available three shifts per day over the whole year

control, provisions for cold-ironing, use of renewable energy, etc.) and demands for safety and security (cameras, entrance control, training). On top of that comes the rapidly growing demand for data communication, both internally (control of automated systems, work orders, *F*ailure *M*ode and *D*efects *A*nalysis (FMDA), etc.) and externally (process info to shipping lines and shippers, tracking and tracing, Customs, port authorities, governmental bodies, etc.). The realization of secure data exchange (especially for radio data communication) will be a challenge for large terminals.

5.3 State-of-the Art in Terminal Automation

Over the last 25 years, automation has entered the operations of container terminals and today almost 30 terminals have installed automated handling and/or transportation of containers with centralized control systems and combined with some kind of automated gate control and features for automated container ID and X-ray inspection. The most elaborated automation has been installed in terminals at Hamburg (HHLA *C*ontainer *T*erminal *A*ltenwerder – CTA), Long Beach (*L*ong *B*each *C*ontainer *T*erminal – LBCT), and Rotterdam (ECT Delta Terminal, Euromax Terminal, *APM T*erminals Maasvlakte II – APMT and *R*otterdam *W*orld *G*ateway – RWG), where both the stacking and waterside transportation is fully automated and the landside delivery/receipt to the road is done remotely controlled. Even the transportation to the railhead could be automated (APMT with *A*utomated *G*uided *V*ehicles designed as active Lift-AGVs). Also in China the first fully automated container terminals have been installed. The first one has been put into operation at Xiamen in May 2013 (Xiamen Yuanhai Container Terminal). There as well the proven concept of AGVs for the transportation on the apron, connecting the STS cranes with *A*utomated *S*tacking *C*ranes (ASC) in the yard, has been selected as an effective terminal handling concept.

Notwithstanding the large benefits from cost savings and reliable, well-planned operations, the implementation of automation in terminals developed rather slowly. Some terminals even decided to take a risk-avoiding approach and selected a partly automated concept, limited to an automated stacking yard and a control system for the scheduling of manually operated transportation equipment between the STS cranes and the stack area, for example, using 1-over-1 straddle carriers (also referred to as *Sprinter*) at the Virginia International Gateway terminal (Portsmouth) or common 1-over-3 *S*traddle *C*arriers (SC) at the HHLA *C*ontainer *T*erminal *B*urchardkai (CTB) in Hamburg.

Overall, the automated stacking of containers is widely accepted as beneficial for terminals and a majority of automated stacking yards are realized with *R*ail-*M*ounted *G*antry (RMG) cranes in an end-to-end configuration (perpendicular to quay wall), safely separating waterside and landside operations by stacking modules perpendicular to the quay wall (see Rijsenbrij and Wieschemann 2006). Almost all of these automated operations have been installed at new, greenfield terminal areas, mostly comprising 60 hectares or more. Typical examples in this regard are CTA and the terminal DP World London Gateway at the mouth of the river Thames (UK), see Fig. 5.1.

In the Middle-East and Asia the configuration of automated stacking yards is often a parallel layout arrangement where manually driven vehicles realize the interchange of containers alongside the stacking modules, which are operated with cantilever RMG cranes, allowing a remote-controlled interchange (see Fig. 5.2 with terminals at the ports of Dubai (left), Pusan (middle), and Kaohsiung (right)).

More than a decade ago, one terminal operator in Australia (Patrick Container Terminals) installed an automated SC operation at the port of Brisbane which looked promising for the modification of existing SC terminals. So far, automation of SC terminals is limited, e.g. Patrick's Sydney terminal at Port Botany, DP World's West Swanson Terminal (Melbourne), and POAL's container terminal at Auckland (New Zealand). A different SC automation concept is shown at terminals in Los Angeles (TraPac) and Melbourne (VICT), where automated SCs (for transport only) are applied in combination with automated RMGs. An advantage of automated SCs could be the possibility to apply them rather easy in existing, mid-size SC terminals, although special measures will be required to safely separate manual and automated operations. However the infrastructural modifications to convert a manually operated SC terminal into an automated SC terminal will be much lower than a conversion from SC operations into an automated RMG operation. The CTB

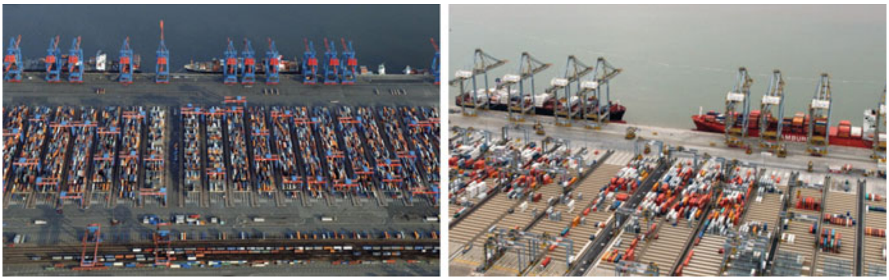

Fig. 5.1 Automated stacking in end-to-end arrangement – CTA (left) and London Gateway (right)

Fig. 5.2 Automated stacking in a parallel arrangement

at the port of Hamburg is a good example for the conversion from pure manual SC operations to automated RMG crane operations in the yard, still using manual SCs at the water- and landside for container transport between yard and STS cranes or railhead, respectively.

The issue of converting existing manual handling systems will get more attention in the future as an increasing number of terminal operators have recognized the advantages of automation and are considering installing an automated handling system in their existing facilities. Today terminal operators see the following drivers for automation:

- more logistic control, supporting priority-based scheduling, and last-minute changes;
- more predictable and reliable operations, less dependency of operator's skills;
- cost reductions, repetitive service quality, and less damages (accidents);
- less liability for injuries, reduced sickness percentage, and less vulnerability to labor shortages.

Some additional remarks on the above summary of advantages should be made:

1. Many ports face extremely high land costs (e.g. Shanghai or Singapore) and even when labor costs are low, this scarcity of land is a major reason for automation. Automated handling systems provide more storage capacity per hectare (certainly valid for end-loaded ASC concepts) and this characteristic of high area utilization is an increasing demand in concessions (lease contracts) from port authorities, looking for more throughput per hectare. As a result, such (automated) high-density stacking systems will enable Port Authorities to increase their income per hectare of port area.
2. Human beings and labor unions demand more flexible working schedules. This will complicate the design of shift systems covering the 24/7 demand in ports. The application of automation will give room for more flexible work rosters and will support an increased participation for lower management in the daily operational decision-making. Moreover, automation supports the avoidance of monotonous jobs and allows the upgrading of employee's satisfaction resulting in less sickness and more motivated employees.
3. In many areas of the world terminal operators cannot find enough qualified personnel to run manual equipment. Moreover the training of personnel is a major effort which must partly be realized during real time operations, impacting productivity and a higher chance on damages. The continuous turnover in personnel may result in a training effort of sometimes more than 100 training hours per operational job per year (includes operator to be skilled, instructor and equipment resulting in several hundreds of dollars per training hour).
4. Automated operations are less vulnerable for extreme climate conditions (both warm and cold/windy conditions) and save energy for comfort conditions in manned equipment. Requirements for lighting are much lower, again a cost saving.

5. In general, automation includes less downtimes and less maintenance, because automated equipment is uniform and orderly operated and independent from driver's behavior. Moreover in icy or snow conditions, automated equipment can be better controlled resulting in less accidents and continuing service.

The developments up till now have learned that especially for fully automated terminals the integration of automated equipment and all kinds of related subsystems into one efficient, terminal handling system is a real challenge. Various types of equipment must be efficiently controlled by means of equipment control systems integrated in the terminal's operations control system. On top of that large amounts of data from RFID systems, container weighing, gate control systems, equipment status and condition monitoring, remote operations (such as STS crane operations, landside ASC operations, X-ray activities) must be processed. Process information must be made available for operator's decisions (and manually controlled equipment) through standardized human interfaces and menu-driven graphical user interfaces.

At the start of terminal automation, operators themselves arranged the integration of all these various subsystems. Recent terminal automation projects have emphasized the need for a well-structured, timely integration of all components and subsystems. Extensive testing and training with emulation tools showed their benefit for a successful go-live of automated terminals.

This integration process of a growing number of features requires well-defined interfaces and protocols; more and more an expert activity. Therefore terminal operators are increasingly interested to acquire complete systems with guaranteed performances. For that reason, system suppliers may offer a total automated terminal handling system, including the installation and commissioning of all components necessary for the entire functionality.

5.4 Approach for Successful Implementation of Terminal Automation Projects

In the design of an automated terminal a large variety of equipment, control systems, data communication, priority rules, etc., has to be combined into one reliable handling system, capable of performing all handling functionalities, even under peak conditions. A variety of equipment, control systems, IT software and hardware, labor organization, etc., has to be selected and combined into one efficient system, often resulting in a number of feasible solutions for a terminal system.

5.4.1 Concept Assessment

Alternative concept solutions should be analyzed and assessed on a multitude of topics, such as the potential to grow stepwise with the projected terminal throughput development and the requirements for sufficient service, provided by stacking capacity and ample handling productivity at waterside and landside. The assessment should not be limited to the initial investment (i.e. the capital expenditures) but should include the mid- and long-term operational expenditures (someday inflation will rise again) and more qualitative criteria such as the complexity of applied technology (proven or new), required maintenance skills, and earlier experiences with computer-controlled operations.

5.4.2 Concept Selection and Integration

The selection process should not be a “battle between concepts”; to the contrary, right from the start of the conceptual design a systems approach should be taken. In other words, terminal operators should try to minimize their “nice-to-have’s” and should try to recognize critical interfaces in an early stage of the terminal design process. That will help to determine which type(s) of tests and commissioning efforts will be required to get a controlled integration. Moreover this will support a proper specification of the required functionalities, necessary when purchasing large subsystems from key system suppliers (which avoid the often occurring extra costs due to underestimated interface definitions). Lessons learned from terminal automation projects during the last decade have emphasized the need for a well-structured, timely integration of all components and subsystems. Extensive testing and training with emulation tools are necessary to meet start-up dates successfully.

5.5 Developments in Electric Drive Technologies

During the last decade many port authorities and governmental bodies have put increasing demands on terminals to install more sustainable and environmentally friendly technologies, such as the Long Beach and Hamburg Port Authorities to name a few (see Meier and Wegner 2015). Parallel to this general trend, terminals face growing uncertainties about energy sources and their cost. This has caused a search for alternative drives, not only for cranes but also for mobile equipment used for stacking and container transportation at terminals.

5.5.1 Technology Use of Terminals from Adjacent Industries

Especially for (automated) stacking operations there is a clear tendency to shift towards electrically supplied RMG cranes and also *R*ubber-*T*yred *G*antry (RTG) cranes (so far with diesel-electric drives) are increasingly connected to the public grid through bus bar systems or cable reels with flexible cables, see Naicker and

Allopi (2015) for a rough technology overview. For RTGs with their relatively high idle (but stand-by) time, the primary advantage is an emission free drive system with reduced energy cost and less maintenance.

Nowadays manually operated and automated RMGs, as well as some RTGs are electrically supplied using medium voltage supply cables at the same time benefitting from the possibility of high-speed data transmission (see Naicker and Allopi 2015). Supply cables with fiber optics allow for high-density data communication up to 10 Gbit/s; via the conductors of the bus bar system transmission rates of about 100 Mbit/s are feasible. This is especially an advantage when applying remotely controlled operations which require a fast data transfer to remote visual displays, e.g., for RTGs serving in a (partly) automated stacking system. The application of sensors, cameras, and laser systems for automated motions, remote (video-controlled) handling and safety systems (to avoid collisions and trigger emergency stops when people or equipment enter the operational area around the RTG) need reliable, undisturbed, data transmission. Often, the available Wi-Fi systems cannot fulfill these demands.

However, it is not that easy for rubber-tired equipment, running over the terminal without predetermined tracks (e.g. *T*erminal *T*ractors (TT), AGVs, SCs, reach stackers, and empty handlers). For many years that mobile equipment was powered by a diesel engine connected to an automatic gear reducer as the standard drivetrain with a power take-off to a hydraulic system, powering lifting, and steering. However for SCs (in the late 1970s) and AGVs (in the new millennium), diesel-electric drivetrains proved to be an improvement with regard to energy consumption, speed control, reliability, and maintenance cost. Also RTGs were in general designed with diesel-electric drives for all functions (see Fig. 5.3).

During the last decade energy efficiency, emission control, and a concern about fuel cost resulted in the application of new technologies from adjacent industries, such as:

- Energy recuperation during vehicle braking or load lowering through the use of energy storage systems. For instance, batteries and super-caps in RTGs and TTs (very few) and hydraulic pressure vessels (in some mobile cranes).
- Electric drivetrains supplied from on-board batteries to be charged when remaining in the vehicle or through battery exchange. A proven technology for electric

Fig. 5.3 Rubber-tired terminal equipment: RTG (left), SC (middle), AGV (right)

forklift trucks and vehicles at airports and warehouses and recently AGVs and a few TTs;

- Combustion engines fueled with less costly and/or less polluting fuels. CNG (*C*ompressed *N*atural *G*as) and LNG (*L*iquefied *N*atural *G*as) engines have been developed for public transport (busses, road trucks) and these engines have some advantages. This concerns their lower CO_2 production per mega Joule of fuel (compared to regular diesel engines). However, recent (legal) requirements for diesel engines have resulted in matching characteristics from state-of-the-art diesel engines. The better efficiency of diesel engines partly compensates their higher CO_2 emission, inherent for diesel fuel. Overall the CO_2 emission of CNG/LNG engines is around 15% lower than for diesel engines, a moderate advantage.
- Hybrid drives, compiled of a combustion engine, a generator, a transmission, a smaller energy storage device, and an electric motor. The energy storage (battery, super-caps, etc.) can be charged by the on-board generator and/or by recuperated (braking/lowering) energy or even by an external energy source. There is a large variety of hybrid concepts with either parallel or serial arrangements of combustion engine, energy storage device, and electric motor. However, the enlarged number of components and the more complex control units influence reliability and still the remaining emissions cannot match the more favorable figures of full-electric drivetrains. So far hybrid drives are not very attractive for mobile terminal equipment.

5.5.2 Evaluation and Selection of Drivetrains

The selection of an appropriate drivetrain for terminal equipment is a complex process for terminal management. Obviously they want to support societal demands to be assessed from pollution figures measurable from the WTW (*W*ell-*T*o-*W*heel) or less correct the TTW (*T*ank-*T*o-*W*heel) pollution figures. On top of the well-known exhaust gases (like NO_x), the CO_2 emission from energy sources, applicable for mobile equipment, is becoming more important.

Terminal economics are equally (or even more) important and that is determined by fuel consumption per operating hour, fuel cost, maintenance cost, availability and cost of provisions for fuel storage, fuel supply, and safety measures. In general, a full-electric drivetrain offers by far the best energy efficiency and lowest maintenance cost; however, when the selection is, nevertheless, made for a combustion engine, the modern diesel engine is still attractive due to its rather high efficiency and the high energy content of diesel fuel. Nowadays equipment designs should be eco-efficient: This also includes the reduction or avoidance of the use of fossil energy (see Rijsenbrij and Wieschemann 2011). Considering terminal system suppliers, such as Konecranes, the experience with diesel-electric drivetrains, applied in AGV transportation systems, triggered research aimed at even more environmentally friendly AGVs. Many alternatives were analyzed, including some hybrid drivetrain concepts and full-electric drivetrains, supplied with either Lead-Acid or Li-Ion batteries. The advantages of full-electric drivetrains are illustrated in Fig. 5.4, which clearly shows their simplicity when removing the diesel-generator and connected AC/DC converter.

Another major improvement is the much better energy efficiency of full-electric drivetrains, obtained by avoidance of the unfavorable energy conversion in a combustion engine. Figure 5.5 shows the energy efficiency for a Lead-Acid battery energy supply.

Compared with a diesel-electric drivetrain, the overall efficiency is more than two times better, a real contribution to better eco-efficiency (see Fig. 5.6). On top of that, a battery-supplied AGV shows zero energy consumption during operational stand-still periods (e.g. waiting for jobs in a buffer or when receiving a load under a crane).

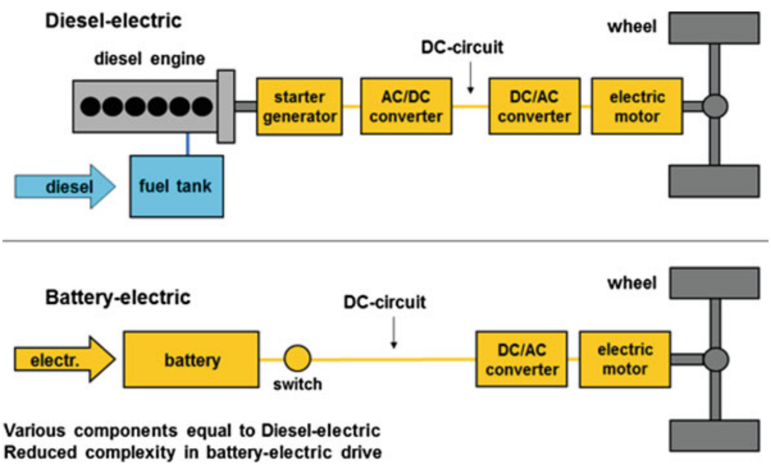

Fig. 5.4 Diesel-electric and battery drivetrain schematic

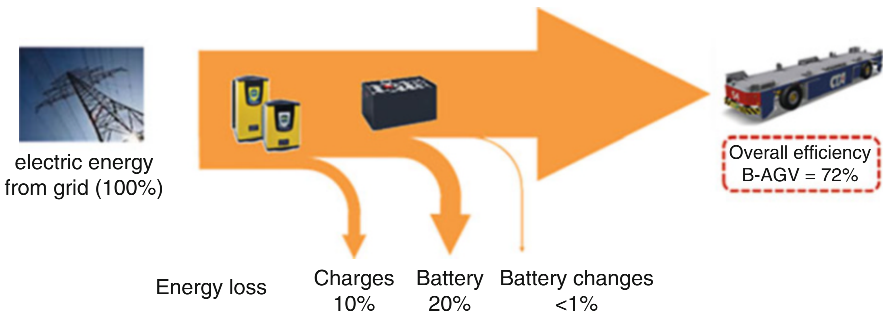

Fig. 5.5 Energy transfer efficiency for battery drivetrain

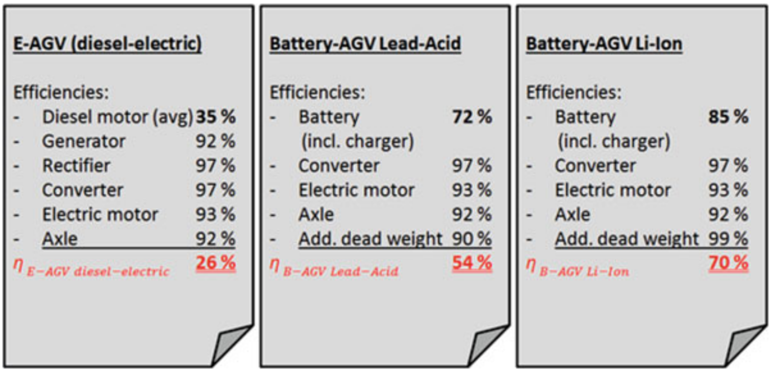

Fig. 5.6 Overall drivetrain efficiency

The availability of (large) Li-Ion batteries for industrial mobile equipment will further increase the eco-efficiency. The present Lead-Acid battery drivetrains realize a 72% efficiency which will further increase to over 85% when applying Li-Ion batteries.

The intensive utilization of AGVs with a maximum gross vehicle weight of 100 tons (compared to 1.8 tons for a luxury road car) necessitates a Lead-Acid battery capacity of gross 360 kWh, allowing 18–20 operating hours (280 kWh net) and after that period, the battery has to be charged or exchanged with a fully charged one. For reasons of economics and proven design, today the Lead-Acid battery offers a good feasible concept and at present there are more than 200 Battery-AGVs operational worldwide, all of them with recyclable Lead-Acid batteries. The required large battery capacity for AGVs, applied in container terminals, could not be met economically with Li-Ion batteries so far. Nevertheless, the technology and economics of Li-Ion batteries have considerably advanced over the last years and therefore this battery type can become a good alternative for day-to-day operations in the near future (as of mid-2017) although the possibilities for recycling are still of some concern.

During the last decade various types of Li-Ion batteries have been developed for the automotive industry (cars and city buses), both for hybrid and full-electric drivetrains. Advantages such as a high energy density, low weight, better energy transfer efficiency, lower maintenance, increased lifetime, and the ability for fast charging are attractive for automotive applications. However, this type of batteries is much more complex and requires higher investment than the proven Lead-Acid batteries. For safe operation, Li-Ion batteries need a sophisticated battery management system and may need an additional cooling/heating system (climatic conditions). Today there is only little long-term experience, especially in the rough port environments. A proper charging of Li-Ion batteries still requires 1–2 h. This outage for charging might be acceptable for private cars and city buses, but for the 24/7 continuous terminal operations outages on this level are problematic and require either a surplus of equipment or a battery exchange facility (see Sect. 5.5.3).

Figure 5.7 shows the AGV demand of Lead-Acid battery capacity, compared to the Li-Ion batteries applied in automotive electric vehicles for the year 2015.

The high eco-efficiency of battery-supplied drives also results in a considerable decrease in *G*reen*H*ouse *G*ases (GHG). Compared with a diesel-electric drive, the full-electric drive reduces the CO_2 emission by 50% (see Wieschemann 2014). The WTW results are shown in Fig. 5.8 and this figure is based on the actual energy sources used in German power plants. Obviously a full-electric drivetrain will be zero-emission in case of solar, hydro, or wind turbine power generation.

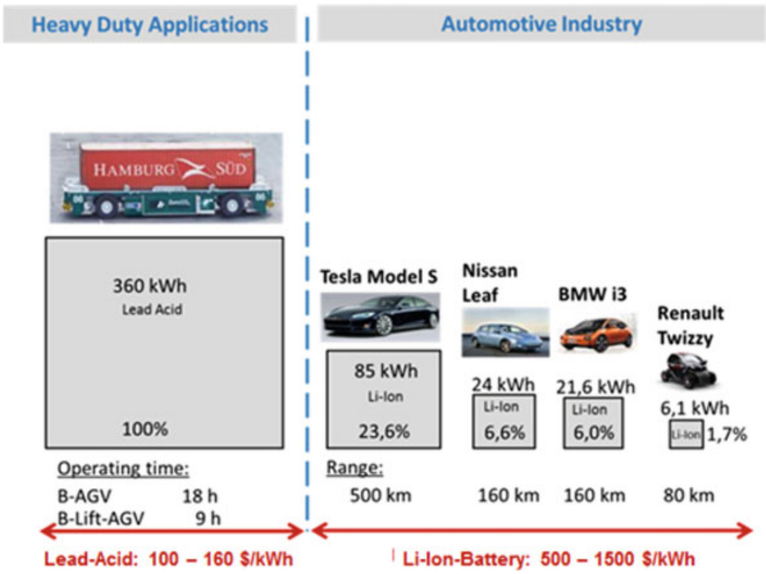

Fig. 5.7 Comparison of battery capacity demand (2015)

Fig. 5.8 AGV well-to-wheel GHG production for *D*iesel-*E*lectric (DE) and battery drivetrain

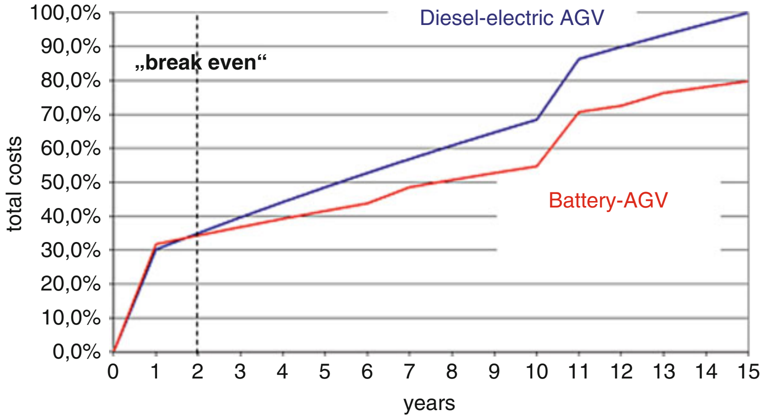

Fig. 5.9 TCO results for diesel-electric and battery-AGV (for the years 2010 to 2025)

When selecting battery type and charging method, it is recommended to analyze the *T*otal *C*ost of *O*wnership (TCO) with an NPV (*N*et *P*resent *V*alue) approach for the various alternatives. The TCO approach is increasingly used for purchasing, covering all costs during the lifetime of an investment (see also Ellram and Siferd 1993). The analysis should cover AGV and battery(ies), the charging method and charging provisions, the planned outage algorithms, the installed transformer capacities, and resulting peak loads at the grid.

During the last 5 years the TCO analysis for the comparison of diesel-electric and fully battery-supplied AGVs clearly showed a much better TCO result for the battery types. Reduced energy cost and much lower maintenance cost highly compensate the slightly larger initial investment (see Fig. 5.9).

The future will enlarge the favorable TCO results for battery-supplied vehicles; these will be forthcoming from the reduced battery cost and performance improvements driven by the automotive industry and the forecast that the gap between electric energy cost and diesel fuel cost will further enlarge as a result of the world's massive energy transfer from fossil fuels towards renewable energy sources. Nowadays energy from wind turbines is already competitive with coal or gas-fired power stations.

5.5.3 Alternatives for AGV Battery Charging During Terminal Operations

To support a continuous terminal operation, it is necessary to timely realize a battery recharge which should be cost-attractive and ideally should have no impact on the terminal's logistic performance. The charging time for batteries does require an outage of the battery for hours, e.g. 6–8 h for Lead-Acid batteries and

1–2 h for Li-Ion batteries, applied in heavy-duty transport vehicles. For Li-Ion batteries a too short recharging time with high power will decrease the lifetime (measured in load cycles). Daytime operations like warehousing do not suffer from such recharging times, as they are executed during evening/night. However, the continuous operations in container terminals require a 24 h uptime of equipment and then there are three possibilities (see Fig. 5.10):

1. Battery exchange
   In this option, the terminal has to realize a central BES (*B*attery *E*xchange and charging *S*tation incl. storage function for batteries), preferably with automated processes for battery exchange into and out of the equipment as well as for battery storing and retrieving from the storage area. Due to the ratio equipment investment/battery investment in case of Lead-Acid batteries, until 2017, this solution proved to be the more economic one for container terminals as can be seen in four terminals, recently installed with battery-supplied AGVs (see also Fig. 5.11).
2. Opportunity charging
   In this case the battery (staying in the equipment) has to be charged during normal operation processes. As waiting times during operations will be short, the amounts of energy that can be charged will be small and for that reason many chargers have to be installed at terminal positions where AGVs stop during

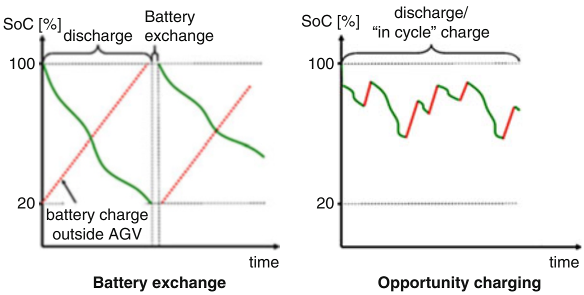

Fig. 5.10 Schematic of alternative battery charging methods

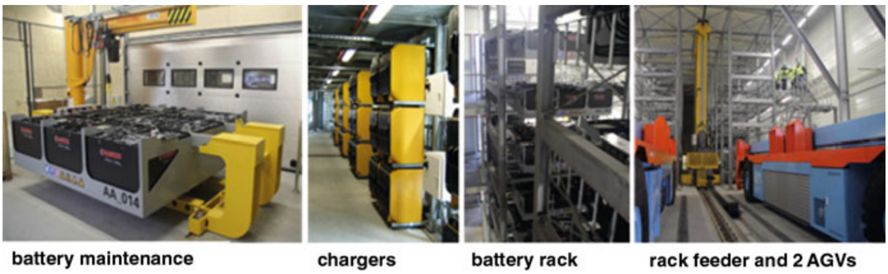

Fig. 5.11 Details of automated BES at Rotterdam Maasvlakte container terminals

their transportation cycles. Obviously, vehicle operations and battery charging processes have to be aligned and thus a high number of battery chargers is required, resulting in a low utilization of chargers and a relatively high investment in charging equipment and power supply distribution to these chargers.

3. Dedicated quick-charging
   At a limited number of locations, the terminal will install quick-charge provisions and purchase more equipment, to exchange equipment in case of a discharged battery. This will definitely result in more investments (5–10%, depending on battery type and size) and some additional area for equipment parking and connections to the electric charging provisions. Obviously, the major part of the additional investment (in extra equipment) is balanced through delayed replacement investments resulting from an elongated equipment lifetime (hence the same workload is distributed over more equipment).

For an effective *BES implementation*, the logistical characteristics of automated container terminals must allow the integration between logistic control and battery recharge/exchange management systems. Practical experiences at the abovementioned terminals show that the actual vehicle outage of 5 min for battery exchange has no influence on the transportation performance of an AGV fleet. Using BES, the fluctuating utilization of the AGV fleet and the installed battery capacity even allows the (future) application of smart grid technology. This enables to benefit from low electrical energy cost during low periods (e.g. night time) or during wind turbine or solar surplus periods when the energy cannot be distributed to the end users. Spot prices for energy often decrease to 50% or less than the normal prices; however, in order to benefit from such situations it is necessary to be connected and known as a potential user. That means that benefits from smart grid technology can only be used when batteries are stored in a BES with some flexibility in charging demands. The design of an automated BES requires a systems approach between logistics, infrastructure, and economics, covering battery storage capacity, electrical supply (transformer) power, maintenance facility, ventilation, and fire-detection provisions (see Fig. 5.11). The design should have some flexibility to adapt to new battery technologies that will come in the next decades. Nowadays Lead-Acid technology is proven in some major terminals and the electric supply from the grid allows a long-term cost control and the potential of applying green energy when the power utility purchases solar, hydro, or wind energy. In that case terminal transport will be a real zero-emission system.

Opportunity charging for waterside transportation with AGVs so far is not recommended. The short waiting times during the AGV transport cycles and the large variety of locations to be connected by the AGVs would require many charging points, spread over the entire apron area; very difficult in that dense traffic area. This will result in an extensive electric supply network with related (safety) switchgear, all to be designed for the large power demand when an AGV has to be supplied with as much as possible energy in the short parking periods. Beside of the large investment for these connection points also the maintenance of the outdoor connections (direct contact or inductive) in an automated operational area will need a (costly) attention. Possibly in the coming decades, the automotive industry may trigger cost-attractive developments for opportunity charging with induction; up till now this method is not feasible for waterside AGV operations.

Quick-charge provisions for container terminals are under development and are promising. Nevertheless, it should be considered that AGVs require battery sizes up to 5 times larger than the currently largest car battery (see Fig. 5.7). This size influences battery design (hot spots) and charging control equipment, which also requires five times more power (impacting infrastructure and high peaks in electric supply, causing extra charges from the energy supplier).

Today, the technology developed by the automotive industry for the quick-charging of public transport vehicles can be applied to terminal equipment. Such quick-charge provisions can be realized either through a direct connection with receptacle or pantograph or in the future with inductive power, although the latter method is neither feasible nor cost-attractive for port operations. When required operationally, quick-charging will allow a fast (short) energy supply; not necessarily until the fully charged battery status.

Recently, such a quick-charging technology has been applied e.g. by Konecranes for AGVs in an automated terminal. In the near future, 25 Li-Ion battery-powered AGVs and six *A*utomated *Q*uick-*C*hargers (AQC, see Fig. 5.12) will come into operation at the automated CTA in Hamburg entailing a new concept for battery-powered mobile equipment in day-to-day operations of related facilities. A TCO analysis for this case was carried out and it was learned that the reduced battery cost of the next-generation Li-Ion batteries and the improved AQC design outperformed the current concept of Lead-Acid batteries and BESs.

In the future, it can be expected that the TCO results for battery-powered vehicles will become even more favorable. The choice between Lead-Acid batteries and BESs or Li-Ion batteries and AQCs depends upon many variables. Case-by-case,

Fig. 5.12 Li-Ion battery-AGV at an AQC at CTA, Hamburg

TCO analyses will need to be carried out. Both concepts are viable and valuable in transferring operations away from fossil fuels towards renewable energy sources.

5.6 Short-term Developments in Terminal Automation

In the coming 3–5 years the efforts to install new automated terminals or to modify existing (manual) terminals will increase, especially because of the growing pressure in terms of cost and performance being transferred from container liner shipping to the terminal business. Many operators will select available proven concepts, but of course with improvements on earlier detected shortcomings in system components. Parallel to this evolution in existing concepts new developments can be expected, partly driven by new demands from operators, interested to automate manually controlled operations and improve service and utilization of their present-day handling concepts. The introduction of new technologies from adjacent industries will also trigger a further development of automated handling systems. Some indications of such developments are already recognizable, for example the "Internet of Things," sensors and software for autonomous driving, obstacle recognition systems, etc.

The majority of worldwide installed stacking systems operate with RTGs, stacking concepts that require TTs/trailers and road haulers to pick up or deliver a container in the stacking area. The interchange of containers between trailer (internal or external) needs a lot of (human) attention to guarantee a safe operation. The simplicity and flexibility of the RTGs is very attractive; however, when it comes to operating costs, labor cost represents a growing part especially for container delivery operations where the idle time share can exceed 50%. For that reason terminals tend to apply remote control for the handshake which requires a lot of sensors, cameras, and safety provisions both at the RTGs and the order control systems. So far data transfer with radio data communication systems could not fulfill all demands for a fail-safe (semi-)automation of RTG operations. However, the developments in electric supplied RTGs will enable a further automation of the RTG stacking yards; safety and productivity will be key topics.

During the last decade the exchange of data between equipment and control centers has increased tremendously (FMDA, Remote Control, Order Control, safety, security, etc.). Moreover there are all kinds of organizations active in or around terminals, also using wireless data transfer in the public domain (WLAN, Internet). This is a concern, not only the available capacity but also the risk of cyber-crime and this issue should get much more attention, especially when terminals plan remote-controlled and/or automated operations. When terminals require safe, reliable, and high-speed data communication then a private band might be a good investment.

The "Internet of Things" is a technology that will bring new applications to the terminals. Addressable, network capable, components will allow online condition monitoring, fault management, and self-acting service planning. The industry in particular is developing all kinds of new applications that might become of interest to terminals as well. Terminal stakeholders (e.g. shipping lines, customs, tax departments, inland transportation companies, security authorities) may also ask for new functionalities to be installed in steadily growing interconnected networks with all the risks of reliability, data integrity, and management of such large scale IT systems. Terminals will increasingly be confronted with the question: is there a positive trade-off between the benefits of new “Internet of Things-gadgets” and the growing complexity, maintenance cost, and cyber risks of these systems and applications.

In a number of ports the authorities are encouraging container terminals and shippers/consignees to reduce road transportation, as trucking still has an environmental impact. Moreover truckers complain about waiting times and traffic jams in port areas and that has resulted in satellite terminals at distances of tens or even hundreds of kilometers from major ports. Daily shuttle services by trains or barges connect these satellite terminals (often managed by deep-sea terminal operators or shipping line), avoid empty trips for truckers, and can reduce the dwell time of containers at the deep-sea ports, supporting these terminals to realize more throughput per hectare. Examples are the *Alameda Corridor*, connecting Los Angeles/Long Beach with a few large *Inland Container Transfer Facilities* managed by the large railroad companies; other examples are some satellite terminals in Belgium, The Netherlands, and Germany (see e.g. Port of Rotterdam Authority 2017). This type of satellite terminals and connecting shuttle services is likely to expand in the future. The high-density, terminal controlled transportation is very attractive for automation and the application of electric drives. Trains are easy to supply with electric power and also barges are changing over from direct diesel drives towards electric drivelines with generator sets powered by environmentally friendly energy sources. LNG is attractive for shuttle barges (fixed supply stations can be realized) and when distances are limited to some tens of kilometers even battery supply is feasible.

Such shuttles can be supported with automated transport to railheads and barge loading/discharging sites and even automated inter-terminal transport in large port areas will be feasible in the future. When doing so, a really low emission transport can be made available to the society.

5.7 Conclusions

Automation in container terminals has been established over the last 25 years. Port Authorities and container terminal operators, driven by the need to reduce costs and reduce their carbon footprint, are increasingly turning to automated container handling systems and electric drive technology.

The container handling industry is increasingly focusing on electric drive technology in order to reduce costs, reduce carbon footprint and emissions, and improve sustainability. The trend is definitely towards the installation of automated handling systems and the application of electric drives; this will be enabled by the following topics:

- Li-Ion or other composite batteries will be further developed and will become attractive for large industrial vehicles as well. The developments of Li-Ion batteries are promising (with their potential of short recharging times and enlarged capacity) but still, the selection of type and size should be based on a proper TCO analysis.
- Increasing fossil fuel prices (from scarcity and tax measures) and directives for reductions in greenhouse gases and emissions (exhaust, sound) will further encourage the application of full-electric, battery-supplied drives. Today's technology allows a truly zero-emission operation when the energy provider supplies green energy (hydro, solar, and wind power).
- Electric supply enables a safe and reliable, high-density data transfer to equipment, a requirement for complex logistic control systems, remotely controlled operations and equipment monitoring associated with FMDA.
- The attainable cost savings, the potential performance, the better area utilization, and the availability of proven technology will encourage terminal operators to apply automation. Electric drives are a must for such automated systems and on top of that will result in decreased operating cost and do support the demands from society for sustainability and environmental control.
- Terminal operators are increasingly interested to acquire complete systems with guaranteed performances. That will encourage system suppliers for terminal equipment to offer a total transportation/handling system, including installation and commissioning of all components necessary for the entire terminal functionality.

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Chapter 6
From Digitalization to Data-Driven Decision Making in Container Terminals

Leonard Heilig, Robert Stahlbock, and Stefan Voß

Abstract With the new opportunities emerging from the current wave of digitalization, terminal planning and management need to be revisited by taking a data-driven perspective. Business analytics, as a practice of extracting insights from operational data, assists in reducing uncertainties using predictions and helps to identify and understand causes of inefficiencies, disruptions, and anomalies in intra- and inter-organizational terminal operations. Despite the growing complexity of data within and around container terminals, a lack of data-driven approaches in the context of container terminals can be identified. In this chapter, the concept of business analytics for supporting terminal planning and management is introduced. The chapter specifically focuses on data mining approaches and provides a comprehensive overview on applications in container terminals and related research. As such, we aim to establish a data-driven perspective on terminal planning and management, complementing the traditional optimization perspective.

6.1 Introduction

In recent decades, terminal operators have strongly invested in automation and digitalization to improve the operational efficiency of their container terminals. While information systems have already become indispensable for terminal planning and management, the current wave of digitalization strives for a better integration and transparency among all parts of the supply chain. Extending terminal infrastructure and equipment with sensors, actuators, and mobile technologies, e.g., lead to new

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levels of transparency allowing to constantly monitor and control resources, cargo flows, and the environment. Existing data, such as from terminal operating systems, together with data from a variety of new data sources, including those available from external systems, however, mostly remain under-processed or under-analyzed to be of real value.

One central aspect of human intelligence is the ability of learning, i.e., of inferring repeating patterns and relationships from observations that are often reflected in data. Especially in the highly competitive environment of maritime ports and container terminals, it seems that discovering *patterns*, *regularities*, or even *irregularities* in operational data has become even more important. Many data-analytic methodologies, approaches, and algorithms have been developed with different terminology and objectives. The main common topic among all – whether an approach is called *data mining* or *machine learning*, etc. – is to estimate or learn good data-analytic models of real business phenomena in order to provide description, analysis, understanding, prediction, and prescription. This can be useful for decision making in organizations. Traditionally, quantitative research has been focused on the optimization of logistics processes and operations in container terminals using operations research methods (see, e.g., Stahlbock and Voß 2008; Steenken et al. 2004). Given that the amount of complex data is growing, data-analytic models for extracting information and knowledge from data before it is used in optimization routines are set to become a vital factor in improving port operations. At present, however, we only find a few studies presenting data-driven approaches for understanding and addressing problems in container terminals or other port-related operations. Besides mathematical models and optimization methods, business analytics considers the use of data, information technology, statistical analysis, and computer-based data-analytic models to gain improved insights about business operations and to make better decisions.

Note that business analytics is only one part of the even more general digitalization in the maritime industry. Since the beginnings of the containerization in the 1960s, efficient cargo flows rely on efficient information flows. Many port-related information systems have been established to facilitate intra- and inter-organizational information flows in different phases of the container transport. Nowadays, collecting and storing transactional data is not a main challenge, neither from a technical point of view nor as a financial one. However, the challenge is to collect and organize only the relevant data with respect to specific business problems and to derive new knowledge out of it, thus creating value (in combination with required domain knowledge of managers and decision makers). To address current problems in seaports, the maritime industry increasingly recognizes the value of information and respective decision support tools. Thus, digital transformation in ports is nowadays not only focused on collecting more data generated along the logistics chains, but especially on facilitating a clever usage of data in order to gain competitive advantages, such as by adapting business models and improving customer experience, processes, and costs.

Novel concepts and technology drivers of the current phase of digitalization, such as related to the *I*nternet *o*f *T*hings (IoT), cloud computing, mobile technologies, and big data, imply huge potentials and challenges in transforming port operations. Those concepts and technologies have not only increased the number of potential data sources and the amount of captured structured and unstructured data (e.g., by using mobile devices and integrating sensors and actuators in port operations), but also provide affordable and highly scalable data storage and processing services (e.g., offered by public cloud providers). It can be observed that costs of storing data are below the costs of deciding which data should be kept and which should be deleted, resulting in a massive flood of data. Some parts are important and valuable, some are not, and some not today but maybe in the future. Furthermore, highly scalable computational processing power allows for performing (nearly) real-time analytics at appropriate costs. In this context, the current phase of digital transformation in maritime ports, referred to as the generation of smart procedures (Heilig et al. 2017b), aims to adapt novel concepts, information technologies, tools, and methods providing means of advanced gathering, processing, and analysis of (real-time) data in order to better understand, plan, control, and coordinate port operations. This transformation shall allow to better utilize port-related resources, equipment, and space, on the one hand, but also an improved information exchange and collaboration within and between maritime ports.

After giving a brief overview on developments and trends of the digital transformation in ports, this chapter provides an introduction to business analytics and its application in container terminals. With respect to different operations areas of the container terminal, divided into quayside, yard, and landside, we discuss potential data sources and provide an overview of data mining applications that are currently discussed in academia and practice. Thus, the chapter is primarily focused on data mining approaches for descriptive, predictive, and prescriptive analytics in container terminals. Although a lack of studies can be identified, the chapter reviews all relevant works from academic literature addressing terminal-related problems with data mining methods. As such, the chapter represents, to the best of our knowledge, the first state-of-the-art review of data mining applications in container terminals. The remainder of this chapter is structured as follows. Section 6.2 outlines the main developments of three generations of digital transformation in maritime ports and discusses current trends of the digitalization. The concept and methodology of business analytics is introduced in Sect. 6.3. Section 6.4 outlines various data mining approaches with respect to the different terminal operations areas and discusses related literature. Finally, a conclusion and outlook are provided in Sect. 6.5.

6.2 Digitalization in Maritime Ports

Since the beginning of containerization, the digital transformation of port operations has become indispensable for driving innovation and modernization in maritime ports. The ability to share information between involved actors and to track cargo is critical for reducing uncertainties (Zhou and Benton 2007), increasing reliability (Panayides and Song 2009), and improving the coordination in integrated transport processes (Crainic et al. 2009; Lai et al. 2008; Wiegmans et al. 2017). Moreover, advanced information systems can provide a basis for addressing environmental sustainability in maritime ports (Heilig et al. 2017a; Mansouri et al. 2015). Due to their important role in achieving a competitive edge, a plethora of information systems and technologies have been adopted in port operations in recent decades. Heilig and Voß (2017a) provide a comprehensive overview of those port-related solutions. Although past developments have led to a high degree of automation and digitalization, especially in container terminals, there is still considerable potential for improvement. In particular, a better integration of existing information systems and data sources as well as a more intelligent use of data may help to improve planning, controlling, and management of intra- and inter-organizational operations and thus may have a considerable impact on supply chains (for further information and examples, the interested reader is referred to Heilig and Voß 2018).

The current impact of digitalization can be observed in many contemporary ports. We define the current phase of digital transformation in ports as the generation of *smart procedures* (see Sect. 6.2.3). One current trend is related to the concepts of *Industry 4.0* and *Logistics 4.0*, which are strongly related to the development of cyber-physical systems and IoT infrastructures. Here, the focus is to measure, monitor, and control physical processes and objects including their environment by means of automation and connectivity. An example is the *smartPORT logistics* project in the Port of Hamburg (Germany). By collaborating with SAP and T-Systems, the *H*amburg *P*ort *A*uthority (HPA) has developed a cloud-based platform to improve traffic flows in the port area. This is supposed to be achieved by enhancing the control of port infrastructure (e.g., movable bridges, traffic lights, and parking space) through smart devices and IoT technologies (e.g., sensors and actuators) as well as by managing collected traffic data and real-time communication with port community actors via mobile applications (HPA 2017). Due to a lack of a critical mass of users within the port community, however, the introduction of the mobile application failed (NDR 2017).

Moreover, an emerging impact of *big data* can be identified in the maritime industry, which mainly refers to different technologies and techniques to process and analyze large and complex sets of data that exceed the capacity or capability of conventional methods and systems. The *M*aritime *P*ort *A*uthority of Singapore (MPA), for instance, is collaborating with IBM to tap big data solutions for improving maritime and port operations, e.g., through a prediction of vessel arrival times and a better detection of movements, authorized activities (e.g., pilotage), and unauthorized activities (e.g., illegal bunkering). Although the term is often misinterpreted or used as buzzword in the industry (e.g., as a substitute for data mining or *B*usiness *I*ntelligence (BI)), the growing interest in big data is also reflected in products and services of cargo-handling equipment providers and software vendors. Kalmar, a leading provider of cargo-handling equipment and services, has developed a cloud-based platform to display real-time productivity and operational data as well as maintenance information. Navis, a leading vendor of *T*erminal *O*perating *S*ystems (TOS), has launched a Terminal BI Portal to better understand the historical and real-time performance of terminal operations and further aims to use machine learning to gain additional insights from the TOS data. Besides, the increasing interest regarding the general topic of digitalization is reflected by diverse hackathons (e.g., World Port Hackathon) and competitions (see, e.g., PEMA Student Challenge) encouraging students and scholars to develop new and innovative digital solutions for maritime ports. To better understand the development – from *paperless procedures* to *smart procedures* – a brief overview about the main phases of the digital transformation is given in the following (Heilig et al. 2017b).

6.2.1 First Generation (1980s): Paperless Procedures

Traditionally, paper-based procedures were established for organizing the information flow, which has been labor intensive, time-consuming, error-prone, and costly. To further handle the enormous volumes of containerized cargo, the development of *E*lectronic *D*ata *I*nterchange (EDI) in the 1960s and 1970s built the basis for the first generation of digital transformation in the maritime industry. Knowing that efficient container transportation and handling is highly dependent on the efficiency of all involved organizations and the handover of containers in between, the need for inter-organizational systems supporting a paperless communication became increasingly apparent.

One of the first EDI-based *P*ort *C*ommunity *S*ystems (PCS), enabling an electronic document exchange between actors involved in port operations, started in 1983 with DAKOSY[1] in the Port of Hamburg (Germany). A PCS can be defined as an inter-organizational system that electronically integrates heterogeneous compositions of public and private actors, technologies, systems, processes, and standards within a port community (Heilig and Voß 2017a; Van Baalen et al. 2009). This development of a PCS was supported by the development of the UN/EDIFACT message standards, and specific message standards for the maritime industry in the late 1980s. Important paper documents, such as the *B*ill *o*f *L*ading (BoL), were transformed in the late 1980s into electronic documents. Still, the availability and quality of a PCS is seen as an essential determinant for a sustainable growth and competitiveness (Wiegmans et al. 2008). Moreover, a PCS can build the basis for establishing a *single window*: "as a facility that allows parties involved in trade and transport to lodge standardized information and documents with a single entry point to fulfill all import, export, and transit-related regulatory requirements" (UNECE 2005).

In the late 1980s, first commercial TOS, such as CITOS[2] in 1988 and Navis[3] in 1989, was developed and henceforth built the foundation for planning and

[1] https://www.dakosy.de/en/solutions/.

[2] https://www.singaporepsa.com/our-commitment/innovation.

[3] http://www.navis.com/timeline.

automation in container terminals. Generally, a TOS can be defined as an information system aiding an integrated management of core terminal processes (Heilig and Voß 2017a). Major advances in *E*nterprise *R*esource *P*lanning (ERP) systems during the 1980s, driven by companies like SAP, fertilized the idea to develop TOS for improving the integration of different terminal activities. A TOS commonly integrates different sub-systems and technologies to manage and monitor the flow of cargo and handling resources, e.g., based on an integration with equipment control systems. Common TOS supports EDI standards, such as UN/EDIFACT. If available, a link to the PCS is established to enable the exchange of certain information with other port-related actors over a shared platform. The integration of different internal systems and applications was essential to support individual terminal operations like berth and yard activities.

6.2.2 Second Generation (1990s–2000s): Automated Procedures

The adopted information technologies and systems, such as TOS, provided an essential foundation to drastically increase the automation in container handling procedures during the 1990s and 2000s. The first automated container terminal was the ECT Delta Terminal in Maasvlakte Rotterdam (Netherlands) opened in 1993. It introduced *A*utomated *G*uided *V*ehicles (AGV) and *A*utomated *S*tacking *C*ranes (ASC) to handle transports between the quay and container stacks, and within the container stacks, respectively. This major step towards automated container terminals required a seamless integration between the automated handling equipment and the TOS containing all work orders. The trend of using information systems as a backbone to further automate and to further increase the visibility in port operations continued during the mid and late 1990s. In particular, automatic identification systems (e.g., *R*eal-*T*ime *L*ocating *S*ystems (RTLS)) and positioning systems (e.g., *G*lobal *P*ositioning *S*ystems (GPS)) were introduced in the mid 1990s to improve the efficiency and safety of port operations. Similar applications could be found in global supply chains (see, e.g., Leung et al. 2014). In the late 1990s, first *O*ptical *C*haracter *R*ecognition (OCR) systems were launched for supporting inspection procedures. This included the installation of OCR systems in the gate area as well as image-based damage inspections, which were often combined with the capabilities of laser and video technologies, for instance, to detect container damages (Heilig and Voß 2017a). Also other information systems, such as vessel traffic services, used by port authorities to monitor and control vessel traffic within the port, benefited from the application of automatic identification systems in the late 1990s, allowing the tracking of vessels as a means to prevent collisions. After facing severe traffic problems, the first information system approaches for managing truck appointments were introduced in the beginning of the twenty-first century. At the Los Angeles/Long Beach ports (USA), for instance, the development of the first truck appointment system started in 2002 in response to state legislation aiming to reduce truck queuing at terminal gates and to mitigate vehicle emissions (see, e.g., Giuliano and O'Brien 2007). In the meantime, the development of automated container terminals proceeded apace resulting in the most modern *C*ontainer *T*erminal *A*ltenwerder (CTA) in the Port of Hamburg (Germany) in 2002. Furthermore, it can be observed that there was a growing interest in e-commerce systems in the late 1990s as a result of the dot-com boom, for example, to facilitate trade and shipment management between carriers, shippers, and forwarders. INTTRA[4], developed in 2000, for example, is still the leading e-marketplace for the maritime industry providing an industry network and various functionality to support maritime shipping commerce. The global economic crisis of 2008–2009 led to a more stringent evaluation and selection of ports regarding several decision variables (e.g., cost, capacity, accessibility, connectivity, and eco-friendliness) and cargo shifted between ports (Laxe et al. 2012). This has intensified the competition among ports drastically. According to Pallis and De Langen (2010), a structural implication of the economic crisis was that sustainable performance can be achieved through two key strategies. While the first strategy aims to strengthen the cooperation between ports, the second strategy focuses on improving the coordination between port actors to solve, e.g., accessibility problems. Especially the current phase of digital transformation, discussed in the next subsection, aims to support these two strategies.

6.2.3 Third Generation (2010s–Today): Smart Procedures

While the first and second generations mostly focused on establishing the foundation for improved information flows in terminals and port communities as a basis for automation and information exchange between different stakeholders in a local or global context, the on-going third generation of digital transformation aims to facilitate real-time communication to further improve the visibility, automation, coordination, collaboration, and responsiveness in intra- and inter-organizational processes in the port community and beyond. On the other hand, a purposeful integration and exploitation of available data sources shall open up new possibilities to support, improve, or adapt processes and business models.

As described in the beginning of this section, it can be seen that current initiatives and projects in the context of *smart ports* are increasingly demanding methods and solutions supporting their business analytics. With respect to container terminals, potential business analytics applications are discussed in Sect. 6.4. Still, a future challenge is the analysis of data in order to make better (e.g., more efficient) decisions and to further automate intra- and inter-organizational processes as well as overall port operations including administrative procedures. A main performance

[4] http://www.inttra.com.

indicator is their capability to pro-actively and quickly respond to changes and errors. The implementation of this vision requires multidisciplinary knowledge and is highly dependent on a successful collaboration between industry and academia. At the same time, we see that the success of those initiatives is highly dependent on the willingness of port actors to participate. While the traditionally asynchronous information exchange allowed actors to perform activities and decisions almost autonomously, new approaches may require an active and on-going information exchange and collaboration between the port and involved actors to partly contribute to a common good. Although this causes not only enthusiasm, maritime ports, especially terminal operators as main stakeholders, need to continue working on solutions for solving major issues related to the flow of cargo and logistics services in order to stay competitive. The current development and adoption of modern information systems further indicate that main factors, such as port authorities and terminal operators, increasingly extend their traditional business scope by acting as an information integrator and provider. Moreover, the impact of the digitalization may further increase security spendings for addressing resulting cybersecurity issues, especially after recent cyberattacks, such as Petya[5] in 2017. To summarize, the new developments will lead to a flood of complex data that need to be handled by advanced methods, tools, and information systems. In the following, the concept of business analytics is introduced as a practice for addressing current potentials and challenges related to the use of data. An in-depth analysis and discussion of the three generations of digital transformation in maritime ports is presented in Heilig et al. (2017b).

6.3 Business Analytics: A Brief Introduction

A common definition of business analytics is the use of data, information technology, statistical analysis, quantitative methods, and mathematical or computer-based models so that managers gain improved insights about their business operations and make better, fact-based decisions. Figure 6.1 shows the methods, tasks, and research areas involved in modern business analytics, i.e., the integration of BI/information systems, statistics, and modeling and optimization. These core topics are traditional ones. The "more modern" components are shown in the intersections, and there have been a lot of improvements and influential developments with respect to methods and tools, hardware and software (Evans 2017).

[5]See, e.g., https://www.porttechnology.org/news/digitization_spurs_port_security_spending.

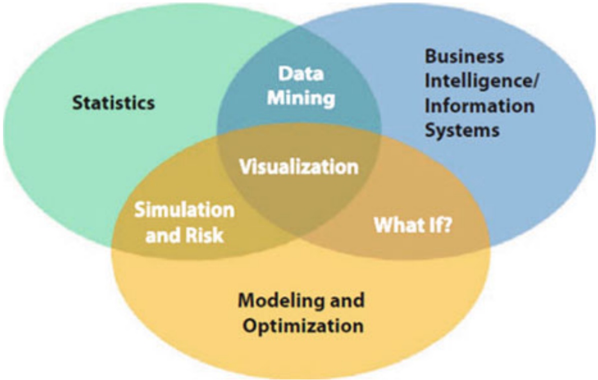

Fig. 6.1 Topics related to business analytics (see Evans 2017, p. 33)

6.3.1 Types of Business Analytics

The concept of *predictive analytics* should be viewed in relation to other types of business analytics that evolved over time. Similar to the view above but with a slightly different focus, four types of business analytics are distinguished by Gartner: descriptive, diagnostic, predictive, and prescriptive analytics. *Descriptive and diagnostic analytics* can be regarded as tasks of sensing and responding, which is a more passive perspective whereas *predictive and prescriptive analytics* are focused on predicting and acting (see, e.g., Davenport and Harris 2007; Evans 2017; Lustig et al. 2010). Figure 6.2 shows the "analytic value escalator" with value gained from higher levels of analytics maturity (and difficulty). The value can be regarded as competitive advantage, or it can at least be turned into it.

By performing business analytics, managers want to gain enhanced understanding of data, content, and meaning. Nowadays, the problem is not to produce or collect and save data. Data is produced more or less permanently and throughout an entire organization in internal data sources and beyond in external data sources. The problem is to unlock (hidden) value out of the enormous amount of complex data. This results in

- increase of the managers' ability to make informed and better decisions, implying that decisions can be made faster without sacrificing the decision quality
- increase of operational excellence within a company
- better processes at the interfaces of a company by having a better understanding of customer needs as well as of suppliers' capabilities
- establishing new business models.

To summarize, the value proposition of business analytics is that it helps companies, such as terminal operators, to achieve strategic objectives (see, e.g., Ferguson 2013). However, this is not done automatically, i.e., it cannot be overemphasized that someone has to take action on data and results of business analytics. For example,

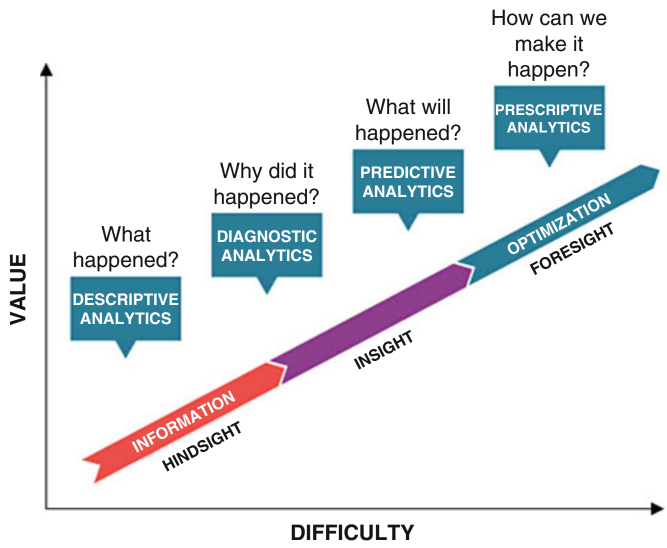

Fig. 6.2 Types and scope of business analytics according to Gartner

presenting real-time data on a dashboard does not solve any real-world problem in terminal operations, but it can help to make better decisions and take better actions. Furthermore, it is common to have difficulties with the implementation of BI systems and tools for data analytics because there are typically different software sub-systems running, making the software and data integration difficult (see, e.g., Rushmere 2017).

The basic idea of data-driven business analytics is closely related to the common hierarchy of data, information, and knowledge. From a bottom-up perspective, data is the basis for information by understanding and interpreting data in a specific context. Furthermore, there are "tools" helping for a better data understanding such as visualization and aggregation. Based on information, knowledge can be derived or created, e.g., by pattern detection, confirmatory data analysis, and causal interference, taking a specific application context into account. Top-down knowledge can be used to create new information which can be encoded in data. *Data science* and *data mining* are closely related, and in fact there is no widely accepted clear definition or differentiation. For example, according to Dhar (2013), data science is regarded as the study of the generalizable extraction of knowledge from data. Currently, one differentiating factor might be the type of data, i.e., data science seems to incorporate new technologies, e.g., related to big data (see, e.g., Provost and Fawcett 2013).

With respect to a process view of data science, there are two well established process models. One model describes the required steps to be performed sequentially as well as in a cycle for improving specific steps for *K*nowledge *D*iscovery in *D*atabases (KDD) process (see Fig. 6.3). Here, data mining is considered to be a

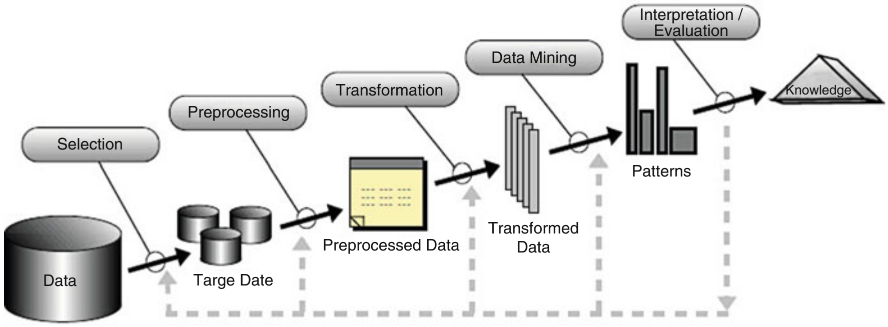

Fig. 6.3 Steps of the KDD process (see Fayyad et al. 1996, p. 41)

part of the entire knowledge discovery process. This shows that, e.g., recognizing patterns is not the final goal but only one step in order to derive useful knowledge. Furthermore, the preliminary steps of selecting, preprocessing, and transforming data are mentioned. These steps are often underestimated in terms of importance and workload by practitioners without deeper knowledge of KDD and data mining.

The second model shows a *CR*oss *I*ndustry *S*tandard *P*rocess for *D*ata *M*ining (CRISP or CRISP-DM – developed by an industry consortium around 1996; see Fig. 6.4) with six high-level phases. Similar to the KDD process, these phases are not strictly sequential but iterative, i.e., typically at a specific phase one previous phase or step has to be redesigned or changed in order to gain improvements. The reference model allows the possibility of going back and forth between different stages, or, even more strict, it is said that moving back and forth is required (although backward arrows are not shown explicitly between all phases). The shown arrows indicate the most important and frequent dependencies only.

The six high-level phases are still a good generic description of a general analytics process. However, details of the phases need to be updated in order to cope with current developments and problems related to big data and "modern" data science.

6.3.2 Data Mining Methods

Data mining can be used either for discovery (of patterns among data) or for verification. Discovery can be partitioned into prediction and description. Both basic approaches aim at deriving useful information and finally knowledge out of given data. The difference is that prediction requires a target variable in the data with its value to be predicted whereas description needs no such target variable (and often problem settings simply do not have one in data). Therefore, prediction is often related to the term supervised learning while description is related to unsupervised learning.

Fig. 6.4 Six phases of CRISP (see Chapman et al. 1999)

6.3.2.1 Descriptive Approaches

Descriptive approaches can further be subdivided into segmentation (or clustering) tasks and association rule mining/sequence mining.

Clustering is very popular for analysis of unstructured multivariate data. The aim of this unsupervised learning approach is to discover clusters among a given data set, i.e., homogeneous classes or subgroups of observations or variables. In real-world applications, the underlying assumption is that there is not one cluster only but that the heterogeneous data set can be separated into "natural" groups familiar to the domain experts. A typical application for marketers is to use consumer profiles and demographics in order to find customer groups so that campaigns can be run more effectively and efficiently. For a deeper look at methods and algorithms, see, e.g., Izenman (2008).

The objective of *association rules* is to find important regularities in data reflected in associations. These are reflected in co-occurrence relationships among data items. A very common application of association rule mining is market basket data analysis. Sequence mining or sequential pattern mining also takes the sequence of purchasing into account. Details can be found, e.g., in Liu (2011).

6.3.2.2 Predictive Approaches

In predictive approaches, past observations or training data are collected in a set of n samples $(\mathbf{x}_i, y_i),\ i = 1, 2, \ldots n$ that are used for estimating a function or model $f(\mathbf{x})$ ($\mathbf{x}$ is a vector of data). The training data includes the correct output values (correct in the sense that it is not a prediction but a value from the past) y_i, the target variable or dependent variable. This model $f(\mathbf{x})$ can be used for predicting an output value for given input values. In machine learning, this task is denoted as predictive/supervised learning. In general, machine learning is devoted to the development of algorithms to automatically extract patterns and generate a model (Murphy 2012). Prescriptive approaches can further be subdivided into classification tasks and regression tasks.

Regression tasks are given if a real value has to be estimated, i.e., predicted. For example, the prediction of a stock price based upon historical time series data of that stock price can be regarded as a regression task. Here, the output y is real-valued, i.e., the target variable is the price, and the, e.g. daily, prediction can be a specific number. The quality of prediction is usually measured as a specific difference between the prediction and the real value.

Classification tasks are given if an indicator function or class boundary has to be learned and estimated in order to divide samples into categories (or classes with a class label). The target variable is the class label, it is a categorical one. For a binary classification problem, the indicator function shows either 0 or 1 (or, e.g., $+1$ and -1), and the function separates the input space into two regions related to different classes.

An example is the prediction of vessel arrivals related to an assumed or estimated time of arrival. The task of vessel arrivals, for instance, can be modeled as regression task or classification task: either the value of earliness/lateness is predicted, e.g., in minutes or hours, or – more roughly but not necessarily worse, and sometimes even more appropriate with respect to the real-world task to be solved – a class of earliness/lateness is predicted, e.g., with five classes "very early," "early," "on time," "late," "very late" and an appropriate definition of those classes.

This example indicates that there are different ways of modeling more or less the same real-world task. The choice of the model type depends on (a) the aim of the decision maker (e.g., is a real-value prediction useful or mandatory for the planning of terminal operations or is a rough classification appropriate or even better), (b) available data, and (c) the method(s)/algorithm(s) to be used.

Depending on the chosen model or task type, there are different well-established methods or algorithms available. For an introduction to machine learning with focus on predictive learning, see, e.g., Cherkassky (2013).

6.3.2.3 Prescriptive Approaches

Prescriptive analytics is closely related to optimization approaches, aiming to identify the best alternative or alternatives regarding a minimization or maximization objective or considering multiple objectives, respectively. As shown in Fig. 6.2, it is about general questions of planning, like "how can we make it happen?" or "what shall we do to minimize the truck turnaround times?" In this regard, it aims to incorporate information and knowledge, extracted through descriptive and predictive analytics, into optimization and simulation approaches, for instance, to better take into account uncertainties, such as concerning demands, arrival times, and disruptions. To put it simple, the novel term is aimed at linking the data-driven perspective with the optimization perspective.

6.4 Data Mining Applications in Container Terminals

Given that means of descriptive and predictive approaches become increasingly important in the current phase of digitalization, this section provides an overview on potential applications with respect to the main operations areas in container terminals at the quayside, yard, and landside. This includes a brief overview on academic works applying data mining methods to produce more accurate forecasts as well as to better understand and address certain problems in container terminals. Before discussing specific applications in container terminals, it should be noted that several works have proposed models to predict the container throughput, mostly based on time series analysis (see, e.g., Gao et al. 2016; Pang and Gebka 2017), or container flows between ports (see, e.g., Tsai and Huang 2017). Another essential application in ports, which is also discussed as an important part of the digitalization, is the use of data analytics for improving customs and security inspections (see, e.g., Jaccard and Rogers 2017; Ruiz-Aguilar et al. 2014, 2017).

6.4.1 Quayside Operations Area

At the interface between seaside and landside operations, the main focus of the quayside operations area is on the discharging and loading of sea-going vessels using quay cranes (i.e., ship-to-shore gantry cranes). Moreover, it involves the horizontal transport of containers between quay wall and the yard operations area, e.g., using AGVs or straddle carriers. Besides providing modern equipment ensuring high productivity, it is important to efficiently allocate and schedule resources (e.g., berths, quay cranes, and vehicles). In this regard, the quayside planning is dependent on many (external) factors, such as regarding vessel arrival times, vessel call patterns, peak demands, and the handling capacities and capabilities of the quayside equipment. Different information technologies and systems are specifically used to collect and manage operational data at the seaside, including:

- *Automatic Identification System* (AIS): A technology that supplements radar systems for tracking vessel positions with the primary objective of avoiding vessel collisions. After enabling the communication with satellites, referred to as S-AIS, the technology nowadays supports a real-time monitoring of vessels. AIS data messages include information about the vessel (e.g., maritime mobile service identity, vessel type, length, width, and draught) and voyage (e.g., port of destination, speed and course over ground, and heading). Using this data, several vessel tracking web services have been established (e.g., *VesselFinder*, *FleetMon*).

- *Vessel Traffic Service* (VTS): A VTS includes functionality to collect, analyze, and disseminate data, especially to navigate vessels in busy, confined waterways and port areas (Filipowicz 2004). The information system integrates various subsystems and technologies, including AIS, vessel movement reporting systems, radar systems, radio communication systems, traffic signals, and video surveillance.

Although operations at the seaside are increasingly supported by information technologies and systems (see Heilig and Voß 2017a), they are still affected by disruptions and uncertainties resulting from a lack of reliable information and forecasting. This includes delays and overpunctual vessel arrivals, weather conditions, tidal conditions, traffic congestion, and equipment breakdowns. With respect to quayside planning, many variations of different optimization problems have been discussed in the literature, in particular the berth allocation problem, quay crane allocation problem, and quay crane scheduling problem. Some of the discrete problem formulations consider uncertainties by using stochastic variables, for instance, stochastic arrival and handling times in the berth allocation problem (Bierwirth and Meisel 2010). Stochastic programming, for instance, has been proposed as a means to address uncertainties in berth and quay crane assignments by taking into account different risk preferences of decision makers (see, e.g., Zhou and Kang 2008).

Having various sources and large amounts of operational data, the application of data mining is also attracting interest in both industry and academia. A strong research focus is on the analysis of AIS data for identifying patterns and anomalies concerning vessel operations and maritime traffic. Most related studies analyze vessel behavior patterns (see, e.g., Arguedas et al. 2017; De Vries and Van Someren 2012) and anomalies (see, e.g., Lei 2016; Ristic et al. 2008) or propose means to reduce the risks of vessel accidents (see, e.g., Hänninen 2014; Zhang et al. 2015). Putting the focus back on container terminals, we identify only a few applications that are currently discussed in the literature with respect to quayside operations.

6.4.1.1 Vessel Arrival Times

While being important for an efficient planning of subsequent terminal operations, reliable forecasts about the actual arrival times of vessels are still scarce in many seaports. This may lead to unused terminal capacities and longer vessel waiting and turnaround times. Means to predict arrival times further allow to operate vessels more efficiently in terms of emissions. In this context, slow steaming and virtual arrival policies are currently discussed in the literature (Meyer et al. 2012), taking into account, for instance, the impact of tides. In the context of container terminals, few studies address the prediction of vessel arrival times. Fancello et al. (2011) propose a feedforward neural network for estimating ship arrival times in order to better determine capacity demands, for which an optimization model is used. The approach aims to reduce the number of additional workers in working shifts that need to be planned to cover uncertain demands. Pani et al. (2014) present a *C* l*A*ssification and *R*egression *T*rees (CART) model to further reduce the range of uncertainty of vessel arrivals using data from the *T*ransshipment *C*ontainer *T*erminal (TCT) of Cagliari (Italy). Compared to related works, the paper specifies in detail the steps taken in the KDD process. The authors demonstrate how the model can be used to identify the causes for delays. In another work, Pani et al. (2015) treat the problem as classification and assess different algorithms (logistic regression, CART, and random forest) using data from the Port of Cagliari (Italy) and the Port of Antwerp (Belgium). Besides vessel data (e.g., physical structure, previous port of call, and position), the authors consider weather conditions, such as account geostrophic wind speeds, wave heights, peak wave periods, and wave directions. Using the Gini importance measure, measuring the relevance of input variables, the high impact of weather conditions on vessel arrival uncertainty is highlighted. Kim et al. (2017) propose a modified framework of *C*ase-*B*ased *R*easoning (CBR) for the early detection of vessel delays using real-time S-AIS vessel tracking data in addition to historical data (e.g., data from bill of ladings). The approach allows to detect delays in real-time and predict movement patterns of a vessel until its arrival. The authors further highlight the potential improvement of predictions when using real-time data.

6.4.1.2 Berth Operations

To predict the performance of vessel loading and discharging operations, Gómez et al. (2015) propose a neural network that takes into account operational data (e.g., berthing time, number of containers, number of gangs, and vessel beam size) as well as wind conditions (e.g., average wind speed, wind direction) during berthing of respective vessels, provided by a Spanish container terminal. By analyzing training errors, the authors highlight the important role of wind conditions.

For addressing the berth allocation problem in bulk terminals, seeking to identify the berthing position and berthing time of bulk carriers, de León et al. (2017) recently propose a machine learning approach for selecting optimization algorithms dependent on the scenario at hand. A k-nearest neighbors algorithm is proposed to classify each problem instance based on its features. Taking into account the historic performance of algorithms in solving similar problem instances, a ranking of algorithms is generated for each problem instance. Compared to other approaches, the study shows that data mining cannot be only used for analyzing operational data, but may also aid the selection of appropriate planning methods and tools.

6.4.2 *Yard Operations Area*

Yard operations mainly involve storage and stacking logistics (Steenken et al. 2004) and serve as a buffer between seaside and landside operations. Several complex planning and optimization problems result from yard operations, such as yard allocation problems, post-stacking problems (e.g., remarshalling, premarshalling, and relocation problems), and crane scheduling (see, e.g., Caserta et al. 2011). The performance of yard operations is constrained by several factors, including the quay wall throughput (per year/in peaks), the size and shape of the yard area, characteristics of containers (e.g. type, size, weight, and destination port), the handling performance of crane systems, and handling equipment (Böse 2011). These factors can have an effect on important performance indicators, such as on container dwell times (i.e., the time a container spends at the terminal), handling performance and utilization of equipment, and operational costs. Different information systems and technologies are in place to support yard operations, such as:

- *Terminal Operating System* (TOS): Functionality for registering new containers and tracking their position within the container yard is provided by the TOS. In particular, *A*utomated *T*ransfer *C*ranes (ATC) rely on the availability and accuracy of job and container data from the TOS to autonomously perform yard moves.
- *Automated transfer points for trucks*: Some container terminals have implemented automated transfer points at the yard to identify and serve incoming trucks. After following the instruction, the driver must leave the cabin and confirm the yard operations by showing a driver's card at the bay station. The latter increases safety and enables the identification of containers based on job data stored on the smart card.

While related optimization problems have been intensively approached and discussed in recent decades, only a few works apply data mining methods to gain insights from operational data related to yard operations.

6.4.2.1 Container Dwell Times

Prolonged container dwell times result in a high storage yard occupancy and may result in adverse effects on the terminal productivity and throughput capacity. While reducing dwell times increases the yard throughput capacity, storing containers in the yard over a longer time may also result in higher revenues earned from demurrage fees. Moini et al. (2012) analyze different methods to predict dwell times at terminal yard operations areas at a US container terminal: *N*aïve *B*ayes (NB), a decision tree (using the C4.5 algorithm) and a hybrid *N*aïve *B*ayes Decision tree (NB tree). Using the well-performing C4.5 model, the authors further assess the impact of changes in determinants on the container dwell times, yard throughput capacity, and terminal demurrage revenues using three scenarios: changing the status of containers from empty to full, closing truck gates in low volume conditions, and changing the ocean carrier. Although more in-depth analysis is needed, the authors demonstrate the impacts of changes and trade-offs between container dwell times and demurrage fee revenues. Kourounioti et al. (2016) analyze the determinants of container dwell times by applying an *A*rtifical *N*eural *N*etwork (ANN) with backpropagation using a data set of 13,733 import containers from the TOS of a container terminal in the Middle East, containing information related to the containers (e.g., arrival/departure times, size, status, type, date of customs inspection if applicable, dwell time), ocean carriers (e.g., name, assigned vessel, and port of origin), and trucks (e.g., departure time from the terminal's gate). Using different sets of independent variables, the authors test their impact on the model's accuracy and show that accuracy can be improved by considering more information, whereas the measured accuracy is with 65.17% not very high for the best case. Gaete et al. (2017) propose a framework of container storage assignment policies using container dwell time classes based on different classification algorithms, including NB, lazy learning (KNN; k-nearest neighbor algorithm), and rules induction learning techniques, such as the *One R*ule (OneR) or the JRip algorithm. The authors use a data set from the Port of Arica (Chile) containing a total of 151,640 import container movements. Based on the results of the classification algorithms (JRip, KNN), a discrete event simulation model of the import processes at the Port of Arica is proposed to evaluate the impact of different stacking policies. The results demonstrate that an appropriate preprocessing and preparation of operational data, as advocated in the KDD process and CRISP (see Sect. 6.3), leads to a substantial reduction of re-handling activities.

6.4.2.2 Container Stacking

Container stacking policies for containers have been widely discussed in the literature. Due to the ever-growing requirements to better use the space of container terminals and the impact of larger vessels, a higher yard utilization and a reduction in the number of reshuffles are desired. Besides advanced optimization and simulation approaches, only a few studies incorporate data mining methods. Jin et al. (2004) present an "intelligent simulation method" based upon fuzzy ANNs for the regulation of container yard operation including the system status evaluation as well as the operation rule and stack height regulation. A two phase approach is proposed: the first phase of the regulation process forecasts the quantity of incoming containers. The second inference phase decides on the operation rule and stack height, addressed as a fuzzy multi-objective programming problem with the objective of minimizing a ship's waiting time and the operation time. A comparison between results of the proposed model and current operation in 30 days shows that the total ship waiting time is reduced from 64 h to 46 h. Kang et al. (2006a,b) focus on the planning of storage locations for incoming containers of uncertain weight. Oftentimes the information about the weight of a container is not accurate;

when dedicated weighing procedures are not in place, the weight of containers is often underestimated or overestimated. As efficient stacking strategies are highly dependent on weight information of containers, it is important to explore means to extract information from available data sets. In this regard, the authors apply different classification algorithms to better estimate the weight group of a container, which is used in a simulated annealing algorithm to determine a good stacking strategy that reduces the number of re-handlings. However, the authors indicate that even though the overall accuracy of weight classification was improved by using the classifiers, the performance of some stacking strategies became slightly worse due to certain misclassifications. They propose to further investigate this problem by considering a cost sensitive learning for the weight classification. In the meantime, the *I*nternational *M*aritime *O*rganization (IMO) has amended new regulations that require a mandatory verification of the gross mass of packed containers, which may help to improve the data quality. Recently, Hottung et al. (2017) propose a hybrid heuristic tree search integrating a deep neural network to solve the well-known container pre-marshalling problem. The neural network assists the heuristic in guiding branching and pruning. The authors show that their approach finds solutions 4% better than state-of-the-art optimization methods using real-world sized problem instances from the literature.

6.4.3 Landside Operations Area

Landside operations involve internal transports, truck operations, and railway operations (Steenken et al. 2004). Related horizontal transport operations rely on an efficient handover of containers at the yard or in dedicated handling areas (e.g., rail or barge terminal) and might be subject to inspections. Improving those operations leads not only to a better hinterland accessibility and inland connectivity, crucial for the competitiveness of ports (see, e.g., Wiegmans et al. 2008), but also facilitates efficient connections to auxiliary and value-added logistics areas within seaports. The increasing container volumes, peak demands, and a lack of coordination, however, lead to growing traffic and congestion at container terminals and within port areas, especially in areas located in urban environments with limited space for port expansion. As those operations highly contribute to congestion, traffic accidents, emissions, and noise, they have a great impact on the sustainable development of ports. In recent years, a large number of publications has been devoted to study and improve landside and hinterland operations, such as concerning gate/truck appointment systems (see, e.g., Huynh et al. 2016), extended gate concepts or dry ports (see, e.g., Roso and Lumsden 2010; Veenstra et al. 2012), and inter-terminal transportation (see, e.g., Heilig and Voß 2017b; Tierney et al. 2014). However, most of the works are conceptual or focus on (combinatorial) optimization and simulation rather than on information systems and predictive analytics. Besides, many port authorities and container terminals have greatly invested in digitalization to better manage landside and hinterland operations. Meanwhile, terminal landside operations and hinterland access are supported by various information systems and technologies.

- *Gate/truck appointment systems*: To better balance the workload and reduce waiting times at terminal gates, many container terminals require truck companies to pre-register containers and to book an available pickup or delivery time window. The planning of gate capacities and time windows requires a good understanding of truck arrival patterns and demand. Trucks that provide all documents in advance and arrive within the time window can therefore expect a guaranteed access to the terminal and a fast clearance process. Moreover, self-service stations have been introduced allowing the truck driver to complete missing data before arrival. Some ports penalize no-shows and late arrivals or charge a fee for day-shift or peak-hour appointments. Given existing appointment systems, several shortcomings have been reported in practice (Giuliano and O'Brien 2007; Huynh et al. 2016), including a lack of flexibility and predictability of arrivals. While truck drivers usually meet morning appointments, keeping subsequent appointments depends on the traffic and whether the previous trips have gone as expected. In this regard, analyzing the causes of high truck turn times or late arrivals as well as the identification of late arrivals may help to reduce/avoid delays or proactively react to missed appointments, respectively.
- *Port traffic management/Intelligent Transportation Systems* (ITS): Some ports have implemented modern port road and traffic control systems to monitor and control traffic flows within the port area. For this purpose, different technologies, in particular sensors and actuators, are applied (e.g., laser vehicle detection systems, induction loops, etc.). The collection and analysis of traffic-related data build not only the basis to analyze motion patterns, infrastructure bottlenecks, and areas with high accident risks, but also allow to timely react to certain traffic conditions, e.g., by adapting electronic traffic signals and displaying relevant information on electronic display for traffic information and control. Cargo-related traffic data is further important to evaluate the performance of truck movements, to explore movement bottlenecks, and to determine the frequency, costs, and environmental burden of recurring events. More accurate weather data and forecasts can be used to better control the traffic and warn vehicle drivers according to certain weather conditions. Moreover, the demand for an efficient parking space management is growing. In this regard, it becomes increasingly important to make reliable predictions about the availability of parking spaces in certain areas of the port. By identifying individual motion patterns and preferences of truck drivers, context-aware recommendations can be provided. As a basis, there are already many IT-based solutions in place to support the collection, management, and dissemination of traffic-related information in ports (for an overview, the interested reader is referred to Heilig and Voß 2017a).
- *Mobile applications*: Mobile devices allow a direct interaction between actors involved in port operations and are equipped with powerful computing and sensing capabilities. Analyzing contextual data may not only help to understand the situation of individuals and to predict forthcoming events in order to provide

guidance and individual recommendations (e.g., recommended travel speed to reduce emissions and to benefit a series of green traffic lights). In many ports, new mobile apps have been introduced in recent years, especially for truck drivers (for an overview, the interested reader is referred to Heilig and Voß 2017a).

- *Rail traffic management*: Besides the truck transport, a large part of cargo movements is handled via rail transport requiring information systems to efficiently manage rail operations. An example for a corresponding information system is *transPORT*, which is a new rail traffic management system of the Hamburg port railway (HPA 2015). The system provides data on train locations, train movements, wagon sequences, track occupations, wagon destinations, and unloading/loading schedules. In the context of synchromodality, for example, analyzing available sources of (real-time) data may be useful for predicting prices, available capacities, and the performance of alternative modalities (see, e.g., Van Riessen et al. 2015).

While a growing need for data mining methods can be identified in the practical context, we currently find only a few works concerned with data mining applications. In the following, we discuss the identified works in the context of their application.

6.4.3.1 Port-related Truck Traffic

The majority of identified research works is focused on the prediction of truck-related cargo volumes in seaports. One of the first series of studies looks at cargo flows and modal split in seaports of Florida (US) in order to support strategic planning regarding the prioritizing of public funds for roadway upgrades (Al-Deek 2001, 2002; Al-Deek et al. 2000; Klodzinski and Al-Deek 2003, 2004; Sarvareddy et al. 2005). More specifically, the authors propose backpropagation ANN models to determine relevant factors and to predict inbound and outbound heavy-truck volumes in the Port of Miami (US) and, additionally, to determine the daily modal split between inbound and outbound rail and truck cargo volumes in the Port of Jacksonville (US). In general, the proposed models in Al-Deek (2001) and Al-Deek et al. (2000) use seaborne import and export freight data of respective ports. By considering the dwell time of containers in the container terminals, representing the lead and lag times (in days) depending on the direction of cargo, the authors were able to improve the accuracy of predictions. In Al-Deek (2002), the author applies a similar methodology for the Port of Everglades (US). As an extension, a time series model is integrated to forecast future export and import container volumes loaded/unloaded into/from container vessels, respectively. The authors do not differentiate between different sizes of containers (e.g., 20-foot and 40-foot container). In later works, the transferability of the methodology has been evaluated for additional ports in Florida, namely Port of Canaveral and Port of Tampa (Klodzinski and Al-Deek 2003, 2004). Klodzinski and Al-Deek (2004) further incorporate the prediction models into simulation models in order to analyze the impact of volume variations and accidents on daily port operations. Sarvareddy et al. (2005) compare the performance of the previously applied ANN with a *F*ully *R*ecurrent *N*eural *N*etwork (FRNN), which the authors apply to better consider relationships between records (e.g., turnaround time and number of trucks) and to consider dynamic temporal behavior. The proposed FRNN model proved to be less accurate, whereas the authors do not specify how the accuracy has been measured. Generally, this early series of studies, conducted in the early 2000s, clearly indicates the dependence on field studies for collecting data about truck volumes resulting in a lack of available data. As discussed above, it is nowadays possible to collect vast amounts of data using different technologies and information systems (e.g., truck/gate appointment systems). In this regard, it would be interesting to more extensively analyze the behavior of neural networks (e.g., learning rate, overfitting, etc.) depending on different configurations (e.g., number of neurons in the hidden layers, training and transfer functions) and sample sizes, while comparing them with other predictive methods.

In the latter sense, Xie and Huynh (2010) apply two kernel-based supervised machine learning methods to predict the daily truck volume at seaports, namely *G*aussian *P*rocesses (GP) based on a full Bayesian framework and an ϵ-support vector machine (ϵ-SVM), and compare them against a *M*ultilayer *F*eedforward *N*eural *N*etwork (MLFNN). As a basis for the model development, the authors use data from Bayport Terminal and *B*arbours *C*ut *T*erminal (BCT) at the Port of Houston (US). Moreover, the authors evaluate the transferability of the kernel-based approaches by applying the models gained from data of one terminal to the other terminal. The authors follow the idea of Al-Deek (2001) to differentiate the independent variables of import and export container volumes according to the different dwell times, but do not consider the potential impact of weekdays. Instead of considering only 3 days of storage (as in Al-Deek 2001), the models consider the previous 12 days for export containers and the next 12 days for import containers, respectively. Dependent on the direction of cargo (import or export) and container terminal, four data sets have been created covering about 5 months of terminal operations, resulting in twelve prediction models. Given the results of the experiments it might be possible to improve the performance of the proposed neural network model by better addressing overfitting and local minima problems.

To identify factors that have a substantial impact on freight trip generation at the Port of Kaohsiung (Taiwan), Chu (2010) conducts a roadside intercept survey at different facilities within the port. For evaluating the use of data mining methods, the author compares the prediction accuracy of a multiple regression model, different time series models (e.g., *A*uto*R*egressive *I*ntegrated *M*oving *A*verage (ARIMA) model, exponential smoothing model), and a backpropagation ANN. By analyzing the *M*ean *A*bsolute *P*ercentage *E*rror (MAPE), *M*ean *A*bsolute *D*eviation (MAD), and *M*ean *S*quared *D*eviation (MSD), the results indicate that the ANN model has the best forecasting accuracy, followed by the regression and ARIMA model, whereas the differences are rather small. In terms of temporal effects and nonlinearity in the truck volume data, the ARIMA model and the ANN model provide a better fit.

While most of the related works use observation data from field studies, we can also identify works that conduct nationwide surveys for identifying main characteristics of truck-trip generation (Chu 2010; Holguín-Veras et al. 2002) or propose other methodologies and give recommendations for collecting data about container truck traffic at seaports (Rempel et al. 2011).

6.4.3.2 Waiting Times and Turnaround Times

Besides the volume of cargo, the planning of landside and hinterland operations requires reliable indicators for waiting and turnaround times, for instance, for a more efficient vehicle routing. While exceeding waiting and turnaround times may greatly affect the schedule of truck drayage and hinterland operators, we can find very few studies applying data mining methods to predict them.

In the work of Hill and Böse (2017), a concept for developing a decision support system based on truck arrival rates and predicted truck gate waiting times is proposed. While the focus is primarily on the system architecture and user interfaces, the authors apply an ANN model based on actual truck waiting times from an empty container depot in Northern Germany. In the experiments, considering weekdays, daytimes, and public holidays in the set of input variables and eliminating night periods increased the model accuracy. It would be interesting to further assess the performance of alternative methods, configuration settings, for instance, by using a cross-validation and different samples sizes.

Van der Spoel et al. (2016) compare regression and classification models for predicting truck turnaround times using random forest and CART. For the regression analysis, the authors further use a linear regression model. Other than in related studies, the authors use a simple simulation model to generate data about terminal operations (e.g., pickups, drop-offs, time in queue, etc.). Certainly, the generated data sets can represent real terminal operations only to a certain extent since most individual factors of daily operations are not considered. Nevertheless, the work somewhat outlines a methodology for benchmarking different predictive methods using existing simulation models of container terminals.

A recent work of Wasesa et al. (2017) takes a macro perspective on truck turnaround times by proposing advanced means to predict the duration of truck operations in seaports using truck trajectory data, representing all truck movements within the port. Thereby, the work contributes to the predictive analytics development using geospatial sensor-based data. The proposed methodology involves a data preparation phase where trajectory reconstruction is first applied to understand the movement of trucks based on historical GPS positions. A geo-fencing technique is used to define the area of the seaport, which determines the trucks' arrival and departure times at the seaport and thus the duration of trucks within the seaport. The authors apply a boosting algorithm, namely the gradient boosting method, known to have a strong prediction performance and robustness against overfitting. A large telematics data set, representing five million data records from over 200 trucks operating in the Port of Rotterdam (Netherlands) over a period of 19 months, is used. Similar to Hill and Böse (2017), the authors take into account temporal effects. Moreover, previous truck durations, truck arrivals, and truck departures serve as input variables to capture travel behavior's inertia effects (see, e.g., Cantillo et al. 2007). The proposed gradient boosting prediction models outperform the generalized linear models used as a benchmark. To the best of our knowledge, the study is the first in applying data mining methods to deeply study and analyze contextual data of drayage trucks based on a sufficiently large data set. As such, the work builds the basis for a promising line of research to better predict and compare the performance of seaports in handling port-related truck operations.

6.4.3.3 Truck Delays

For short-term and long-term planning, identifying the causes of inefficiencies at container terminals is at least as important as the prediction of future developments. However, the literature applying data mining methods for identifying causes and anomalies in landside and hinterland operation areas is rather scarce.

Huynh and Hutson (2008) apply three decision tree models to identify causes of abnormally high truck turn times at the BCT (US), including a *CH*i-squared *A*utomatic *I*nteraction *D*etector (CHAID), CART, and a decision tree (using the C4.5 algorithm). As a data basis, the authors use transactional data from gate operations (e.g., arrival at the gate queue, terminal entry time, use of chassis, etc.) and yard operations data concerning quayside operations, drawn from the TOS, over a period of 8 months. Due to the higher priorities of quayside operations, the terminal operator wanted to know, for instance, whether vessel operations pose a conflict to drayage operations. The models are formulated as binary classification problems, where the indicator function is one (1) if the truck *T*urn *T*ime (TT) is greater than 1 h, and zero (0) otherwise. By analyzing the resulting decision trees, main causes for high truck turn rates at BCT could be identified.

An example of a decision tree of the C4.5 model is shown in Fig. 6.5. In this example, terminal operators can easily see that the main causes for high turn times relate to the use of chassis. If an import delivery is made and it requires a chassis (*IMPREQDCHASSIS*) and if the steamship line is not a chassis pool member (*SHIPCO*), then transactions are likely to have high truck turn times. It can be derived that a significant delay is experienced because of the need to find and get an appropriate chassis, whereas it is even more difficult when chassis are constantly used by yard trucks at the quayside area. Other than expected by the BCT management, not the daily moves of yard cranes contributed to high truck turn times, but the lack of available chassis. Therefore, the study highlights the real benefit of data mining in identifying causes of high truck turn times at certain container terminals.

Here, the authors modeled the problem as classification task and applied decision trees for solving – a well-established approach and therefore a good choice for classification. However, at least from a scientific point of view, this case or experiment could be expanded with respect to the modeling as well as to the used

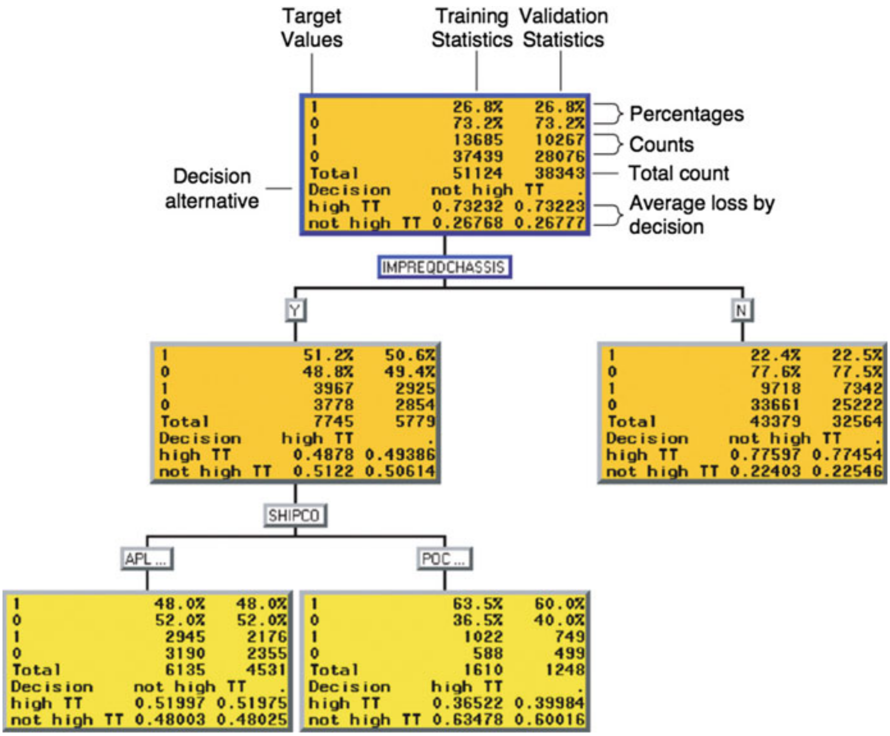

Fig. 6.5 Example C4.5 tree (see Huynh and Hutson 2008). Selected input variables: IMPREQD-CHASSIS (import pickup requires a chassis), SHIPCO (steamship line of the container)

algorithms. It would be interesting to see different algorithms and their pros and cons in this real-world application. For example, ANNs, support vector machines, or even random forests as a combination of decision trees could be evaluated. Furthermore, one can think of modeling this problem as a problem of association rule mining, i.e., finding associations (if-then-relationships) among coincident facts (here: usage of specific chassis and delays).

In another study, data of webcams was used to observe truck queuing patterns and to analyze the distribution of truck processing times, truck interarrival times, and truck queuing times at the entry gate of container terminals to better understand reasons of inefficient truck queuing (Huynh et al. 2011). The authors conduct goodness-of-fit tests to identify best-fit distributions using data of two container terminals. Several implications are drawn from the distributions, such as reasons for long queues in front of the gate. For example, long queues can be observed at the opening hour as truck drivers aim to perform as many moves per day as possible (usually they are paid per container) or in case of long turn times of other trucks within the gate.

First, at some terminals, the queues at the opening hour could be extensive because of the drayage drivers' desire to make their first move at the beginning of the day to allow for more time for subsequent moves later in the day; most drivers are paid by the move. Second, there is extensive queuing during the lunch hour at some terminals because of the policy to close for lunch. Moreover, analyzing those distributions allows to identify peak hours (e.g., arrival of a new vessel) and daily/weakly variations. The results of the authors further demonstrate that truck queuing is higher during heavy rains, thus indicating an impact of weather on terminal operations. Although some findings derived from operational data may be common sense knowledge, analyzing the data helps to accurately measure and quantify causes of inefficiencies.

6.5 Conclusion and Outlook

In recent decades, maritime ports and container terminals have invested in automation and digitalization to improve the productivity and operational efficiency of related processes. Following the developments of the current generation of digital transformation, the amount of complex data is growing at a fast pace, while remaining mostly under-processed or under-analyzed if not handled appropriately. In recent decades, quantitative research is mainly focused on optimization methods from the field of Operations Research. Therefore, the gap between the data, produced in and around terminal operations, and its use for terminal planning and management is growing. Business analytics represents a concept for closing this gap: to be able to use better information and knowledge in decision making processes, e.g., supported by means of optimization methods, it is essential to first process and analyze operational data. To put it concisely, a "data-driven" perspective needs to enrich the traditional "optimization" perspective.

This chapter has aimed at establishing this data-driven perspective on terminal planning and management by taking into account the current developments of the digitalization. First, the chapter has presented an overview on the three generations of digital transformation in maritime ports and then put a high level introduction to the concept of business analytics. Data mining – as a process of discovering patterns, regularities, or even irregularities in operational data – as well as methodical approaches has been briefly explained. Given this foundation, the chapter provided a comprehensive overview on data mining applications in the context of container terminals. With respect to the different terminal operations areas, divided into the quayside, yard, and landside area, the chapter has reviewed related academic works of past decades. Most of the works focus on predictive analytics to either reduce uncertainties by data-driven forecasting models or to better understand causes of inefficiencies or delays. In general, however, a lack of studies and applications can be identified in the field of terminal management and operations. Moreover, important methodological insights of the data mining process, such as regarding the data preparation (e.g., data cleansing, feature selection), algorithm selection and configuration, and model evaluation, are not discussed in great detail in literature.

Although fractional interest has been shown by a few researchers, it can be concluded that data mining research in this application domain is still in its infancy. Nevertheless, we have seen promising examples and therefore expect more research and results in the near future. Especially in terms of real-time analytics, there is a large potential to improve the responsiveness, resilience, and coordination in intra- and inter-organizational terminal operations.

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Chapter 7
Pavements for Container Terminals

David Schnabel

Abstract The pavement of container terminals requires high investment costs. In case its design is not appropriate to subsoil conditions and load impacts, any necessary reconstruction is time-consuming and costly. The latter also implies to an overdesign of the pavement. After a compilation of terminal equipment loads, the chapter gives an overview of practical proven pavement solutions for different operational areas on container terminals. Both advantages and disadvantages of different available pavement types are summarized and suitable wearing courses for the different operational areas are proposed.

7.1 Introduction

A container terminal requires extensive paving of the stacking and transport areas. The pavement of these areas usually causes one of the largest shares of capital costs in terminal development. Inappropriate pavement design may result in serious financial implications, as necessary reconstruction is not only time-consuming and costly, but will also hinder the terminal operations and increase its associated operating costs. Additionally, overdesigned pavement consumes capital unnecessarily. Since there is no standard design for the pavement of a terminal, the choices are usually a compromise between durability and costs.

Generally, the pavement design at port facilities is based on "The Structural Design of Heavy Duty Pavements for Ports and Other Industrie" (see Knapton 2007). In the first edition, the manual was published by the British Ports Association in 1984, considering both the relevant American and European standards.

In the following section, characteristics such as container loads (depending on stacking height), terminal equipment loads, and other design parameters are provided. In Sect. 7.3, a design approach is introduced that is proposed by the British

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Ports Association and frequently used in practice to determine pavement thickness. Subsequently, different pavement types are described, especially highlighting their advantages and disadvantages as well as their suitability for the major operational areas of container terminals (see Sect. 7.4). The chapter closes with a summary and some general conclusions in Sect. 7.5.

It should be mentioned that this chapter can only introduce general solutions for container terminal pavements. The design approach for the pavement of a specific terminal has to consider the local conditions of the facility such as soil parameters and handling equipment. In order to allow for flexible and unimpeded operations of the equipment fleet on all accessible areas, the same pavement type should be applied to widespread sections of the terminal – resulting in lower construction costs as well.

Furthermore, a detailed software supported traffic model should be the basis for all design decisions. This allows the simulation of different traffic frequencies, and thus the determination of the respective impacts on the pavement.

7.2 Operational Terminal Areas and Load Assumptions

The following section focuses on the load assumptions typically considered for the pavement design of the operational areas of a container terminal. In general, container terminals consist of the following different areas providing specific operational functions:

- Container stacking yard for standard containers, i.e., pure metal boxes mainly of 20 ft or 40 ft length
- Reefer container storage area
- Hazardous goods and tank container storage area
- Maneuvering and handover areas at terminal water- and landside
- Empty container storage area
- Internal terminal road network
- Gates.

7.2.1 Storage Areas for Standard and Reefer Containers

At many seaport container terminals, 20 ft and 40 ft containers are stacked up to 1-over-5-high. The load characteristics of stacked full containers being usually considered for pavement design are given in Table 7.1 for one layer of containers. These values have to be multiplied by the stacking height chosen for the particular terminal.

Reefer containers are stacked up to 4-high by using reefer racks. Related steel constructions enable access for reefer mechanics to containers located at tier two

Table 7.1 Load characteristics of stacked full containers

		Full load				Average operating load			
Stacking height (cont.)	Cont. size (ft)	Weight of cont. (*t*)	Corner weight (kN)	Contact pressure (corner fitting) (N/mm^2)	Equivalent area load (kN/m^2)	Weight of cont. (*t*)	Corner weight (kN)	Contact pressure (corner fitting) (N/mm^2)	Equivalent area load (kN/m^2)
1	40	35	87.5	3.0	2.9	25.0	62.5	2.2	2.1
1	20	30	75.0	2.6	5.1	22.5	56.3	2.0	3.8

and higher. The mechanics are responsible for checking the container temperatures as well as to connect/disconnect boxes after/before discharging/loading in a timely manner. Reefer racks are to be fixed to the ground or to a foundation beam depending on the stacking height and pavement type. Foundation beams are considered as a structural design task and are not discussed within this chapter.

7.2.2 Storage Area for Dangerous Goods and Tank Containers

The exact stacking height of containers classed under the *I*nternational *M*aritime *C*ode for *D*angerous *G*oods (IMDG) as well as of tank containers has to be discussed with the local authorities, such as civil defence (or fire departments) and environmental departments. In general, it can be assumed that these containers are stacked up to 2-high on dedicated areas only. The surface has to be sealed with, e.g., asphalt or concrete layers, in order to prevent contamination in case of leakages. Leaking liquids have to be retained from flowing off the terminal area by the use of emergency shutdown valves or intermediate storage basins in the dedicated storm water system.

7.2.3 Maneuvering and Handover Areas at Terminal Water- and Landside

Depending on the operational concept for horizontal container transport at the waterside, e.g., straddle carriers or automatic guided vehicles serve the ship-to-shore cranes at quay wall, the handover of boxes is in the crane portal or in the backreach (or sometimes in both areas). At the terminal landside, licensed public trucks with trailers carry out container transports exclusively or in combination with the terminal's own equipment and pit stops at dedicated handover areas. Additionally, point loads induced by trailer jockey wheels of terminal and/or road equipment frequently stress the pavement at the landside handover areas.

The internal terminal road network perpendicular and parallel to the quay wall is used by the same equipment as on the water- and/or landside maneuvering areas. In contrast to these areas, the pavement requirements for the internal road network are lower due to the fact that the traffic within this network is more evenly distributed and characterized by a lesser number of acceleration, braking, and turning processes.

7.2.4 Empty Container Storage Area

Empty 20 ft and 40 ft containers are stacked up to 7-high at many terminals. The load characteristics for one layer of containers are listed in Table 7.2 (see, e.g., Hapag (2017) and other container suppliers) and have to be multiplied by the stacking height chosen for the particular terminal. Handling of empty containers is generally carried out with reach stackers and/or empty container handlers – also known as top lifters.

Empty container stacking areas are highly influenced by frequent dynamic stresses and strains due to acceleration and braking processes caused by operating equipment. In addition, related areas are subject to point load impacts induced by the corner fittings and trailer jockey wheels.

7.3 Design Approach

7.3.1 Design Aspects and Life Span

Based on the experiences from countless projects, for designing heavy duty industrial and port pavements, the so-called British Ports Association design method has become established in civil engineering practice. Likewise, in the field of container terminals, it is usually used to determine the pavement thickness for areas with heavy duty requirements. The method is based on the principle, that occurring strains do not exceed the permissible critical loads which the material is able to withstand in different pavement depths. It uses the elastic layer theory and follows a four-step approach in determining the pavement thickness required due to operational and environmental conditions:

- For container terminal pavements, firstly, the critical wheel load or *P*ort *A*rea *W*heel *L*oad (PAWL) is calculated by accounting for wheel proximity and dynamic load factors for the equipment in use.
- Secondly, the average and critical damage effects are estimated for the specific PAWL based on the proportion of 40 ft/20 ft containers to be handled. The result of the second step is the *L*oad *C*lassification *I*ndex (LCI).
- The third step is the determination of the total number of load applications and their effective damage over the life of the pavement, taking into account the effects of travel lane width and channelization.
- Given the subgrade strength in *C*alifornia *B*earing *R*atio (CBR) percentage, at step four, the LCI, the number of load applications, the base material strengths, and design charts are used to estimate allowable tensile strains in cement-treated sub-bases or rigid concrete slabs – whereas for granular base, allowable compressive strains are estimated. Given the permitted strain levels, further design charts are used to determine the required base or surface thickness for various CBR values and sub-base thickness.

Table 7.2 Load characteristics of stacked empty containers

		Load			
Stacking height (cont.)	Cont. size (ft)	Weight of container (depending on cont. type) (t)	Corner weight (kN)	Contact pressure (corner fitting) (N/mm^2)	Equivalent area load (kN/m^2)
1	40	3.7–4.6	9.3–11.5	0.3–0.4	0.3–0.4
1	20	2.4–4.5	6.00–11.25	0.2–0.4	0.4–0.8

Economical project evaluations usually estimate the lifetime of port facilities to be 20–30 years. It is generally assumed that after this period of time, the physical condition of facilities and new market developments or lease agreements will bring about the requirements of major rehabilitation or adaptation measures of the pavement.

7.3.2 Equipment Loads

Design formulas for the calculation of load repetitions comprise of various statistically evaluated coefficients and parameters describing traffic ratios, transportation processes, dwell times, etc. The determination of load repetitions generally refers to 1 year. Forecasts on specific traffic have to be integrated and thus have to be assessed sufficiently precise. In this respect, the probabilities of occurrences of various container weight combinations have to be considered when defining design loads. Depending on the operational concept, different equipment is used to handle the containers. Table 7.3 summarizes load characteristics for different equipment types.

7.4 Pavements

Considering the importance of subgrade quality for the durability of heavy duty pavements, the present section introduces proven pavement alternatives for the different operational areas of container terminals. Additionally, the advantages and disadvantages of each pavement type are mentioned.

7.4.1 Subgrade

Damages to heavy duty pavement implemented in port areas often stem from a poor subgrade quality. If the bearing capacity of the subgrade is insufficient, damages will influence the whole cross section of the pavement, resulting in costly repairs. Therefore, special care should be taken when defining subgrade requirements. According to Knapton (2007, p. 51) *"Heavy duty pavements cause significant stresses to develop at much greater depths than it is the case with highway pavements. Therefore, the CBR of soils must be measured at deeper locations than formation. No specific depth can be given for site investigation. Conventional proof rolling may be insufficient to discover a layer of weak material at depths which may cause a heavy duty pavement to fail."*

Based on the author's own experience from numerous projects, subgrade material should be suitable for compaction to achieve a modulus of deformation of

Table 7.3 Container terminal equipment loads

Type of equipment	Utilization	Dead weight (kN)	Axle load (unloaded front/rear) (kN)	Max. axle load (front/rear) (kN)	Wheel load (unloaded front/rear) (kN)	Max. wheel load (front/rear) (kN)
Straddle carrier (1-over-3-high)	Cont. stacking/transporting	550–650	~435/~425	All 8 wheels (evenly loaded in the static state)	~82/~82	~144/~144
Reach stacker	Cont. stacking/transporting	370–410	~220/~170	~372/~105	~55/~85	~93/~52,5
Reach stacker	Cont. stacking/transporting	65–1050	~435/~424	~1170/~256	~110/~212	~300/~130
Empty container handler	Empty cont. stacking and transporting	340–420	~244/~127	~ 380/~80	~61/~63.5	~95/~40
Automatically guided vehicle	Horizontal container transport	~265	~133/~133	~433/~433	~67/~67	~217/~217
Public road truck	Transport of containers	~120	~50/~45	~75/~110 (max. 115)	~25/~22	~37.5/~55

$Ev_2 \geq 45$ MN/m^2. In case the required subgrade compaction is not achievable, a capping layer between the sub-base and subgrade or a thicker sub-base must be placed. Furthermore, the drainage permeability of the subgrade is to be considered. In general, intensive subsoil investigations have to be carried out to ensure a stable design basis.

7.4.2 Heavy Duty Pavement Types

7.4.2.1 General Aspects

When designing the pavement of container terminals, a broad variety of proven combinations of materials may be considered and validated. As there is no standard solution for the pavement design, practical and individual experience of the terminal operator, with regard technical criteria, dominate the decision. These criteria include

- Availability of materials
- Local construction experience
- Durability
- Resistance to chemical exposure
- Resistance to physical exposure (temperature, abrasion, impact, dynamics of driving, and load)
- Wear and tear of equipment wheels
- Ease of repair and remodeling
- Construction costs
- Operational and maintenance costs.

Some exemplary pavement types designated to specific operational terminal areas and proven in heavy duty terminal operations are given below:

- Cast-in-place concrete pavement
- Interlocking concrete block pavement
- Asphalt concrete pavement
- Polymer-modified asphalt concrete and split mastic pavement
- Gravel bed.

7.4.2.2 Cast-in-place Concrete Pavement

The cast-in-place concrete pavement (see Fig. 7.1) is regarded as a very rigid pavement form, providing a durable and hard-wearing surface that can withstand high contact stresses. It consists of 300 mm thick cast-in-place concrete, a 250 mm thick base of wet lean concrete on a 150 mm thick sub-base of aggregates.

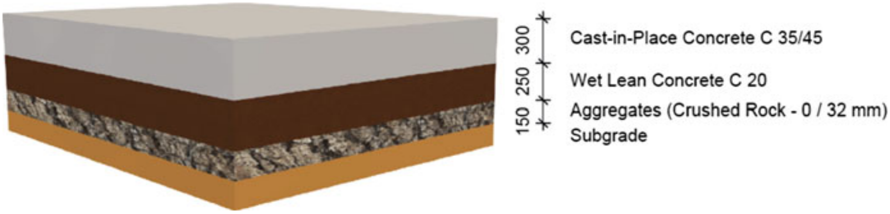

Fig. 7.1 Cast-in-place concrete

Advantages

- Smooth surface resulting in minor wear and tear of terminal equipment.
- High load-bearing capacity and no permanent deformation under concentrated load; concrete pavement is generally resistant to rough usage.
- Excellent resistance to high temperatures and chemicals, especially to oil spillage.
- Materials and construction equipment are available in most countries.

Disadvantages

- Future changes of the terminal operation that necessitate higher design loads will often require a removal and replacement of the concrete pavement; adaptations to operational changes are generally difficult or even impossible.
- Conditionally suitable for areas where major settlements occur.
- Repair of distressed concrete surface (failures, cracks, and deformations) is very difficult and expensive.
- No adjustment is possible to cope with differential settlement. Subgrade settlement cannot be accommodated without excessive cracking due to the high rigidity of the material.
- Cracks and flaking caused by corner fittings of the containers.
- High construction costs per area unit.

Recommendation

– Suitable for hazardous goods container stacking areas, tank container stacking areas, maneuvering and handover areas, gate areas, and other operational areas (e.g., washing bay or repair and maintenance facilities).

7.4.2.3 Interlocking Concrete Block Pavement

When comparing concrete pavers to asphalt concrete and cement concrete, concrete pavers are preferred in many cases for the following advantages:

- Resistance to heavy loads
- Resistance to horizontal loads

- Ease of access to underground utilities and replacement of paving units
- High abrasion resistance
- Rapid draining
- Can be individually colored for pavement marking
- Can be placed manually by hand labor or with the use of machinery
- Immediately ready for traffic upon installation
- Can move with settling grounds and can take substantially more rutting than other pavement types and still remain serviceable
- Can be easily removed and reinstated.

In recent years, concrete pavers have, from the authors experience, become the most commonly used and successful form of surfacing for container terminals throughout the world. This pavement type also withstands concentrated repetitive loads, while combining the high durability of the hard surface with the flexibility associated with asphalt pavement types. Subsoil settlements may be levelled easily and without sophisticated equipment, if surface adjustments are necessary.

In general, local suppliers make concrete pavers readily accessible and economically desirable. Also, concrete block pavement can be used for all applications and all loading areas, whether light, heavy, or static turning loads. The use of one surfacing type for the entire terminal area rather than a mix of, e.g., Portland cement concrete and asphalt concrete pavements allows for greater flexibility in the allocation of terminal areas.

The concrete block pavement consists of 100–120 mm thick pavers, $\geq$ 30 mm of sand on 300 mm of *C*ement *B*ound *M*aterials (CBM) *class 4* as a base, and 150 mm of crushed rock as sub-base, see Fig. 7.2. In high frost influenced regions, the CBM layer should be modified with two aggregate layers, min. 25 cm each, and additional geo grid reinforcement, see Fig. 7.3.

Advantages

- High load-bearing capacity and no permanent deformation under concentrated loads; concrete block pavement is resistant to rough usage.
- For small-sized areas the execution of works has its advantages in terms of stable quality and workflow flexibility.
- Good resistance to high temperatures and chemicals, especially to oil spillage.

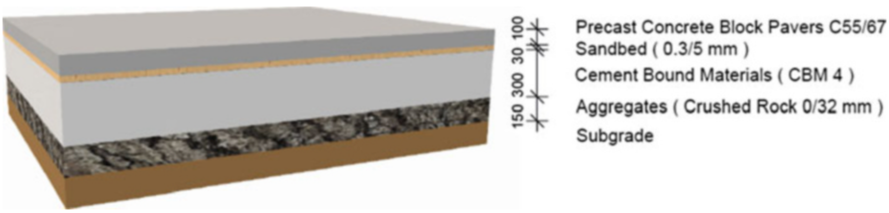

Fig. 7.2 Concrete block pavement – CBM base

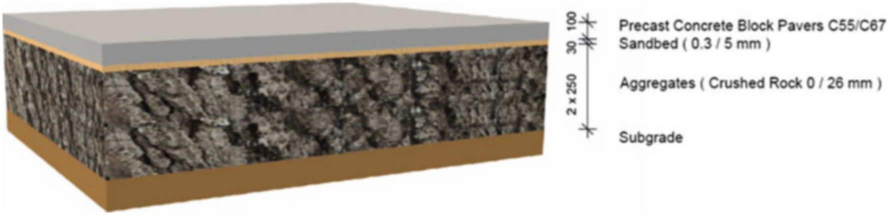

Fig. 7.3 Concrete block pavement – aggregate base

- Full strength achieved in off-site curing which allows for immediate use at full design load after laying.
- Tensile cracking of pavers does not occur, and the surface can accommodate extensive deformation without damage.
- Pavers are easy to remove and replace if needed for settlement adjustment or operational changes (i.e., converting general cargo terminal to container terminal).
- Sandbed is suitable only in regions which are not influenced by temperature below 0 °C – otherwise a cement-sand-mixture has to be considered instead of sandbed.

Disadvantages

- Heavy point loads can cause local dents and cracks. Load transfer due to insufficient bonding between pavers is worse in comparison to cast-in-place concrete or large concrete slabs.

Recommendation

– Suitable for empty container stacking areas, reefer container area, and the internal terminal road network.

7.4.2.4 Asphalt Concrete Pavement

Asphalt concrete, also known simply as asphalt or AC (in North America), is a composite material commonly used for the construction of pavement, highways, and parking lots. It consists of bitumen and mineral aggregate being laid down in layers and compacted subsequently.

Asphalt-based pavements are considered to be very flexible, and therefore this pavement type has been applied in many ports throughout the world. Surface cracking caused by excessive differential settlement can be repaired as easily as rutting by replacing the destroyed worn areas with new ones, while extensive surface settlement can be adjusted by placing of overlays.

The most common type of bituminous pavements is asphaltic concrete that consists of a certain bitumen-aggregate mixture. Unfortunately, asphaltic concrete

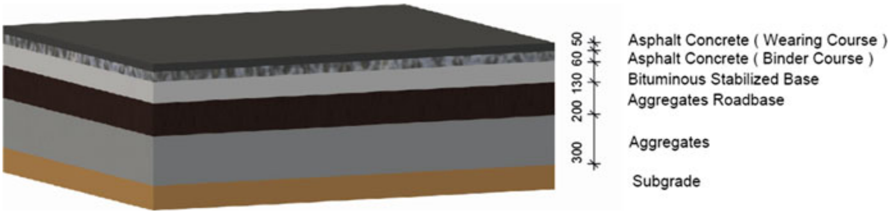

Fig. 7.4 Asphalt concrete pavement – bituminous stabilized base

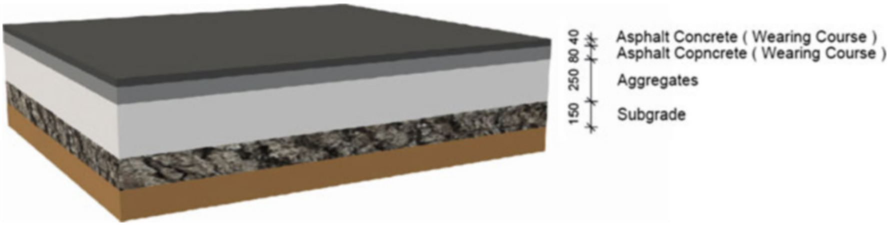

Fig. 7.5 Asphalt concrete pavement – CBM base

tends to form indentations under high wheel loads, high contact stresses (e.g., caused by corner castings of containers), and low vehicle speeds.

Asphalt concrete pavement is selected for roads and areas that are predominantly utilized by licensed public trucks and for container stacking areas. The base of asphalt concrete pavement can either be built with a bituminous stabilized base (see Fig. 7.4) or with a wet lean concrete/cement bound material base (see Fig. 7.5).

Repeated concentrated loads result in permanent deformations. Therefore, only asphalt concrete with special additives (hardener), such as polymer-modified bitumen, should be applied on roads and areas subject to heavy port vehicles as well as equipment and areas where traffic is channelled.

Advantages

- Smooth surface resulting in minor wear and tear of terminal equipment.
- Adaptations to operational changes are feasible, e.g., by placing of additional overlays.
- Repair of surface damage (cracks, rutting, and indentations) and correction of surface settlement can be done by overlays or by replacing the distressed wearing course with a new asphaltic layer.
- Comparatively low construction as well as maintenance and repair costs.
- Materials and construction equipment are locally available.
- Construction time.

Disadvantages

- Surface is too soft to carry large wheel loads, especially in case of low vehicle speeds.

- Permanent deformation under long-term concentrated loads, especially under corner castings of containers. Special load distributing measures need to be provided.
- Poor resistance to high temperatures (if not designed specifically) and many chemicals, e.g., oil and oil products, which slowly dissolve the bituminous binder.

Recommendation

- Suitable for terminal access roads or main internal roads.
- Suitability for container stacking areas and internal terminal road network only in combination with special additives (hardener) such as polymer-modified bitumen.
- Bituminous paving requires particular consideration of material recipes, suitability tests by a qualified site supervisor with experience in laboratory knowledge and laboratory support, respectively.

7.4.2.5 Polymer-Modified Asphalt Concrete and Polymer-Modified Split Mastic Asphalt Pavements

In order to reduce costs, base courses of asphalt pavement solutions are usually composed of a cement-stabilized base layer (see Fig. 7.5) or rather thick granular layers as illustrated in Fig. 7.4. Modified solutions to reduce costs implement a cement-treated base (see Fig. 7.6) or a gravel base (see Fig. 7.7) of moderate thickness, optionally reinforced with geogrids placed within the base course or directly on the subgrade.

Furthermore, state-of-the-art pavement design includes the application of polymer-modified or rubberized bitumen in order to improve the physical and mechanical properties of the binder. This leads to increased resistance to deformation at high temperatures, due to decreased penetration numbers, higher softening points, enhanced toughness, and higher elastic stiffness.

The proven pavement types shown in Figs. 7.6 and 7.7 comply with relevant port-related static and dynamic requirements while considerably reducing construction costs.

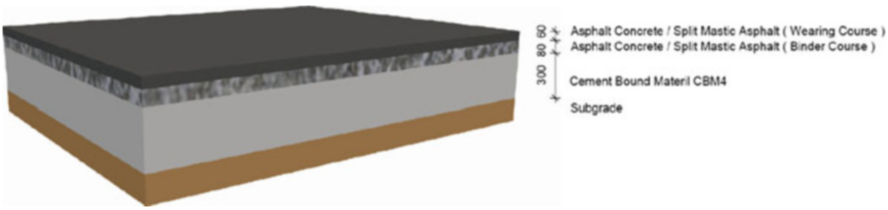

Fig. 7.6 Variant 1 – Polymer-modified asphalt pavements

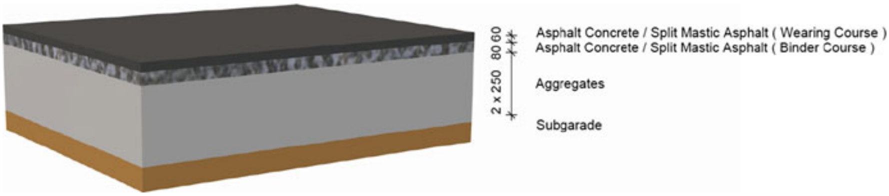

Fig. 7.7 Variant 2 – Polymer-modified asphalt pavements

Advantages

- Smooth surface resulting in minor wear and tear of terminal equipment.
- Adaptations to operational changes are feasible, e.g., by placing of additional overlays.
- Repair of surface damages (cracks, rutting, and indentations) and correction of surface settlement can be done by placing, or by replacing, the distressed wearing course with a new asphaltic layer.
- Relatively low maintenance and repair costs compared to asphalt-based pavements.
- Materials and construction equipment are usually readily available.
- Surface is able to carry large wheel loads, especially in case of low vehicle speeds.
- Permanent resistance to deformations under long-term concentrated load, especially under corner castings of containers; no special load distributing measures need to be provided.
- Economic pavement solution due to reduced thickness.

Disadvantages

- Higher construction costs of wearing course compared to asphalt concrete pavement.
- Poor resistance to high temperatures (without special additives) as well as to many chemicals, e.g., oil and oil products, which slowly dissolve the bituminous binder.

Recommendation

– Suitable for service roads, the internal terminal road network, and terminal access roads.
– Suitable for container stacking areas.

7.4.2.6 Gravel Bed with Container Supporting Beams

A gravel bed solution for the container stacking areas should only be implemented when containers are placed on special reinforced concrete bearing foundation beams (see Fig. 7.8). By doing so, containers will not be subject to unbalanced settlement and lie directly on their corner fittings so that damage of the hull will not occur.

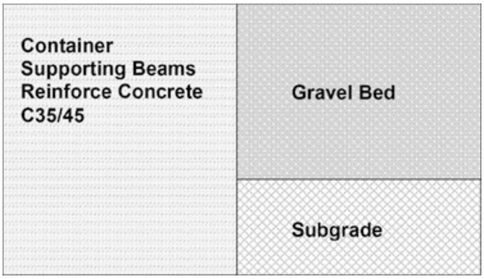

Fig. 7.8 Gravel bed between container supporting beams (thickness: 40–50 cm)

A gravel bed solution for the container stacking areas without concrete bearing foundation, although requiring lower construction costs, is frequently to be rejected for suitability due to the disadvantages listed (following the advantages).

Advantages

- Construction, maintenance, and repair costs are much lower than those of bounded pavement types.
- Gravel beds cannot be damaged by differential settlement and heavy static and impact loads.
- Certain amounts of rainfall may be held temporarily from outflow by the void within the gravel bed.

Disadvantages

- Additional gravel beds and further subsoil improvements can be applied for storage areas being served by gantry cranes operating on rails (*R*ail-*M*ounted *G*antry – RMG) or on reinforced concrete foundation beams (*R*ubber-*T*yred *G*antry – RTG).
- Requires curbing around the perimeter of the gravel to act as an edge restraint and to differentiate the different pavement areas.
- Increased wear and tear of yard equipment, as stones caught in castings drop down on the terminal road network, affecting equipment tyres.

Recommendation

– Suitable for container stacking areas between container supporting beams.
– Supporting concrete beams are suitable for construction of RTG travel paths parallel to the container yard blocks.

7.5 Summary

Table 7.4 summarizes different operational terminal areas and the respective recommended proven pavement solutions. Distinct container terminal areas serve different operational functions. They are exposed to wear and tear from wheel impact of the assigned equipment fleet or from stored containers.

Table 7.4 Wearing courses of different operational terminal areas

Operational area	Type of pavement
Container stacking area	Concrete block pavement
	Polymer-modified asphalt concrete pavement
	Polymer-modified split mastic asphalt pavement
	Gravel bed between supporting foundations
Reefer container	Concrete block pavement
Dangerous goods and tank container storage area	Cast-in-place concrete
	Polymer-modified asphalt concrete pavement
Maneuvering area and handover area	Cast-in-place concrete
Empty container storage area	Concrete block pavement
Internal terminal road network	Asphalt concrete pavement
	Polymer-modified split mastic asphalt or polymer-modified asphalt concrete pavement
	Concrete block pavement
*Ro*ll-on / *Ro*ll-off (Ro-Ro) handling area	Concrete block pavement
General/break bulk cargo handling area	Polymer-modified split mastic asphalt or polymer-modified asphalt concrete pavement
	Concrete block pavement
Heavy cargo/break bulk cargo handling area	Cast-in-place concrete
Gate areas	Cast-in-place concrete
Traffic corridors/terminal access roads	Polymer-modified asphalt concrete pavement
	Polymer-modified split mastic asphalt pavement
Other operational areas with particular pavement requirements (e.g., fuel station, washing bay or repair and maintenance facilities)	Cast-in-place concrete

Though the handling equipment is frequently allowed to operate in several areas or even everywhere within the terminal, distinct areas are to be paved specifically and adapted to their functions, in order to withstand operational requirements as long as possible and to provide the lowest abrasion rates of equipment wheels. It is common practice to limit the number of different pavement types on a container terminal. This approach is based on the aim to increase flexibility, to ease maintenance and repair works, and to achieve lower construction costs.

For the final design of each of the pavements, a thorough analysis is required, based on actual subgrade material characteristics and technical experience gained locally. In addition, the equipment of the operations system in use, local construction experience, and material availability as well as the prospective terminal development determine the pavement selection for a container terminal.

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Chapter 8
Quay Wall Structures in Container Sea Ports and Influences on the Design

Jan Meyer

Abstract The decision for a quay wall construction type for a new container terminal is made at the end of a comprehensive planning process, taking into account local conditions, ecological factors, building and operational aspects and economic considerations. In this chapter, different quay wall construction types are presented as well as it is given an overview of the most important criteria in the process for finding a preferred option.

8.1 Introduction

Main functions of quay walls are to secure a level difference between terminal area and port depth and to provide quay equipment such as mooring facilities, supply connections and crane rails to enable handling operations for discharging and loading of vessels. In addition to earth pressure from soil behind the quay wall and water pressure, which is especially decisive in tidal waters, loads from the terminal operations such as *S*hip-*T*o-*S*hore (STS) cranes, reach stackers, fender loads and bollard pull forces are to be taken into account for the design of quay walls. Wave loading can be important in unprotected ports and, in areas with a high probability of strong earthquakes, seismic loads determine the design significantly.

8.2 Quay Walls: Typical Structures, Equipment and Costs

This section presents some typical quay wall options, which can be the basis for a good design for different requirements. Other quay wall types and sub- or mixed variants of the presented types are available in a large number. Furthermore, major

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equipment components for quay walls are highlighted and a rough estimate of costs is provided to be expected for the building of quay walls. For more detailed information on the quay wall types, please refer to Grabe (2015) and British Standard Institute (2010) as well as Thoresen (2014).

8.2.1 Anchored Sheet Pile Wall with Shielding Slab

This type of quay wall is made of an earth retaining sheet pile wall with anchorage and a shielding slab as shown in Fig. 8.1.

Sheet pile walls for the latest port facilities usually consist of steel king and intermediate piles, so-called combined sheet pile walls (see Fig. 8.2). They are suitable to resist the high earth and water pressures from the large difference in ground levels and carry them by bending into the subsoil and into the anchorage. A saltwater-induced high corrosive attack to the sheet piles must be taken into consideration in the design by means of additional wall thickness, coating and/or cathodic corrosion protection.

Combined sheet piles can be constructed either on a landside building site or from the waterside. Due to the need for high accuracy for alignment of the king piles, a complex construction technology is required. A shielding slab of reinforced concrete reduces the load on the sheet pile wall by carrying traffic loads and a part of the upper earth load via piles directly into the ground. The soil above the reinforced

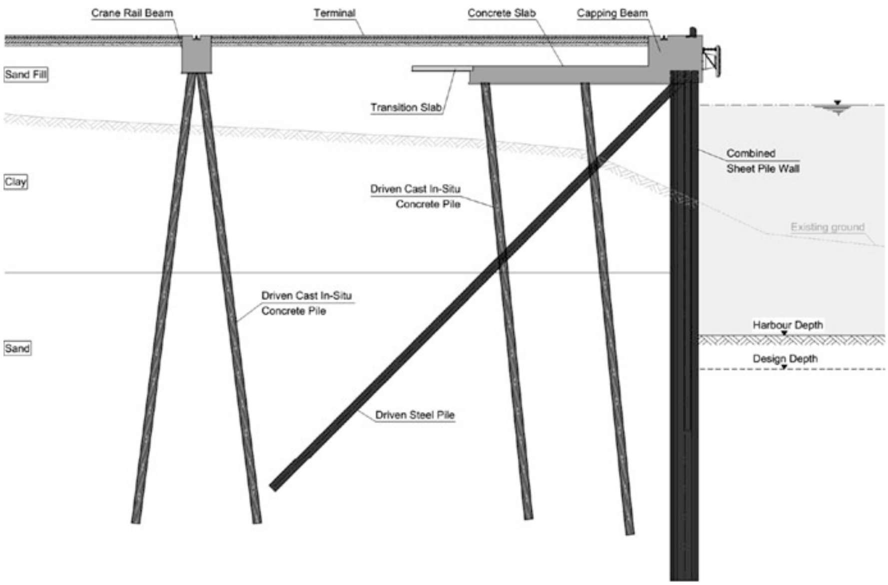


Fig. 8.1 Anchored sheet pile wall with shielding slab (cross section)

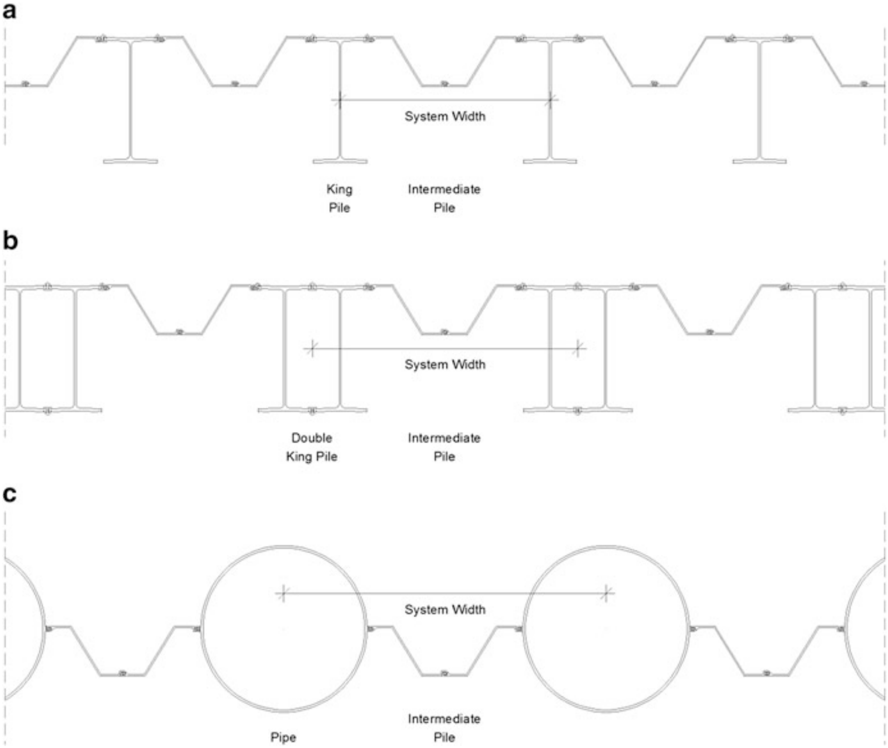


Fig. 8.2 Cross section of different types of combined sheet piles walls (plan view). (**a**) Single King Piles. (**b**) Double King Piles. (**c**) Pipes

slab allows for installation of cables, pipes and pavement up to the capping beam, which forms the water side end of the shielding slab.

The capping beam accommodates the quay equipment such as bollards, fenders and ducts as well as the waterside crane rail (see Fig. 8.1). Figure 8.3 shows the example of a sheet pile wall set back by fender piles combined with a slope under the shielding slab, which reduces the load on the sheet pile wall. Due to the deep foundation of the shielding slab, the quay apron is unaffected by settlements in the case of underlying soft soils. An additional transition slab (see Fig. 8.1) between the shielding slab and the reclaimed area behind might be useful in order to prevent a mismatch at the surface even after several years of operation. The landside crane beam for the gantry cranes is usually founded separately as the shielding slab is less wide than the crane rail span. A pile foundation is used for the beam if soft soil layers are present (see Figs. 8.2 and 8.3). For anchorage of the quay walls, many different systems are available. Common to all of them is that they generate their bearing capacity only in stable subsoil:

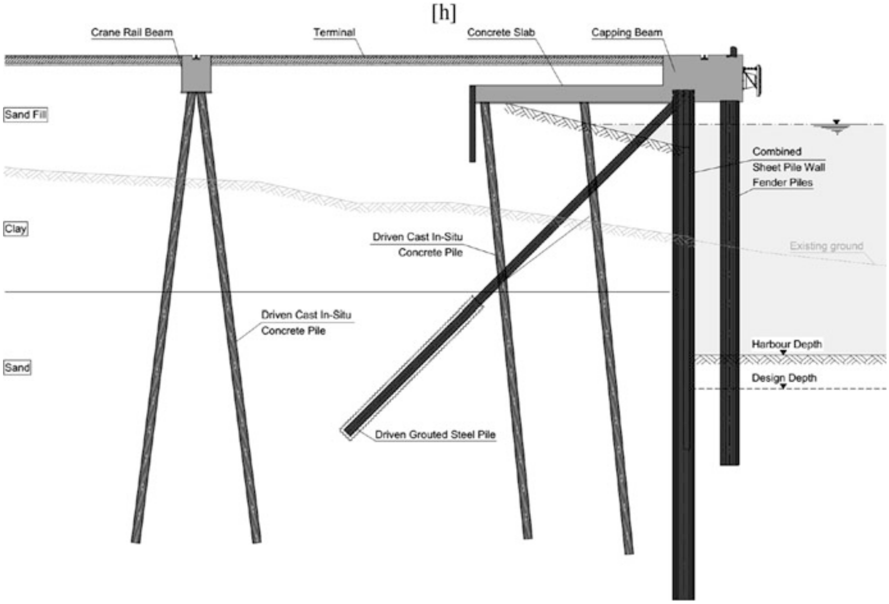
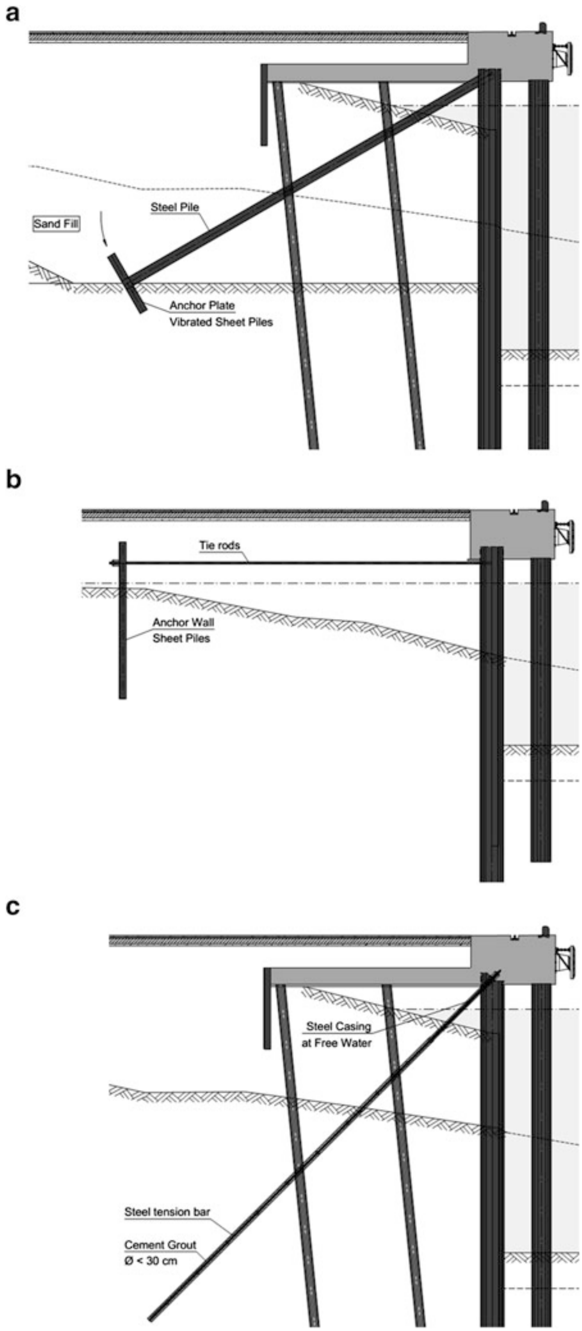


Fig. 8.3 Anchored sheet pile wall with shielding slab, slope and fender piles (cross section)

- Driven inclined steel piles are a very robust anchorage solution. Very high bearing capacities can be achieved with additional cement grout between steel profile and subsoil (see Fig. 8.3).
- Prefabricated raking piles with anchor plates can be efficiently installed at water construction sites; the steel piles are hinged connected to the sheet pile heads and the plates are vibrated in good bearing soil (see Fig. 8.4a).
- Anchor walls connected with tie rods to the quay wall are a solution which can be used at relatively small quays and which can be realized with simple means (see Fig. 8.4b).
- Bored micropiles allow for penetration through obstacles and for installation with low vibration (see Fig. 8.4c). Because of their thin diameter, restraints, as they might occur from settlements of overlaying sand fill in soft subsoil, have to be prevented. Often they are used for strengthening an old wall or building a new one directly in front of an old one.

  Because of their thin diameter, restraints as they might occur from settlements of overlaying sand fill in soft subsoil or similar have to be prevented.

Fig. 8.4 Different types of quay wall anchorage. (**a**) Prefabricated raking pile with anchor plate. (**b**) Anchor walls. (**c**) Micropile



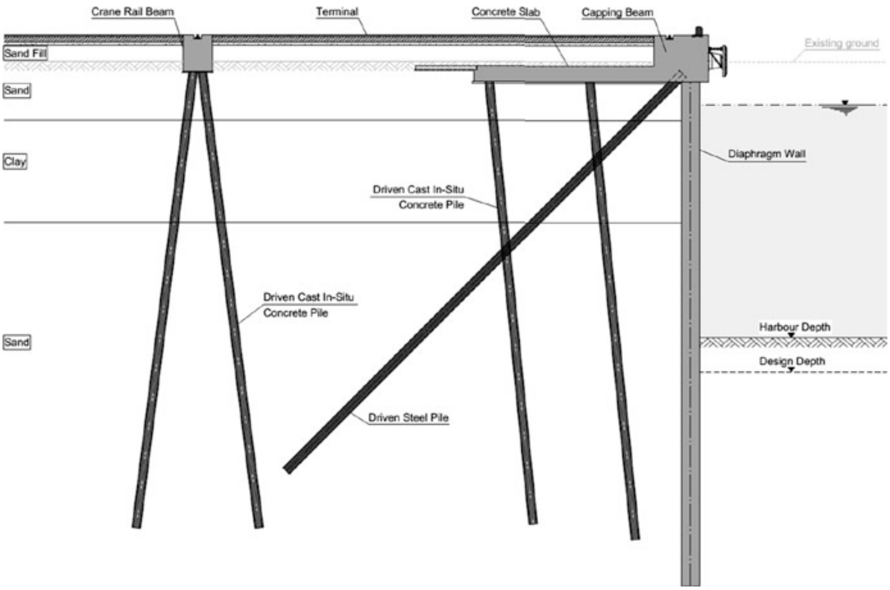


Fig. 8.5 Anchored diaphragm wall with shielding slab (cross section)

8.2.2 Anchored Diaphragm Wall with Shielding Slab

If the quay shall be erected at a land site, the combined sheet pile wall of Sect. 8.2.1 can be replaced by a diaphragm wall (see Fig. 8.5). Diaphragm walls are characterized by a very high bending capacity, can bear very high vertical loads, for example, from STS cranes designed for tandem lift operation, have advantages in the case of obstacle clearance and noise development during construction. The reinforced concrete construction offers a good protection against corrosive attack. Last but not least, it should be noted that diaphragm walls are a very cost-intensive construction type.

8.2.3 Suspended Deck on Piles

For the option deck on piles, a slope is arranged between the terminal height and the port depth. Above the slope, a deep-founded reinforced concrete slab is arranged to form the quay apron. In addition to the vertical loads, horizontal loads must be transferred from the quay apron into the subsoil. Therefore, raked piles are necessary, or vertical piles (see Fig. 8.6) have to be designed sufficiently strong to transfer these loads by bending. Moreover, the vertical piles have to be rigidly connected to the slab. For variants with pile bents, prefabricated concrete piles or

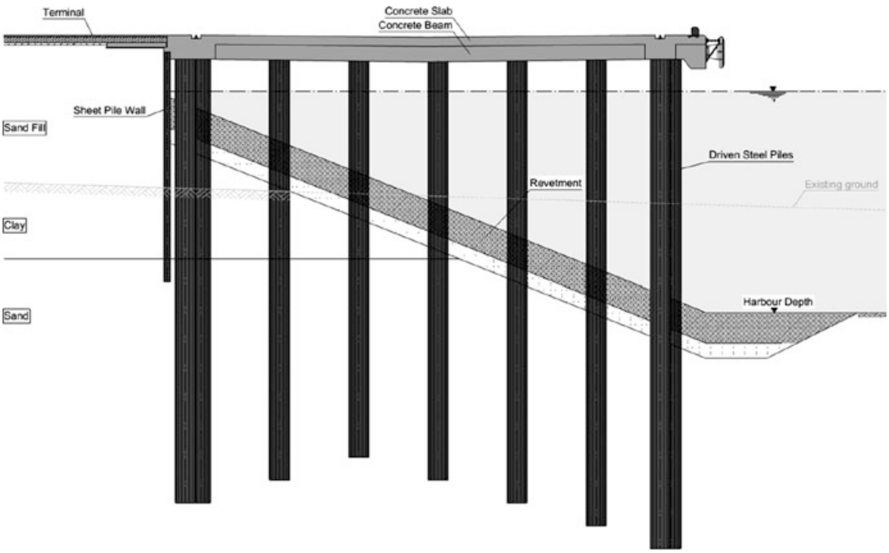


Fig. 8.6 Suspended deck on piles (cross section)

steel pipe piles of small diameter are suitable, for example. For variants with vertical piles only, piles with large diameters are required, which can be steel pipe piles or bored piles.

The reinforced concrete slab can be realized as an in-situ concrete solution or as a combination of precast elements with in-situ concrete topping. Since the slab forms the terminal surface and pipes and cables have to be installed in an empty pipe system within the quay slab, later adaptations to the pipe network are more complex than in other options.

The width of the slab results from the allowable inclination of the slope in the existing or improved subsoil and the required port depth. The slope has to be protected by loose or (partly) grouted rip-rap against wave impact and natural or propeller-induced currents. The length of the slope can be shortened by a sheet pile wall at the landside edge of the quay slab. In general, both crane rails are arranged on the slab, so that the crane span is fixed and no differential horizontal deformations between the rails can occur. Deck on piles can be erected in soft soil conditions, and they are favourable to seismic forces due to their lightweight construction especially with vertical piles only.

8.2.4 Block Wall

Un- or reinforced prefabricated concrete blocks are stacked on top of a prepared load-bearing foundation to form a block wall (see Fig. 8.7). The construction of a block wall is generally possible with relatively simple construction equipment.

Since the weight of the wall determines its stability, terminals with large water depths require large blocks. The maximum block size is dependent on the available (floating) crane equipment. The requirements can be reduced with prefabricated hollow blocks, which are weighted with a stone filling after placing. Extensive diving work is required during the preparation of the foundation level, placing of blocks and other control works.

The top of the wall is formed by a capping beam of in-situ reinforced concrete, which takes up the quay furniture. The capping beam interlocks with the blocks below to gain a better load distribution for fender loads and bollard pull forces. The landside crane beam is founded separately from the quay wall.

Block walls can be built from the waterside only, except when the water level is lowered below the foundation level during construction to allow dry access. No or very limited soft layers may be present below the foundation level in order to avoid settlements and an inclination of the wall. Preloading of the block wall before construction of the capping beam is often required to prevent future uneven settlement. Washout of the base must be prevented by means of an appropriate scour protection.

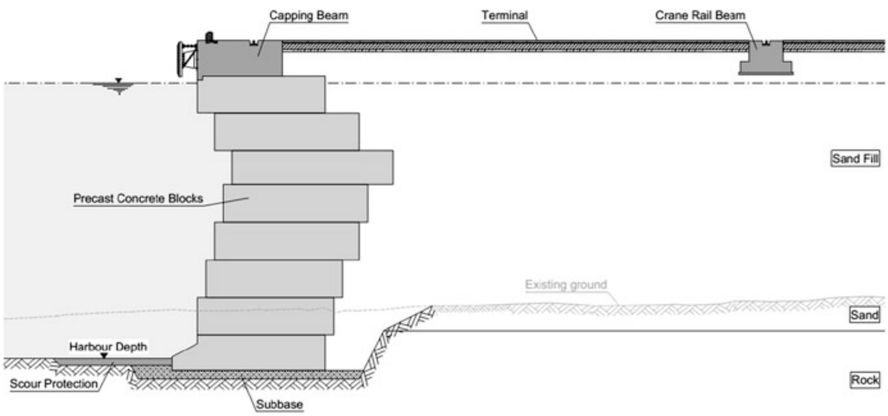


Fig. 8.7 Block wall (cross section)

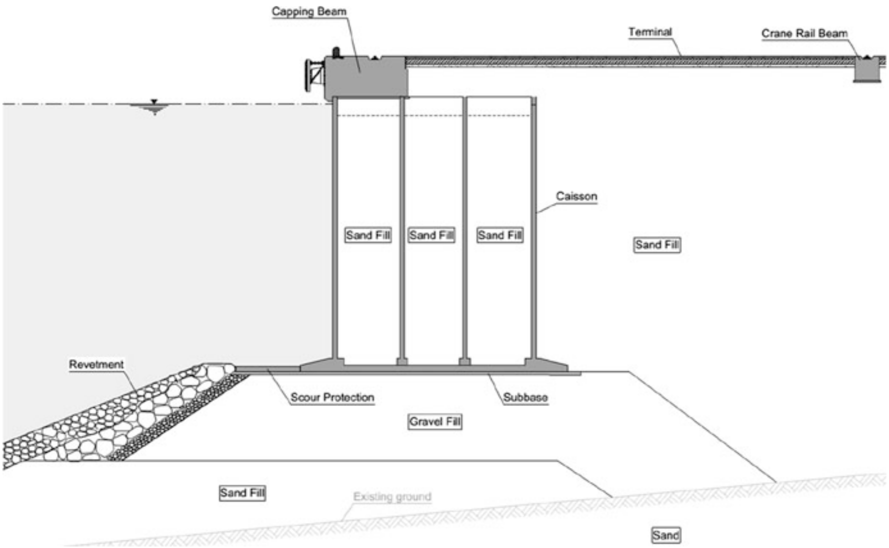


Fig. 8.8 Floating box caisson (cross section)

8.2.5 Caissons

Like block walls, caissons also withstand external loads by their own weight and place high demands on the load-bearing capacity of the foundation. A commonly used type of caisson is a floating box (see Fig. 8.8), a thin-walled hollow reinforced concrete box with an open top. The box is built in a dry dock and floated to site when completed. There, it is lowered to a prepared foundation level by controlled sinking. It is then back-filled with sand, gravel or stones. The capping beam, which is made of reinforced in-situ concrete, stiffens the upper walls of the caisson and takes up the quay wall furniture. The capping beam should not be concreted before settlements due to the caissons are completed. Preloading of the caissons is often required to prevent future uneven settlement. As alternatives, compressed-air caissons or open caissons that are lowered by excavating the soil below their base are conceivable on dry building sites.

8.2.6 Cellular Cofferdam

Cellular cofferdams are dams supported by sheet piles that can be used as quay wall. One type of a cellular cofferdam are circular cells (see Fig. 8.9) which are acting as closed rings, transferring the internal earth pressure loads into tensile ring forces. This quay wall type has no need for anchorage, which might be advantageous in rocky subsoil. Initially, circular main cells are constructed.

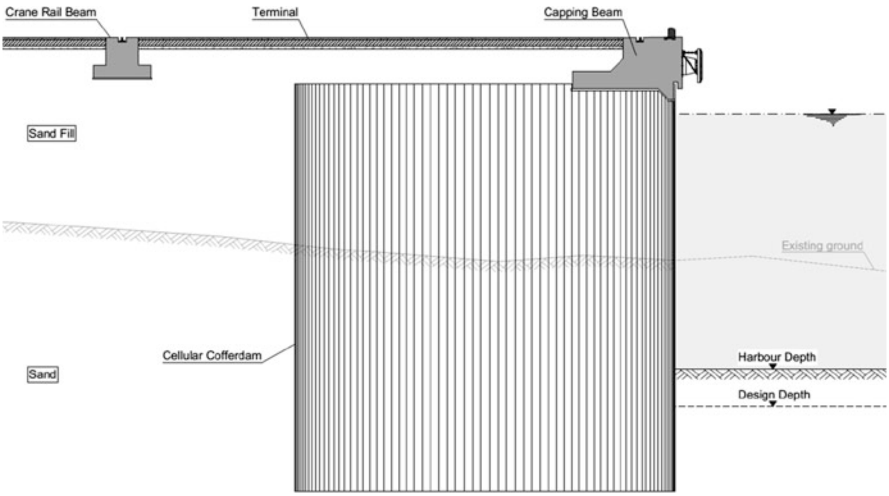


Fig. 8.9 Circular cellular cofferdam (cross section)

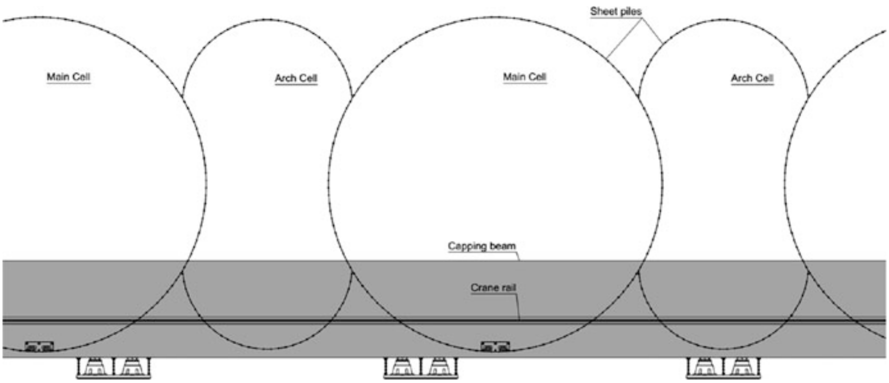


Fig. 8.10 Circular cellular cofferdam (plan view)

Each of them can be individually constructed and filled and is therefore independently stable. Arch cells connect the main cells and form the continuous wall (see Fig. 8.10).

Each cell consists of straight-web steel sheet pile profiles, which are placed on rock or driven into the subsoil, whereby the drivability of the slender profiles can be problematic in dense soils. For the construction of the cells, a temporary guide frame construction is necessary in order to support the sheet piles, because stability of the cells is gained only after filling with sand.

Cellular cofferdams can also be designed as diaphragm cell cofferdams (see Fig. 8.11) if the ring tensile forces exceed the allowable limits at large-diameter circular cells. But single cells of a diaphragm cell cofferdam are not stable due to

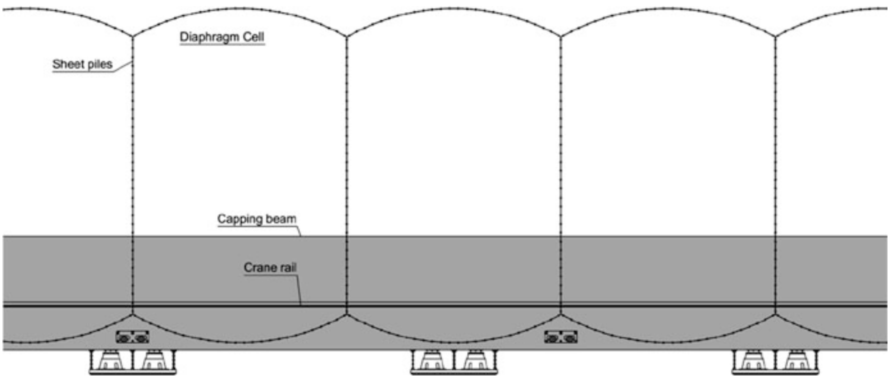


Fig. 8.11 Diaphragm cell cofferdam (plan view)

the lack of the favourable circular shape. This is why a more complex filling concept of the cells has to be followed and a ship collision might lead to a damage of several cells.

8.2.7 Quay Wall Equipment

Nowadays STS cranes at container terminals operate with a rail span of 30.48 m (100 foot), 35.00 m or even more dependent on the outreach and the operation mode (single, twin and tandem). Some quay wall options, such as deck on piles, allow a rigid connection between crane rails and prevent a possible deviation from the nominal distance due to displacements in the ground. The waterside crane rail shall have a minimum distance of about 2.5 m to the edge of the quay to allow the installation of bollards, storing of gangways and line handling (see Grabe 2015) and both crane rails should normally be lowered into the crane beams to allow crossing of vehicles.

For the electrical connection of the cranes, turnover pits (funnel pits) and crane cable channels have to be installed at the capping beam. The cable channel should be covered to protect the power cables against damage (see Fig. 8.12). To lock the crane against horizontal movement in a storm event, locking pits shall be provided to arrest the crane against sliding on the rail. Jacking pits shall be provided as support points for the locked crane. At each end of the crane rails, buffer stops shall be installed. All pits and channels require drainage pipes. Further technical components like bollards, fenders, safety ladders, edge protection of concrete with steel nosing and potable water pits belong to the general term of quay wall equipment as well. Pilots, operators, port authority, etc. shall agree upon quantity and quality of these components to guarantee that all aspects of the handling processes are considered.

Fig. 8.12 STS crane rail with crane cable protection system

8.2.8 Building Costs

Estimation of building costs of a quay wall is a very important result, particularly for the client. In order to achieve reliable costs at the end of the planning phase, it is necessary to incorporate the knowledge of the local conditions and the requirements of the client into the planning process.

Particularly high cost impacts on the finished structure are, for example, the earth and water pressure that should be investigated at a very early stage, the risk of earthquakes at the site as well as the required difference in levels between the port depth and the terminal area. The task of the civil engineer is to determine the most cost-effective quay wall out of the possible options based on the local conditions. As a rule of thumb for construction costs, € 50,000–€ 200,000 per linear meter of quay wall length can be set. Dredging works for access channel and port basin, land reclamation works as well as the building of the terminal surface are also subject to high costs, but are not subject of this chapter and therefore are not included in the costs.

8.3 Considering Local Conditions for Quay Wall Design

With the site selection for a new container terminal, the local conditions are determined as well. Related conditions form the basis for the design of a suitable quay wall structure since they represent restrictions on the solution to be developed for the site. Accordingly, for achieving a feasible and economic overall solution, given local conditions should be taken into account for the design process.

8.3.1 Water- or Landside Building Site

Some quay wall types can only be built if there is an area that is above high water level and into which a port basin is dredged later. These types include "diaphragm walls" or the "suspended deck on piles with bored piles."

If a sufficient water depth of several meters is available for low water, it is possible to work with floating equipment, i.e. from a lifting platform or from a pontoon. "Sheet pile walls with prefabricated raking piles with anchor plates" or "deck on piles with steel pipe piles" are typical options. If the site is a shallow water area, either a working plane has to be filled up or a sufficient water depth has to be dredged. As mentioned above, floating equipment, like floating cranes, jack-up platforms or big pontoons, is required at a waterside building site for some of the quay wall types.

8.3.2 Subsoil

Due to sedimentation of fines, the subsoil at terminal locations is often characterized by thick cohesive soft layers consisting of mud, clay, peat or silt. These soft layers have a low strength and are therefore only very limited suitable for the bearing of vertical loads, e.g., from crane loads, and horizontal loads, e.g., from earth pressure or from bollard pull. By this, the subsoil layering and strength determine the decision for the quay wall construction type as well.

8.3.2.1 Settlements

Soft soil layers lead to large, long-lasting settlements, for example, as a result of a terminal reclamation or back-filling of a quay wall. Since settlements occur mainly due to pressing out of pore water, the impermeability of soft soils causes long periods of relevant settlements, which can last from several years to decades. The settlement can have a magnitude of some meters for soft layers of several meters thickness. At the terminal area, settlements might occur where soft soil layers are loaded by reclamation material or payloads. The installation of vertical drainage into the soft layers is a suitable measure for accelerating the settlements, if high maintenance effort for the pavement shall be avoided. The drains lead the pore water into the adjacent non-cohesive soil layers like sand or gravel. For this purpose, textile strips having a cross section of approximately $10\,\text{cm}^2$ are pressed down to the base of the soft layers. The path taken by the pore water is thus reduced from half the thickness of the soft layer to half the distance between the drains, which also shortens the period of consolidation. The consolidation process will be further accelerated with a temporary preloading of several meter of fill material above the later terminal surface. Besides soil improvement works, like the installation of vertical drainage, structural measures, such as a piled shielding slab or a slab at the transition between a deep-founded area and the land behind, reduce the effect of settlement. Quay walls, as block walls or caissons, or landside crane beams that are erected at a prepared foundation level will settle or incline, if soft soil is present below their base level. In this case, constructions with deep foundations have to be chosen to prevent limitations on the operations or even structural damages.

8.3.2.2 Bearing Capacity

If there is soft soil at the foundation level of block walls or caissons, these quay wall types cannot be realized respectively extensive ground improvement measures such as soil exchange are required. In these conditions, other quay wall types will be a more economical solution. If the new terminal is located in an area with a good bearing subsoil (e.g. sand and gravel), all the above-mentioned quay wall types can be realized. In the case of rocky subsoils, dredging as well as driving or vibrating of piles is possible only with difficulty or measures such as pre-drilling before the installation of piles. In addition to rocks, also stone layers, boulders, high densities and unnatural obstacles can influence the choice of construction method.

8.3.2.3 Contamination

If contaminated soil is present at the construction site, the disposal costs may lead to a choice of a quay wall type, which requires only a small amount of soil excavation. Accordingly, the types “suspended deck on piles with its slope below the deck” and “anchored diaphragm wall with shielding slab with the excavated trench” should be avoided at related sites, for example.

8.3.3 Aggressiveness of Water

Depending on the port location, there are differently aggressive conditions with the salinity and the further composition of the water. In the case of a high aggressiveness, a quay wall of reinforced concrete should be given preference to a steel structure, or durable corrosion protection measures have to be foreseen.

Local experiences, which can be obtained from steel thickness measurement on existing structures, provide a good basis for the design of necessary corrosion protection. If such experiences are not available, reference values are given in Grabe (2015) or in Technical Committee CEN/TC250 (2007).

8.3.4 Maritime-Related Conditions

8.3.4.1 Water Levels/Tide

The design of the quay wall must take into account the periodical changing water levels as well as maximum and minimum water levels to be expected during lifespan. Several works can only be carried out with a high quality standard if the lowest working level lies a few decimetres above the mean tide high water. This applies, for example,

- to concreting of in-situ constructions, since otherwise the formwork had to be cleaned beforehand from mud,
- coating works on steel structures,
- welding works on load-bearing components, e.g. necessary for anchor connections,
- concrete restoration works, etc.

For the choice of fender system, large differences between high and low water may exclude systems such as single super cone fender or cylindrical fender. Under these conditions, floating fenders with large fender tables may be required. The terminal shall be set at such a level that flooding in the case of extreme high water or high waves is prevented. While a high terminal level causes strong and costly quay wall constructions, the installation of a flood protection wall on a lower terminal apron might be an economical alternative.

8.3.4.2 Currents

Currents cause sedimentation and erosion. Maintenance dredging at the berth may be required to restore sufficient port depth if sedimentation occurs. Scour protection or additional design depth may be required if erosion occurs. Currents at the port location influence the mooring manoeuvres of the vessels and must be taken into account, especially when designing fenders and bollards.

8.3.4.3 Waves

Quays are often built in protected port basins and behind breakwaters. If the location of the quay is open to the sea, a wave chamber may be necessary to reduce wave overtopping to the terminal area at high water levels. For example, at the suspended deck on piles (see Fig. 8.6) a wave chamber is formed between the concrete deck and the slope.

8.3.4.4 Icing

Ice load to the structure may be caused by impact through ice floes or by ice pressure through thermal expansion. Structural components such as piles exposed in the water have to be designed for this purpose. Non-structural components, such as ladders or outlets, should be protected.

8.3.5 Wind and Temperature

Wind load on the quay itself is of lesser importance. But with regard to safe mooring, the wind load on the vessels must be taken into account when designing the bollards. Storm bollards, which are arranged further back on the terminal apron, offer reliable mooring at strong winds but are usually difficult to realize due to container terminal operations.

Elongation and shortening of the quay wall construction, which are caused by seasonal temperature variations, can be permitted by means of movement joints. Or, if no joints are built, resulting restraints (inner forces) have to be considered in the quay wall design. High and low temperatures have also to be taken into account during the construction process, as for concreting works or coating works.

8.3.6 Earthquakes

In many parts of the world, earthquakes are a determining load for the design of quay walls. The Global Seismic Hazard Map (see Fig. 8.13) provides a first overview of endangered regions.

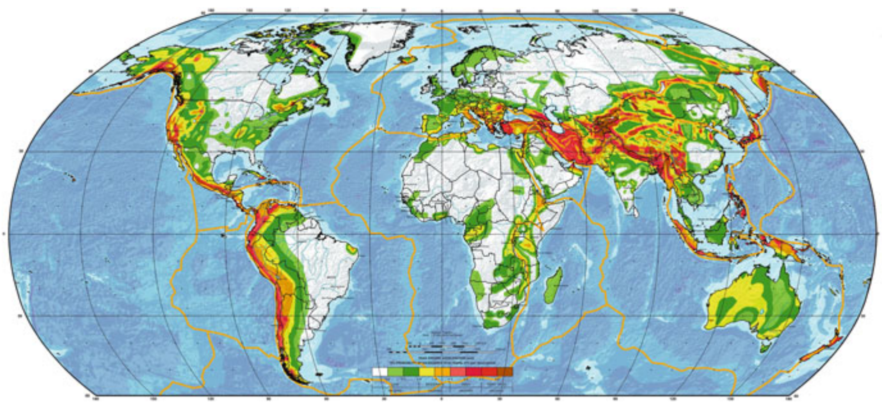


Fig. 8.13 Global Seismic Hazard Map by Giardini et al. (1999)

The design for earthquake resistance requires special considerations. In addition to the weight of the construction and the payloads, back-filling of the quay wall as well as pore and free water is also subject to the mainly horizontally acting mass forces which stress the quay wall and its foundation. This is why these parameters should be kept as small as possible. Stiff quay wall constructions such as anchored quay walls or deck on piles with pile bents have to be dimensioned strongly while more flexible solutions as a deck on piles with vertical piles (see Fig. 8.6) allow seismic energy to dissipate.

8.3.7 Construction-Related Conditions

8.3.7.1 Availability of Materials

In some cases, also the availability of materials influences the decision on the quay wall type and ultimately the specific design of the quay wall. Subsequently, typical examples for related availability issues are highlighted:

- Import restrictions to strengthen the local producers, e.g. for special types of cement, may hinder the realization of sophisticated construction methods such as jointless concrete deck.
- Long transport routes for rock of high strength may lead to high costs for revetments.
- The required dredging of an access channel may lead to huge amounts of sand that can be used for a higher terminal level and shallow slopes.
- Reinforcement and steel girders may be available only in low steel grades.

8.3.7.2 Required Space During Construction

When building a quay wall within an existing port, the temporarily required space can be large in relation to the space available. Sufficient area for storage of materials such as sheet piles, area for the movement of cranes or drilling rigs and area for site facilities, e.g. for the production of blocks for block walls have to be provided. A dock or a shipyard may also be necessary, e.g., for the manufacturing of floating box caissons. In case of renewal or new building of quay walls during running terminal operations, building concepts usually subdivide the quay wall (re-) construction process in several phases. For instance, all measures being necessary for (re-) constructing a single terminal berth are frequently summarized in a related construction phase. This is intended to minimize disturbing influences on the daily discharging and loading of vessels.

8.3.7.3 Man-made Aspects

In many quay wall projects, the site was previously subject to various man-made activities which need to be considered during planning and construction of a new quay wall. For example, existing buildings, quay walls and facilities, explosive ordnances in the subsoil, ship wrecks or pipelines.

8.3.7.4 Restrictions at Existing Ports

If a new quay wall is not planned on a greenfield site but within an existing port, structural constraints as well as operational aspects arise. Some of them are to be addressed in the following. The replacement of a quay wall at exactly the same cope line is often desirable. From a structural point of view, this can hardly be realized, since the old quay would have to be demolished first, which would lead to long slopes and loss of terminal area. Due to the width of the existing quay walls and their anchorages, it is normally not possible to build a new quay wall directly behind the old one. Therefore, it is suitable to build the new quay wall directly in front of the old one into the port basin and leave the old wall untouched behind. This leads to the following considerations:

- To reduce the size of an existing port basin as little as possible, a small distance between the old and the new cope line is necessary. For this, sheet pile walls are suitable, whose anchors can be drilled through the old structure.
- If it is allowed by the new construction and the carrying capacity of the old quay, the existing crane beams can be reused. Then, the length of the crane boom is reduced by the thickness of the new quay wall. But it should be noted that the construction process itself and filling operations can lead to settlements and damages of the crane rails.
- If the old quay was in line with adjacent quay walls, the latter have to be equipped with fenders of greater thickness, in order to obtain a new uniform fender line.
- If the old quay wall is a deck on piles structure, it is necessary to check whether the load-bearing capacity of the existing deck is sufficient for the possibly greater loads from terminal operation during the whole lifespan of the new quay wall. In general, the concrete deck has to be demolished and embankment areas have to be filled up.

If the new quay wall extends an existing one, the cope line of both should be the same. It is necessary to check whether moving of container cranes from one quay wall to the other one is required. In this case the rail span must be kept as it was. The transition has to be designed in such a way that differences in settlements between the crane rails of both sections are avoided. Further restrictions can hinder operations at berths that are next to the site, too. Construction equipment that works at the edge of the site can lead to restraints in the availability of the berths. Bow ropes and stern ropes cannot be moored at bollards within the construction site; therefore, the maximum vessel length is reduced. Additionally, breakage of ropes may require a protection system at bollards that are directly next to site to guard workers.

8.3.7.5 Construction Approach

It may be helpful to design quay walls that correlate with local experiences. This facilitates the participation of local construction companies with their equipment which saves mobilization costs and allows for considering the local conditions, respectively. For example, it might be easier to find a construction company with experience in the construction of combined sheet pile walls in Northern Europe than in many other parts of the world. In Turkey, decks on piles are often built because of the high earthquake risk. Block walls are widely used in Arabic countries due to the good bearing subsoil. Another aspect is that noise and vibrations occur to varying degrees in different construction methods. For example, it might be necessary to exclude driving processes to avoid harmful influence in the vicinity of existing buildings or on species diversity and endangered species.

8.4 Considering Durability and Operations Aspects for Quay Wall Design

8.4.1 Durability of Materials

The main materials that are used for quay walls are steel and reinforced concrete. Both materials are used for the wall itself and for piles that are effected directly by corrosion processes within the saltwater. Coating of steel members can provide a protection for up to 20 years and cathodic corrosion protection needs frequent maintenance. Additional wall thickness extends the lifespan of the steel structure, while it is favourable that the high corrosion rates occur at the low water zone where usually only low stresses occur. Renewal of coating is not common for steel members under water but shall be foreseen for parts above water like bollards. Reinforcement of concrete members shall be covered by a sufficient thickness of concrete cover. The concrete itself has to be durable to combined chemical attack of chloride and sulphate by using a special concrete mix design. The capping beam and the deck, if there is one, are reinforced concrete structures, in general. For these, de-icing chemicals and abrasion through wheels of terminal operation vehicles have to be considered within the concrete mix design as well. With regard to a relatively short lifespan of container terminal quay walls due to changes in port operation or port traffic or deepening of port basins (see Recommendation R46 in Richwien (2006)), both materials are suitable for a design lifespan of a few decades at normal conditions. If high aggressiveness of water or soil is present, reinforced concrete structures might have advantages in durability.

8.4.2 Application of Joints

Settlements of the foundation of a quay wall or thermal expansions may cause restraints and cracks within a structure, if they are not prevented. For this reason, movement joints are often planned at an interval of about 30 m in capping beams and concrete slabs. Disadvantages of this type of construction are higher effort for formworks, additionally required reinforcement at the joints, and an additional load for the piles at the joint edge. Also, spalling of the concrete at the joint edge and erosion due to leaks in the joints can lead to consequential damage and increased maintenance work required. Alternatively, jointless structures are possible, for which the corresponding maintenance works do not apply. However, increased quantities of reinforcing steel are required, as well as higher demands on the concrete mix and the concrete works are made. Jointless structures are preferred for quay walls with earthquake-loading. The determining earthquake-loads lead to a high amount of reinforcement with the effect that no additional reinforcement is needed for restraint inner forces.

8.4.3 Vessel Discharging and Loading Operations

For the increasing loads of STS cranes (twin lift, tandem or quad lift) the vertical bearing capacity of quay wall constructions becomes more important. Because of their greater footprint, diaphragm walls are advantageous compared to sheet pile walls, for example. At the apron of container terminals, *M*obile *H*arbor *C*ranes (MHC) were considered only for small quays or in addition to STS cranes. The apron has to be designed for the high outrigger loads of MHCs, this is why special consideration has to be given at a deck on piles as the slab may not be strong enough to withstand these loads and beams should be located directly below the designated location of the outrigger pads. Other equipment, such as reach stackers and trailers with their high wheel loads may be decisive for some details of the quay construction, such as manhole covers, but not for the quay wall type itself.

8.4.4 Berthing Manoeuvres

For berthing manoeuvres, a closed wall structure is slightly advantageous compared to an open structure, like a deck on piles. In the former case, the water pushed by the vessel functions as an additional buffer, thereby reducing the berthing energy.

8.4.5 Future Development

Over the structure lifetime, demands on the quay wall structure can change. It should be thought ahead whether a reserve for deepening the port basin in front of the quay or heavier STS cranes shall be considered. An over-dimensioning of fender plates can also be useful to consider future development of vessel sizes. For the extension of pipe networks, additional empty sleeves are recommended especially within a concrete deck on piles as it is difficult to add additional sleeves later.

8.5 Evaluation of Quay Wall Construction Types

Based on design and construction requirements which are common in practice, Table 8.1 gives a brief overview on the suitability of the quay wall construction

Table 8.1 Overview of quay wall types

	Quay wall type					
Requirements	Anchored sheet pile wall	Anchored diaphragm wall	Suspended deck on piles	Block wall	Caissons	Cellular cofferdam
Main material at [STEEL]	X		X			X
Water zone [CONCRETE]		X	X	X	X	
Quay wall construction from landside	X	X	X			X
Quay wall construction from waterside	X		X	X	X	X
Subsoil at port depth is of soft nature	X	X	X			X
Later adaptations to the pipe network	X	X		X	X	X
High seismic requirements			X			
Complexity of [HIGH]	X	X				
Construction [MEDIUM]			X		X	X
Technique [LOW]				X		
Fixed crane span			X			
Wave chamber	(X)		X			
Solid against ship impact	X	X		X	X	(X)
Renewal of quay wall short in front of the old one	X					

types presented in this chapter. An “X” indicates that the quay wall type meets the respective requirement well.

However, requirements can be systematically adjusted in connection with the decision on the quay wall type. For example, it is possible to reclaim land at a waterside construction site before constructing a diaphragm wall or to improve soft subsoil before constructing a block wall.

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Chapter 9
The Value of a Cluster and Network Orientation for Container Terminals

Peter W. de Langen

Abstract *C*ontainer *T*erminal *O*perating *C*ompanies (CTOC) are very focused on operational excellence today. Major reasons for this are the dominating position of shipping companies in the supply chain and highly competitive market conditions in many regions of the world. Such a focus on efficient terminal operations causes many CTOCs to put their "own processes" into the center of attention. In this chapter, we argue that in addition to an orientation on the terminal processes, CTOCs benefit from an orientation on the overall supply chain of which they are a part, as well as an orientation on the port cluster of which they are a component. First, the literature on an orientation beyond the company boundaries in general is briefly discussed. Second, the embeddedness of CTOCs in international supply chains is discussed, with examples of how a supply chain orientation is valuable for CTOCs. Relevant issues include information exchange, extended gates, and the revenue model of the CTOC. Third, the role of CTOCs in port clusters is discussed with examples of how a cluster orientation is valuable for CTOCs. Relevant issues include, e.g., education and training, intra-port container flows, and port marketing. The chapter ends with a concluding section providing insights on how CTOCs can improve their cluster and network orientation.

9.1 Introduction

It is widely understood by management scholars that firms are not isolated islands that transact with others across markets, but instead are deeply linked with others through all kinds of relationships. These relationships deeply influence the performance of firms. Various streams of literature emphasize different types of networks and relationships of firms.

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One important stream of literature deals with the embeddedness of firms in *geographical clusters* of related economic activities. This cluster concept has been described already in the nineteenth century by Marshall (1890) and has been popularized in management by Porter (2011). The core concept of this literature is that spatial clustering of interrelated companies provides economic benefits,

- through lower transaction and transport costs of transactions within a cluster (for instance, pipeline networks that connect companies in a chemicals cluster),
- through a better labor pool for companies in the cluster (for instance, the talent pool available in Hollywood's media cluster),
- and through the local spill-over of knowledge (for instance, in Silicon Valley's technology cluster, see Bathelt et al. (2004)).

While scholars have criticized the policy advice derived from cluster studies (see, e.g., Martin and Sunley 2003), in particular, the benefits arising from spatial clustering (sometimes also termed co-location) are widely accepted (see Delgado et al. (2014), van den Heuvel et al. (2014) as well as Sheffi (2012)).

While most of the research has gone into knowledge-intensive clusters, the cluster concept has also been applied to transport and logistics. For example, de Langen (2004) analyzed the cases of Durban, the Lower Mississippi, and Rotterdam and demonstrated these ports can be analyzed as *port clusters* (see also de Langen and Haezendonck 2012). Likewise, Sheffi (2012) analyzed logistics clusters, such as Zaragoza and Singapore and argues for government policies to develop such logistics clusters.

In addition to the embeddedness of firms in spatial clusters, scholars have analyzed the embeddedness of firms in networks in general (see Jarillo 1988). This has, for instance, led to the introduction of the concept of an *extended enterprise* that has been defined as "the entire set of collaborating companies both upstream and downstream, from raw materials to end-use consumption, that work together to bring value to the marketplace" (see Davis and Spekman 2004, p. 20). It has been widely established that such embeddedness in networks influences a firm's competitiveness (see Delgado et al. 2010).

The recognition of the relevance of the embeddedness of firms in clusters and networks also led to research into the *network/cluster orientation* of firms. Such a network (or partnership) orientation is often associated with supply chains (see Mentzer et al. 2000). The benefits of a network/cluster orientation have been established. For instance, Sorenson et al. (2008) found that network orientation is related to company success, and that there is a gender difference: female entrepreneurs are more network oriented than their male colleagues. Regarding ports, the role of ports in supply chains/networks has been addressed (see Song and Panayides 2008), just as the supply chain orientation of ports (Tongzon and Lee 2009). In addition, the relations between terminal operators and users have been studied from a supply chain perspective (see Demirbas et al. 2014).

This chapter addresses the value of a network and cluster orientation for terminal operating companies. Nowadays, quite a few of these port companies are very focused on operational excellence, and for the right reasons. In this chapter, we argue that in addition to an orientation on the terminal processes, terminal operating companies benefit from an orientation on the overall supply chain of which they are a part, as well as an orientation on the port cluster of which they are a component. Both orientations are discussed in the next sections. While this issue applies to all terminal operating companies including those that handle liquid or dry bulk or break bulk cargo, the next sections focus on *C*ontainer *T*erminal *O*perating *C*ompanies (CTOC), as the container segment is a dynamic and fast growing part of the terminal handling industry.

9.2 The Embeddedness of CTOCs in International Supply Chains

CTOCs serve shipping lines as well as shippers and forwarders. Their core service is loading and discharging ships. This is one small part of the overall transport and supply chain, through which raw resources and intermediates turn into end products. For this reason, terminal operations are sometimes regarded as derived demand (see Paixão and Marlow 2003). The costs of terminal operations are often only a limited share of the total door-to-door transport costs. Thus, a network orientation may help CTOCs in creating more value through enabling cost reductions in other parts of the chain. This additional value creation may allow the CTOC to charge higher prices. Following, the truck gate handling processes and opening hours and the integrated ship turnaround processes are discussed as important ways in which CTOCs may influence overall transport efficiency. Finally, the implication of a network orientation for the revenue model of a CTOC is discussed.

9.2.1 Truck Gate Handling Processes and Opening Hours

While virtually all CTOCs are operating 24/7 on the waterside, they have more restricted opening hours on the landside. Such restricted opening hours have sense for the CTOC, as the number of truck arrivals in the evening and night is limited and so closed gates avoid bad resource utilization and save money, respectively. But at the same time, such reduced opening hours carry societal costs, and potentially also increase costs for port users, especially in case of ports in urban areas.

First, restricted opening hours may lead to longer waiting times for trucks (see Bentolila et al. 2016). These waiting times impose costs on the trucking companies[1] and also have adverse effects on pollution (see Do et al. 2016). Second, restricted opening hours may aggravate congestion in the rush hours as truck drivers do not have the option to avoid these rush hours. Longer opening hours are not the only

[1] A conservative estimate is around € 30 to € 40 per hour, for developed economies.

solution, a truck appointment system may also alleviate congestion (see Chen et al. 2013). In such a system, trucking companies need to book a slot to be handled at the terminal allowing the CTOC to influence arrival patterns of trucks (see Huynh et al. 2016).

For these reasons, the "CTOC business case" differs from the "ecosystem business case[2]" for longer opening hours, as the latter business case includes the costs of restricted opening hours for truckers and society at large. A detailed empirical analysis of this issue is beyond the scope of this chapter. The benefits of a truck that is shifted from the peak hours to the off-peak hours are:

- Benefits for other trucks due to reduced waiting times,
- Benefits for other road users due to reduced congestion,
- Benefits to society at large due to reduced emissions.

The last two effects are regarded by Bentolila et al. (2016) as external effects. They are jointly estimated to be around \$30 per truck shifted to the off-peak period. Holguín-Veras et al. (2011) calculate that in the case of the port of New York and New Jersey, these total benefits are sufficiently high to provide a large number of receivers with a significant subsidy to shift cargo to off-peak hours. Thus, it is important to note that a network orientation does not mean that a CTOC would cover all costs of longer opening hours, it does mean that a CTOC takes an active and constructive approach towards joint initiatives to develop schemes to provide financial incentive for the CTOC to offer its users longer opening times. As one example, the program of the terminals in Los Angeles and Long Beach works with an additional fee for truck arrival in the peak period (of more than \$60 per truck) to partially offset the costs of longer opening hours for the terminals.[3] In Israel, the government owned port authority pays an incentive of around \$25 per truck for nighttime delivery. This resulted in roughly doubled nighttime volumes (from below 4% to over 7%), but well below the target of 25% nighttime delivery (see Bentolila et al. 2016).

9.2.2 Integrated Ship Turnaround Processes

While shipping lines clearly press CTOCs hard for increased terminal productivity and consequently reduced *terminal* turnaround times, ultimately, what matters most is the *port* turnaround. This port turnaround time includes the time a ship is waiting for *tugs*, *pilots*, *bunkering services* as well as *terminal operations*. Consequently, all these actors play a role in improving port turnaround times, together with the port authority that is in charge of the vessel traffic in the port. Often, more coordination

[2]A business case in which the benefits of longer opening hours for all stakeholders are taken into account.

[3]These costs are especially high given the strong labor unions and resulting high wage levels.

can reduce turnaround times. As one example, more accurate information from the CTOC regarding the estimated end of the cargo handling operations allows the pilots and towage company better planning of their resources. Likewise, information on the most appropriate departure slot (because of locks or heavily utilized access channels, pilot availability, etc.) is valuable for the CTOC, since, if needed, the terminal may align its operational processes to local conditions hampering the port departure of ships. A CTOC with a network orientation may be more likely to share information with benefits for third parties than a CTOC focused on internal processes. One example of a port where such coordination is promoted is Rotterdam, where a project termed “Port Call Optimization” aims to reduce turnaround time through better coordination.[4]

9.2.3 The Revenue Model of a CTOC from a Network Perspective

Prices send the “signals” in the sense that the behavior of (potential) customers is directly influenced by pricing. For instance, pricing structures with premiums, rebates, and discounts all influence purchase decisions. In the same way that restaurants may give discounts on weekdays, CTOCs may give discounts at off-peak hours, for example. The pricing structure of a CTOC can create alignment between various components of the supply chain. *Four aspects* of pricing are relevant in this respect.

First, CTOCs may benefit from developing *extended gate services* or *hinterland services*. Various CTOCs, such as ECT in Rotterdam, Hamburger Hafen and Logistik AG (HHLA) in Hamburg, the BEST terminal in Barcelona, and SIPC in Shanghai, in some cases through subsidiary companies, are active in this respect. The introduction of hinterland services extends the “service bundle” of the CTOC and can appreciably increase the competitiveness of its terminal(s) in comparison to other facilities in the region (see Biermann and Wedemeier 2016). Furthermore, such an extension is attractive from an operational perspective: a CTOC that manages flows to inland terminals has more information about the transport mode and timing of the containers. This information reduces operating costs, for instance, because containers can be stacked more efficiently (see, e.g., Jürgens et al. 2011). In addition, the CTOC can reduce the “dwell time” at the deep-sea terminal, by moving containers faster to hinterland destinations, which generally have a lower yard utilization as space is less costly. Thus, a revenue model around hinterland services may yield operational advantages and may also be commercially attractive. Such an effort to develop an inland network is especially interesting for a CTOC that operates in a port with calls from a large number of shipping lines. Each of these

[4]See PoRA (2017). A second relevant initiative is the EU funded project “Sea Traffic Management” for enhancing coordination of all parties involved in freight flows at sea and in port, see EU (2017).

shipping lines controls a fairly small volume of containers – namely those that are booked as "carrier haulage" with the respective shipping line (see Rodrigue et al. 2010). In comparison, especially in ports with one terminal operator, this operator handles all volumes in the port and thus can create scale economies by managing flows to inland terminals (see van den Berg and de Langen 2015).

Second, the *pricing for storage of containers* may benefit from a network perspective. Shipping lines generally negotiate agreements about the number of free storage days. However, the storage of containers at deep-sea terminals creates value not for the shipping lines but for their customers: the shippers. CTOCs may seek to introduce direct partnerships with large shippers regarding storage fees, rather than having indirect relationships only. Especially for import containers that move to final destinations by road, the storage at the container terminal is efficient. An alternative storage location would result either in additional handlings or in more container storage at the site of the shipper, which may result in high costs for shippers. Thus, storage fees are better viewed as prices for a product that creates value for users than as a mechanism to reduce dwell time at the terminal (see Kim and Kim (2007) as well as Lee and Yu (2012) for a more detailed treatment of pricing for storage). This issue is especially relevant for container terminals that are not operating at full capacity – quite common at many facilities due to the gap between expectations and realized volumes in the past years.[5]

The third issue where a network orientation is useful is the issue of *pricing for inland handling moves*. Often, competition between ports is fiercest for intermodal container volumes. Container terminals at Rotterdam and Hamburg compete fiercely for containers to/from Bavaria, and the US Eastcoast and Westcoast ports compete fiercely for container to Chicago. By contrast, competition is more limited for short haul containers that move by road. Thus, CTOCs may seek to differentiate prices for containers destined to *captive hinterlands* versus *contestable hinterlands*. The most straightforward instrument in this respect are the prices of inland handling moves at the hinterland interfaces of a container terminal: charge premium prices for truck handlings and competitive prices for intermodal services, that is, lower prices for barge and rail moves. Alternatively, a discount on handling fees for shipping lines (carrier's haulage) or sea freight forwarders (merchant's haulage) that have higher shares of intermodal containers is worth exploring (see, e.g., Robinson (2006) for an analysis of options to create value in landside transport chains). In Spain, many port authorities apply pricing differentiation based on the hinterland mode. However, there is no public pricing information on the landside pricing of CTOCs. In relation to this, CTOCs currently generally do not have contractual relationships with inland transport companies (truck, rail, and barge). The "inland move" is paid by the shipping line (or the sea freight forwarder), who passes these costs on to the shipper or inland forwarder through the "terminal handling charges." Even though this pricing structure makes sense from a transaction cost perspective,

[5]The issue was also addressed in a McKinsey publication on the container terminal industry, see Glave et al. (2014).

it prevents the introduction of incentives by the CTOC to align their interests with those of the inland transport companies. For instance, CTOCs could incentivize off-peak delivery by trucks as well as combining delivery and pick-up trips. For barge transport, CTOCs could offer quantity rebates to incentivize larger call sizes of barges (see Konings et al. 2013).

The final issue for which a network perspective may be relevant is the presence of peaks at the truck gates of the terminal and the ability to use price differentiation to "shave off" these peaks. While from an "operations" perspective, peaks incur costs and are best removed, the network perspective suggests that the peaks are a consequence of the design of supply chains. Shippers often have specific time windows for the delivery of containers. These reduce the flexibility for delivery of containers and thus lead to peaks, generally in the morning, when truckers start with picking up a container to deliver it in the morning, and at the end of the day, when truckers pick up a container and leave it on the truck overnight to secure timely delivery the next morning. These peaks are the result of a supply chain design that is efficient, even though it incurs costs at the terminal (see Phan and Kim 2015). Consequently, solutions for this peak may not lie in differentiated prices during the day. Alternative solutions include container yards that function as buffer for the deep-sea terminal (sometimes called "extended gates" or "transferia," see Veenstra et al. (2012)) other systems for decoupling the pick-up of the container from the delivery, as is the case in a chassis exchange system proposed in Dekker et al. (2013)[6] or better predictive tools for truck waiting times at terminals.[7]

9.3 The Role of CTOCs in Port Clusters

An increased understanding of the embeddedness of companies in ports/logistics clusters is emerging. Various scholars have analyzed spatial clustering in ports (see de Langen and Haezendonck 2012) or logistics nodes in general (see Sheffi 2012; van den Heuvel et al. 2014).

9.3.1 Co-location Benefits for Container Terminals at Ports

The core characteristic of spatial clusters is that companies derive benefits from co-locating in the same area with related companies that are active in identical or

[6]This proposal is based on industry interest, but never materialized. The idea is to place containers on another chassis in a location close to the terminal, allowing the truck to make a fast turnaround. The containers would then be delivered to the terminal in off-peak periods. The "business case" is positive when the benefits from reduction in turnaround are higher than the costs of additional transport to the terminal.

[7]See, e.g., APM (2017).

similar business areas and supply chains. This applies to a chemical plant that is located next to an oil refinery, or a cold storage warehouse that is located next to an LNG terminal to re-use the "cold" required for the re-gasification of the LNG. It also applies to the co-location of warehousing in the vicinity of a container terminal, as well as two container terminals located next door. These co-location benefits are generally not incorporated in the location decision of the "anchor companies" in the cluster. An understanding of co-location benefits is relevant for CTOCs, as container terminals create a demand for land in the vicinity of the terminal, such activities as warehousing, truck parking, and empty container depots. Thus, the decision to invest in a terminal drives up the land prices in the vicinity of the terminal.[8] CTOCs can decide to develop the terminal *and* the adjacent land. This was, for example, done by DP World in their London gateway terminal. The logistics park in London gateway covers about 300 hectare, more than the container terminal area. However, this approach is the exception rather than the rule, partly because most CTOCs develop a terminal portfolio based on bidding for concession contracts from landlord port authorities; in this case they may not be in a position to also develop the logistics park.[9] In addition, the presence of co-location benefits is common, but how large these benefits are depends on investments, both by the CTOC and the port authority, to enable seamless connections between the terminal and the adjacent warehouses. An investment in a specific transport corridor between the terminal and the logistics park with a separate terminal gate and a premium service (such as the Container Exchange Route in Rotterdam) is an example of an investment that increases colocation benefits. Another example of a measure to increase colocation benefits is issuing permits for the use of container tractors (specifically designed for short distance container transport, e.g., a seat that can be turned when the vehicle drives backwards) on public roads in the logistics park. These permits are, for instance, in place in the inland container terminal in Tilburg[10] (The Netherlands) making the "last mile" from the terminal to the warehouse much more efficient. The use of such tractors can significantly reduce the costs of the short haul moves between the terminal and the logistics zone; further cost reductions can be achieved with permissions to pull multiple trailers.

In addition to the benefits of co-locating warehousing and value added services in the vicinity of terminals, there are also co-location benefits due to the location of various terminals in the same area. For example, this may provide sufficient scale for investments in rail terminals,[11] some form of labor pooling between the terminals, and shared services such as security and potentially also in the field

[8]This mechanism is also relevant for airports, where the investments in "airside facilities" create huge passenger flows that drive up the value of "landside" assets such as retail and leisure space.

[9]For instance, in the case of Hamburg, the HHLA operates the Container Terminal Altenwerder and the Hamburg Port Authority develops the adjoining zone destined for transport and logistics companies.

[10]See BTT (2017) for the Barge Terminal Tilburg.

[11]See, e.g., the near-dock railyard ICTF located about 5 miles away from the ports of Los Angeles and Long Beach, LA (2017).

of truck appointments, see, e.g., Port Botany.[12] For CTOCs, awareness of the value creation through co-location and investments to enlarge this value creation is valuable in developing partnerships with landlord port authorities and nearby competing terminal operators.

9.3.2 The Case for Collective Action in Port Clusters

An additional issue derived from the cluster perspective deals with collective action. Cluster studies have highlighted the important issue of *collective action* in ports/logistics clusters (see de Langen and Visser 2005). While one part of the cluster benefits emerges "spontaneously" as a result of "normal" profit maximizing behavior, cluster benefits also partly depend on the extent to which collective action emerges. Collective action does not emerge "spontaneously" or "instantaneously" but it requires cooperation between all relevant firms in the cluster. A *C*ollective *A*ction *P*roblem (CAP) occurs when even though collective benefits exceed (collective) costs, firms cannot be induced to contribute to these costs because it is not in their (direct) interest to do so nor can they be obliged to do so (see Olson 2003). This "free rider" problem is relevant when firms cannot be excluded from benefits, i.e., the benefits are a kind of "collective good." CAPs are widespread, ranging from voting in elections to overusing natural resources. Since firms in clusters have similar interests, CAPs are relevant in most clusters (see Nadvi (1999) for a widely cited example).

In clusters, collective action may or may not develop. When collective action arises, the cluster as a whole becomes more competitive. Collective action is more likely to emerge in the following cases:

- When individual and collective benefits can be combined in one "package deal" (see Olson 2003).
- When there is a widely shared sense of community among firms in a cluster.
- When there are a few large firms in the cluster, because these firms get a substantial part of the benefits. A specific case of this is the presence of a (government or privately owned) cluster development company that operates a "landlord" business model. Examples include a shopping mall developer or a landlord port authority.
- When public organizations actively promote collective action.

Given the wide variety of potential approaches to act collectively (for instance, through establishing an "association," through a public private partnership, based on the initiative of one firm that takes the lead, etc.) it is useful to analyze the

[12]The CTOCs DP World and Patrick operate individual truck appointment systems at Port Botany (Australia). Both systems are accessed through a common web portal which is provided by a jointly owned subsidiary, see Davies (2013).

Fig. 9.1 The relevance of collective action in a port cluster (modified from de Langen (2008))

initiatives to take actions collectively as a *regime*. In line with the wider use of the term *regime* (see Stone 1993) for a widely cited paper on urban regimes), some regimes provide better results than others, but regimes often persist even though they are not effective. Regimes are path-dependent; once established, cooperation tends to re-enforce itself while a lack thereof can persist over time, as firms do not necessarily have incentives to invest in changing a collective action regime (see Notteboom et al. 2013). Figure 9.1 illustrates for the case of training and education, the *relevance of collective action* in a port cluster, and the *characteristics of an effective regime*.

The regime for collective action can be understood as all cooperative initiatives in a certain area – in this case training and education.[13] A key insight from analyzing collective action is that an effective regime generally requires a form of *regime management* (see Doner and Schneider 2000). Regime management essentially consists of bringing all relevant stakeholders together with the aim to identify and implement projects to improve the regime. In some cases this is done by a specific organization, and in other cases by a platform or group (see Fig. 9.2). In this regard, a basic distinction is to be made regarding the implementation of the regime management in practice: Many times there exist management structures on a long-term basis representing an *institutionalized* regime management. But sometimes

[13]It is important to take a certain area where collective action could be beneficial as the "unit of analysis" as the effectiveness of regimes differs. A port cluster may have a very effective training and education regime but an ineffective marketing and promotion regime.

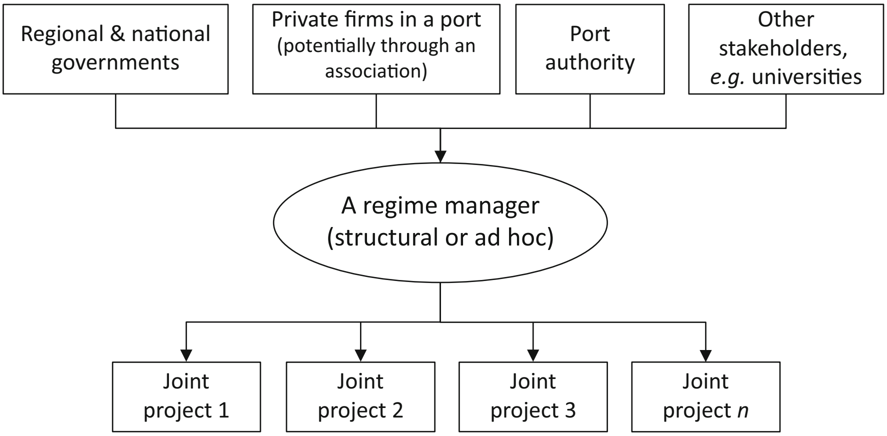

Fig. 9.2 A regime manager for initiating and organizing collective action in a port cluster (modified from de Langen (2008))

also ad-hoc regimes become established using organizational relationships between the parties involved which arise from a specific project.

For instance, the marketing and promotion for the Port of Rotterdam is done through *Rotterdam Port Promotion Council* (see RPPC 2017), a “regime manager” with an established institutional structure for over 70 years. Another example concerns the *C*ontainer *E*xchange *R*oute (CER) on the Maasvlakte at the Port of Rotterdam.[14] It is a cooperative infrastructure project of the port authority and the deep-sea container terminals operating in this part of the port. The project is based on a specific “ad-hoc” organizational structure, i.e., the regime management arises from the project case.

As a final example, the promotion of collective action in employee capability development is done through the *ma-co Maritimes Competenzcentrum* (see ma-co 2017) at the ports of Bremerhaven, Hamburg, and Wilhelmshaven. In this case, a competence center (as institutionalized regime manager) takes charge of joint projects in vocational education and training.

9.3.3 Typical Collective Goods in Port Clusters and Examples for Effective Projects of Collective Action

At least five important collective goods are relevant in port clusters. First, *education and training* has collective benefits. All firms in the port complex need well-trained

[14]The project aims at improving the efficiency of inter-terminal transport (see Anonymous 2016). A more detailed analysis of inter-terminal transport is presented by Tierney et al. (2014).

staff. Thus, they all benefit from investments to enhance port-related education and training. In virtually all sizeable ports, some sort of public private cooperation in this field develops (see Notteboom 2010).

Second, *marketing and promotion* has collective benefits. Port users perceive one port product that consists of nautical access, terminal handling, towage, pilotage, customs clearance, hinterland transport, and so on. Thus, port marketing and promotion is also partially a collective good: all ports benefit from a stronger brand of the port. This explains the emergence of collective marketing platforms in various ports (e.g., the *HumberPort partnership*, see HP 2017).

Third, *information exchange* has collective benefits. A *P*ort *C*ommunity *S*ystem (PCS) that allows for efficient and demand-oriented data exchange between the various firms in the port can substantially improve port efficiency and competitiveness (see Hill and Böse (2017) as well as Tsamboulas et al. (2012)). Such a system works best (or works only) when large numbers of firms in the cluster are willing to make such a PCS successful (see Jürgens et al. (2011) as well as Carlan et al. (2016)). A for-profit PCS is problematic, mainly because of reluctance of firms to become dependent on such a PCS. Thus, a PCS is often developed in partnership and can be considered a collective good. Such a PCS can increase data availability and thus improve the terminal operations (see Zhao and Goodchild (2010) as well as Heilig and Voß (2017)).

Fourth, *congestion reduction* has collective benefits. An individual firm will not have sufficient incentives to shift traffic away from congestion hours, but a collective effort to do so will improve overall accessibility of the port.[15] The same applies for a container exchange system in ports with various container terminals. There is generally a substantial flow of containers between different terminals in a port, for instance, because a train arrives at one terminal, while the shipping line departs from another terminal. An efficient container exchange system that includes all terminals also requires collective action of all CTOCs in a port.[16] The collective benefit is a better service for port users, which leads to more volumes.

Fifth, a *societal license* to operate for port activities has collective benefits. A lack of societal support for port activities can substantially constrain port operations and port development. For instance, it may prevent port expansion and lead to policy measures that hurt port companies (e.g., tighter environmental regulation).

[15] See, for example, the *PierPass* initiative of 13 container terminals at the Ports of Los Angeles and Long Beach, PP (2017).

[16] An example for a joint initiative that reduces costs for inter-terminal container transports within ports and simultaneously alleviates congestions on port roads is the CER project at the Port of Rotterdam (see Sect. 9.3.2).

Looking at the waterside access of ports, the *Hamburg Vessel Coordination Center* shall be mentioned exemplarily (see HVCC 2017). The initiative is jointly implemented by the biggest CTOCs of the Port of Hamburg (HHLA and EUROGATE) and aims at improved coordination of deep-sea and feeder vessels approaching the port and maneuvering within its basin. Based on proactive vessel management, shipping lines can save time and money when their vessels call the port and the terminals on-site are able to optimize their processes due to more comprehensive information about vessel arrivals and the departure requirements.

Most residents and stakeholders look the "port activities" as a whole and do not differentiate between companies, especially for such issues as noise and air quality. Thus, a societal license to grow is a collective good that requires commitment and cooperative initiatives of all firms in the port cluster, ranging from

- support for events for citizens, such as the "port days" which are organized in various ports,
- or measures to improve the visual attractiveness of the port (e.g., at Rotterdam and Antwerp),
- and initiatives to employ residents from the vicinity of the port with difficult access to the labor market (for instance, minorities).

The areas where collective action can be beneficial for the port as a whole (training and education, marketing and promotion, information exchange, congestion reduction, and the societal license to operate) have an impact on the competitiveness of the port. This explains efforts in all ports to jointly develop effective collective action regimes. Such effective regimes can only emerge with support from leading companies in the cluster, including CTOCs. Given the path dependence discussed above, ports with effective collective action regimes can develop lasting competitive advantages with positive impacts for all companies in the cluster. For this reason, a CTOC with a cluster orientation will be cooperative in joint projects to improve the competitiveness of the cluster as a whole – with positive effects for the CTOC individually.[17]

9.4 Conclusions

This chapter addressed the value of a network and cluster orientation specifically for CTOCs. CTOCs are frequently very focused on operational excellence and overlook the potential which may be tapped by orienting their activities beyond the company boundaries. Considering the globalization of production and market processes and its impact on the competitive position of companies, CTOCs can benefit more than ever from an orientation on the overall supply chain of which they are a part, as well as an orientation on the port cluster of which they are a component.

CTOCs with a supply chain/network orientation may be expected to take an active and constructive approach towards joint initiatives to develop schemes to provide financial incentive for longer opening times of the CTOC. This is because of the huge potential societal benefits of such longer opening times. The issue may

[17] However, the core of collective action problems is that these individual incentives are too weak. Thus, CTOCs cannot be expected to turn a cluster orientation into substantial investments in collective action. They can help develop effective collective action regimes, based on third party funding (in particular, port authorities or regional and national governments).

become more relevant given the increasing peaks in the handling of hinterland traffic due to larger ships and large "call sizes" (number of containers handled per ship).

In addition, a CTOC with a network orientation may be more likely to share information with benefits for third parties than a CTOC focused on internal processes. Data with value for third parties include the estimated (un)loading time (for shippers), the berth planning (for deep-sea, feeder and barge companies, as it allows them to forecast their waiting times), and the estimated end of operations (for pilotage and towage companies).

Finally, a CTOC with a network orientation may consider introducing "extended gate services," as these increase efficiency of land transport and develop advanced – and perhaps dynamic[18] – storage pricing (instead of the rather arbitrary free day arrangements). Both of these initiatives become increasingly relevant with the increase of peaks at terminals and the increase of volumes that have to be handled in short periods of time. In addition, a network-oriented CTOC may consider differentiated prices for barge, rail, and truck moves, partly as a tool to optimize the costs for the CTOC, but more importantly to increase supply chain efficiencies.

The cluster orientation is valuable, as an understanding of co-location benefits may inform decisions of the CTOC. For instance, CTOCs with a cluster orientation may consider integrated development of a terminal and a logistics zone, as the terminal connectivity drives up the land prices in the logistics zone.

The understanding of the benefits of collective action may make CTOCs supportive to collective initiatives in education, stakeholder relations management and open data exchange platforms. Given the huge challenges in relation to data and automatization (such as cooperative planning, truck platooning, seamless ship call processes across terminals, towage, pilotage, or bunkering) collaborative efforts to capture the potential benefits from such innovations are of increasing relevance for the port as a whole and as a consequence the container terminal as well.

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Chapter 10
The Impact of Air Emissions Regulations on Terminals

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Abstract This chapter aims to outline the applicable international and regional regulation on air emissions from ship operations, as well as to analyze their impact on port and terminal decision-making and functioning. The analysis also focuses on effective solutions, especially those promoted by the port or terminal management.

10.1 Introduction

The issue of air emissions from ships, along with the relevant abatement policies and technological options, is a complicated one. Efforts and studies submitted or supported by the *I*nternational *M*aritime *O*rganization (IMO)[1] on the subject emphasize the complexity and the scientific challenges while offering a common ground for further discussion and support of decisions. Many studies and reports, such as Smith et al. (2004), Buhaug et al. (2009), Faber et al. (2009), Wang et al. (2011), Miola and Ciuffo (2011), Miola et al. (2010), provide invaluable data, information, and arguments primarily focused on ships, while Anderson et al. (2015) addresses rather exhaustively the topic from a port and terminal perspective. Contributions in the relevant academic literature are numerous as the topic is interdisciplinary; in this chapter many links to significant contributions are included.

It is important to clarify that the goal of this chapter is neither to exhaustively present the regulatory framework nor to critically assess it. The aim is to examine

[1]The International Maritime Organization is a specialized agency of the *U*nited *N*ations (UN) responsible for the safety and security of shipping, and for the prevention of marine and atmospheric pollution by ships. Its key role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted, and universally implemented.

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the fundamental connections of ship-related regulations to port and terminal issues, as well as to examine the impact and viable solutions available to port and terminal managers. Before going ahead, it is also important to define the term “port” as diverse configurations of port areas dictate varied regulatory action, depending on population density, local activity, and nature. For the scope of this chapter, the approach of Anderson et al. (2015, pp. 11–12) is considered, and a port is defined as the location where one, some, or all of the following operational modes and related activities are concluded:

1. The end of the open water transit part of the voyage,
2. the passage or corridor where the ship should cross with or without the assistance of pilots,
3. maneuvering in confined waters up to the point of berthing or anchorage,
4. at berth at a terminal facility, and
5. at anchor, typically in protected waters and away from the quay.

The approach considered above is wider than the common interpretation of the maritime law and covers many aspects and functions of a port. Nevertheless, such a wide denotation also serves the purpose of overcoming local or regional peculiarities of ports with long passages to the sea, such as Hamburg and Stockton, or those with densely populated vicinity and mandatory traffic corridors, such as Hong Kong and Singapore ports. Air emissions from ships have a global impact and contribution to the deterioration of air quality and of ozone layers. Shipping as an activity is targeted not because of the externalities per unit, e.g. emissions per ton-mile of transport work, but as percentage vis-à-vis the total of transport and economic activity; in terms of carbon dioxide CO_2 emissions, shipping contributes 2–3% (see Buhaug et al. 2009). As Smith et al. (2004, pp. 139–142) point out, in 2050, carbon emissions from international shipping could grow 50–250%, depending on future economic growth, technological developments, and energy prices; therefore, reactive and proactive measures should be implemented. In this respect, the role of the IMO is pivotal, as a global problem needs a global solution and consensus. One should always bear in mind that ships are assets that operate within different jurisdictions, generally other than those of their flags. Therefore, an international framework is required that safeguards the principles set under the *U*nited *N*ations *C*onvention of the *L*aw *O*f the *S*eas (UNCLOS), and deems tonnage as suitable for international unrestricted trade while complying with the standards set by the IMO. However, acute local problems related to air quality, along with the relative political power and sensitivity of local stakeholders, led to regional rules that distort international competition and deem ships unsuitable for operations in their territorial waters, as is the case of California and Europe (see Sect. 10.2.2.3). This is evident when applying stricter environmental rules at the national or regional level, where ships must comply with stricter standards than those internationally in force (e.g. consider the sulfur regulation as outlined in Sects. 10.2.1, 10.2.2.1, and 10.2.2.3) Although there are several provisos for the protection of the coastal state rights in the UNCLOS, national and regional action leads to a patchwork of rules, which is difficult to follow, sparking criticism and prejudice in the industry (see e.g. Psaraftis 2004).

Considering the above introductory points, this chapter is structured as follows: The next Sect. 10.2 aims to outline the problem of air emissions from a regulatory point of view. Therefore, the main pollutants are introduced in Sect. 10.2.1. The analysis of international policy instruments considers both non-greenhouse (Sect. 10.2.2.1) and greenhouse gases (Sect. 10.2.2.2), and summarizes notable regional initiatives (Sect. 10.2.2.3). Thereafter, in Sect. 10.3, the impact on ports and terminals is set forth, while in Sect. 10.4, solutions and options to mitigate the negative externalities are presented. The technical options that will be further analyzed are as follows: the use of LNG as marine fuel (Sect. 10.4.1), the requirement of *cold ironing*[2] (Sect. 10.4.2), financial incentives (Sect. 10.4.3), and smart terminal technologies (Sect. 10.4.4). Many references support the development of the arguments and could guide further research in related fields.

10.2 Emissions from Ships and Regulations

Ships emit pollutants in all modes of their function and throughout their operational life. When ships are sailing in open and unrestricted waters, their main and auxiliary engines, along with boilers and economizers, operate at high levels of load. Thus, they also consume many tons of bunkers and emit many tons of pollutants. The cubic relationship of resistance in the water, i.e. of required energy vis-à-vis speed, for tankers and bulkers ships suggests that an increase in load, e.g. increasing speed by Δv, implies an increase in ΔC^3 of the consumption. In container ships, passenger ferries, and RoRo ships, this relationship holds for a lower exponent. The increase in load might result from heavy weather, currents, or any other adverse condition. When ships are transitioning or maneuvering, they operate at lower speeds. Therefore, consumption and emissions from the main engine are reduced; however, the auxiliary engines are working at higher loads due to the need for electric supply, so significant quantities of pollutants are emitted close, or even in the port zone. Finally, when the ship is at the berth or at anchor, auxiliary engines and systems consume considerable amounts of bunkers to keep all systems warm for the main engine or to enable cargo operations. In all cases, ships emit significant amounts of various pollutants.

Research suggests that the effect of emissions at the port on inland pollution levels is cut in half when the ship is 11 miles from the port and fades out when it is 23 miles from the port (see Moretti and Neidell 2011, Figure 3). Moreover, shipping-related emissions result in about 60,000 deaths annually across the globe, with impacts concentrated in littoral regions along major trade routes (Corbett et al.

[2] *Cold ironing* is the process of supplying shoreside electrical power to a ship at berth, while all its diesel engines, i.e. main and auxiliary, are turned off.

2007). Hence, most mortality reports come from Asia and Europe where most people live close to the coastline and there is heavy traffic of ships. In conclusion, as the externalities of shipping activities expand over many and densely populated areas, the impact is significant for the well-being of humans. Therefore, there is a need for global action and regulation. Communities and cities close to ports, passages, and main routes are more vulnerable, a fact that justifies the special interest of the port managers. Thus, national or regional operational measures, or stricter rules, are required to mitigate the negative impact of ships on local communities. In this regard, other special infrastructure might be considered at the expense of the state budget, or operational limitations that impede usual operations onboard. Owing to the inherent complexity and the inability to address the environmental challenge holistically from a technical and operational point of view, not all pollutants can be abated simultaneously, nor all externalities can be addressed without degrading the safety levels of operations, or increasing expenditures (cost of infrastructure) or the cost of a ship call (operational aspect).

10.2.1 The Pollutants

To understand the problem of air emissions, one should revisit some simplified engineering facts. Most vehicles, including ships, consume fuels, such as gasoline, pure or nearly pure residual *H*eavy *F*uel *O*il (HFO), blended *I*ntermediate *F*uel *O*il (IFO), *M*arine *D*iesel *O*il (MDO), distillate *M*arine *G*as *O*il (MGO), *L*iquefied *N*atural *G*as (LNG), and ethanol, which contain Hydrogen (H) and Carbon (C) atoms. In a *perfect* engine, oxygen in the air would convert the hydrogen in the fuel into water and the carbon into carbon dioxide. Nitrogen (N) in the air would remain unaffected. In reality, the combustion process is *imperfect*, and engines emit several types of pollutants and particularly the harmful unburned or partially burned hydrocarbons, also called *V*olatile *O*rganic *C*ompounds (VOC), nitrogen oxides, carbon monoxide, carbon dioxide, and water. Note that sulfur oxides are only emitted if sulfur is contained in the fuel. The analysis should also consider particulate matter. Currently, particulate matter is included in the regulation addressing sulfur issues, but from a chemical as well as from an abatement point of view, further analysis is required (see Sect. 10.2.2.1). These pollutants are presented below in a nutshell:

Nitrogen Oxides (NO_x) Under the high pressure and high temperature conditions in an engine, nitrogen and oxygen atoms in the air react to form various nitrogen oxides, collectively known as NO_x. Nitrogen oxides, such as hydrocarbons, precede the formation of ozone. They also contribute to the formation of acid rain.

Sulfur Oxides (SO_x) Sulfur oxides, and in particular sulfur dioxide, are major air pollutants and significant affect human health. Acid rain and other detrimental environmental effects are directly associated with sulfur.

Hydrocarbons (HC) Hydrocarbon emissions result when fuel molecules in the engine do not burn or burn only partially. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone, which is a major component of smog. Ozone can irritate the eyes, damage lungs, and aggravate respiratory problems. It is the most widespread urban air pollution problem. Some kinds of exhaust hydrocarbons are also toxic, with the potential to cause cancer.

Carbon Monoxide (CO) Carbon monoxide is a product of incomplete combustion and occurs when carbon in the fuel is partially oxidized rather than fully oxidized to carbon dioxide. Carbon monoxide reduces the flow of oxygen in the bloodstream and is particularly hazardous to persons with heart disease.

Carbon Dioxide (CO_2) Carbon dioxide does not directly impair human health but is considered a *G*reen*H*ouse *G*as (GHG). In other words, as it accumulates in the atmosphere, it traps the earth's heat and contributes to the potential for climate change (see also Sect. 10.2.2.2).

Particulate Matter (PM) As particulate matter is generally defined as the sum of natural or anthropogenic atmospheric aerosol particles, i.e. a mixture that impacts climate and precipitation, thus adversely affecting human health. PM is regulated by many states. Currently, the discussion focuses on PM with a diameter between 2.5 and 10 micrometers (μm). Fine particles with a diameter of 2.5 μm or less (PM 2.5) are associated with lung cancer and other cardiovascular diseases. The less the diameter of the PM, the deeper they can penetrate the bronchi and the cells.

The negative effects of these pollutants should be addressed as they affect human health and well-being. However, this is not an easy task, as the emission of some pollutants depends on the fuel and its quality, such as SO_x and PM, while the emission of some other pollutants depends on the technology of the engine, such as NO_x and CO. Moreover, any abatement initiative will affect other human activities, such as trade and transportation. Coastal regions, especially port cities, where marine activity is concentrated, suffer more from the negative effects of air pollution. Last but not least, in the near future, the problems of methane (CH_4) and ammonia (NH_3) emissions are expected to attract the attention of policymakers and regulators, e.g. the European Parliament (2015a,b), which gives a clear sign of regional interest in promoting stricter environmental legislation.

Recent research suggests that CH_4 and N_2O are very harmful pollutants (see IPCC 2015a). Table 10.1 provides the *G*lobal *W*arming *P*otential (GWP) expressed in Carbon-Dioxide Equivalents (CO_{2e}). Most commonly, the emissions

Table 10.1 Global warming potential (100 years), expressed as CO_{2e}

Pollutant	GWP
CO_2	1
CH_4	28
N_2O	265

Table 10.2 Fuel emission factor in kg pollutant/tonne fuel

Pollutant	Factor
CO_2	3.134
CH_4	0.28
N_2O	0.08

are estimated on a fuel basis. Table 10.2 provides a solid basis for calculations (see IPCC 2015a). Other sources, such as IMO (2005), provide similar data.

Therefore, the consumption of a ton of fuel at a port generates 3134 tons of CO_2, 0.28 tons of CH_4, and 0.08 tons of N_2O, while the total burden in CO_{2e} terms is 32,174 kg, where almost 65% is attributed to N_2O. This simple calculation explains and justifies the attention and priority for abatement of NO_x.

10.2.2 The Regulatory Framework

The international community has identified the issue of controlling air emissions from shipborne operations since the early 1970s (see IMO 2019a). The IMO adopted Resolution A.719 in 1991, paving the way for the new MARPOL[3] Annex VI, the specialized part addressing the issue of air emission (see IMO 2019c). MARPOL Annex VI was originally aimed at abating SO_x and NO_x emissions from ships, as well as at the consumption and production of ozone-depleting substances including *C*hloro*F*luoro*C*arbons (CFC) onboard. Annex VI, which came into force in 2005, has since been improved, revised, and duly amended (see e.g. IMO 2016, 2018a). Currently, Annex VI addresses the *O*zone-*D*epleting *S*ubstances (ODS), NO_x and SO_x, as well as GHG issues, by demanding energy efficiency measures that lead to the reduction in the consumption of fuels and thus to reduced CO_2 emission. Other pollutants such as CO or CH_4 are for the time being overlooked. The focus on SO_x and NO_x is justified as these play a significant role in acid rain, see Fig. 10.1 originally produced by EPA (2009).

The discussion concerning air quality and air emissions in port zones is complicated, as emissions caused by ships, rail and truck operations, as well as industrial and residential activity, are involved (Mueller et al. 2011). Therefore, one could effortlessly argue that bottlenecks in the port zone resulting in delays as well as substantial fluctuation of load factors of the asset involved (transportation means, handling equipment, etc.) also contribute to the general burden. Moreover, ports and terminals are subject to national legislation and authority, so wider policies and

[3]The IMO developed the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78, MARPOL stands for marine pollution and 73/78 for the years 1973 and 1978). MARPOL is the most important international marine environmental convention; its goal is to minimize pollution of the oceans and seas, including dumping, and oil and air pollution. MARPOL as an instrument focuses on “prevention.”

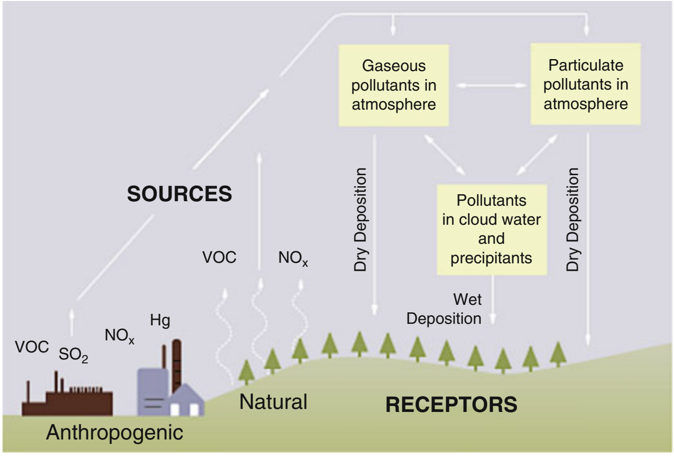


Fig. 10.1 Processes involved in acid deposition

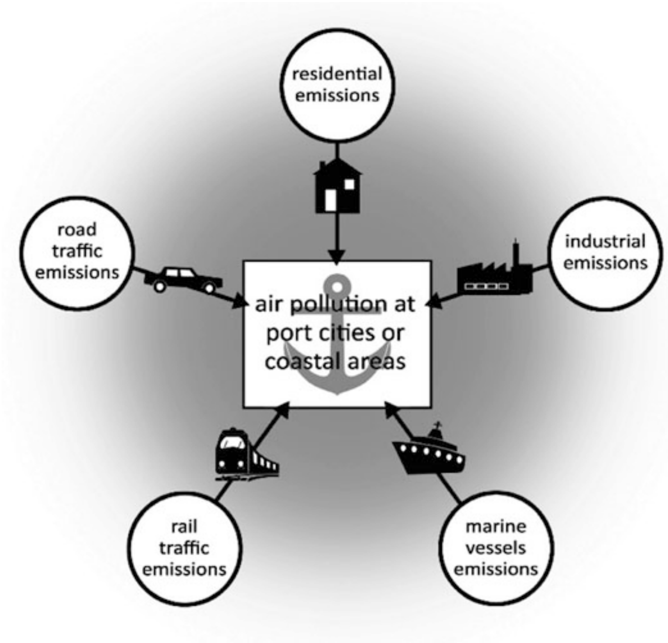


Fig. 10.2 Factors that can influence air quality in port cities and coastal areas (see Mueller et al. 2011)

instruments apply. To illustrate and explain the complexity, the European paradigm will be considered (Fig. 10.2).

In Europe, the general framework aims at addressing emissions by diverse sources. The *N*ational *E*mission *C*eilings (NEC) Directive sets national emission reduction commitments for *N*on-*M*ethane *V*olatile *O*rganic *C*ompounds (NMVOC), ammonia (NH_3), and fine particulate matter ($PM2.5$), SO_2 and NO_x, as these pollutants contribute significantly to poor air quality, thus making a negative impact on human health and the environment (see EC 2016). The NEC is complementary to the *A*ir *Q*uality *D*irective (AQD, see EC 2011), as the NEC Directive addresses the overall amount of emissions (in kilotons), while the AQD addresses the quality of air (in $\mu g/m^3$). The NEC Directive has been the EU's main legal instrument to reduce overall emissions of air pollution since 2001 and sets limits on the amount of air pollution that can be emitted by each member state each year. The revised NEC Directive (2016/2284/EU) updates the limits for 2020 and 2030, expanding the application by covering *PM 2.5* as a new pollutant. As its application is universal for the member states, the directive regulates emissions of inland shipping as well as in the port zones. Emissions caused by international shipping, i.e. ships engaged in international voyages, are not covered by the NEC Directive, although they contribute significantly to the environmental burden of ports. Hence, the EU relies mainly on standards and rules adopted by the IMO while also imposing stricter rules in territorial waters (see the Sulfur Directive in Sect. 10.2.2.3).

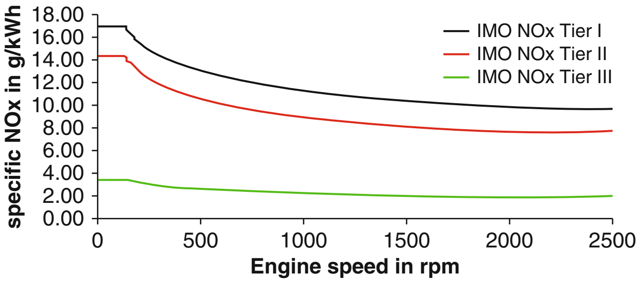
In conclusion, there is no port-specific regulation but a blend of international and national policy instruments. However, from an operational point of view, port and terminal management has to apply best practices to optimize operations, electrify or reduce the load factor and the time of usage of diesel engines either at sea or ashore, and maximize the efficiency of the port as a nodal point.

10.2.2.1 Regulating Non-greenhouse Gases

Regulation 13 of MARPOL Annex VI introduces different levels of explicitly defined control *Tiers* based on the ship construction date and control areas. Regulation 13 has been in force since July 2010 and is applicable to all ships, subject to specific exceptions considered in Annex VI. It also applies to each marine diesel engine with a power output of more than 130 kW, as well as to each marine diesel engine with a power output of more than 130 kW which has undergone a major conversion on or after January 1, 2000. Within any particular tier, the actual limit value is determined from the engine's rated speed, as per Fig. 10.3. The elimination of NO_x emissions from ships depends primarily on the characteristics of the fuel mixture during combustion; therefore, it is linked to the design of the engine.

On the other hand, Regulation 14 addresses the issue of sulfur oxides (SO_x). SO_2 emissions result from the burning of sulfur or of fuels containing sulfur. The current SO_x limits in the exhaust gases are described in Regulation 14 of Annex VI, which are subject to a series of progressive step changes (see Fig. 10.4).

As in other annexes of MARPOL, special attention is given to selected sea areas, declared by the littoral states through an IMO procedure as *E*mission *C*ontrol *A*reas (ECAs). Currently, in sea areas depicted in Fig. 10.5, the stricter limits of Regulation 13 and 14 (see Figs. 10.3 and 10.4) apply. However, it is expected that more sea areas, important navigational corridors, such as the Mediterranean, the



	Remarks
Tier I	Current IMO NOx emission level
Tier II	**Approx. minus 2,5 g/kWh** (approx. –15% to –22%) reduction compared to Tier I. (achievable by Engine Internal Measures)
Tier III	**80% reduction** from Tier I. Applicable in regional Emission Control Areas (ECAs). **Exhaust Gas After-treatment**. Outside the ECAs Tier II limits are applicable.

Fig. 10.3 MARPOL Annex VI, Regulation 13 on NO_x

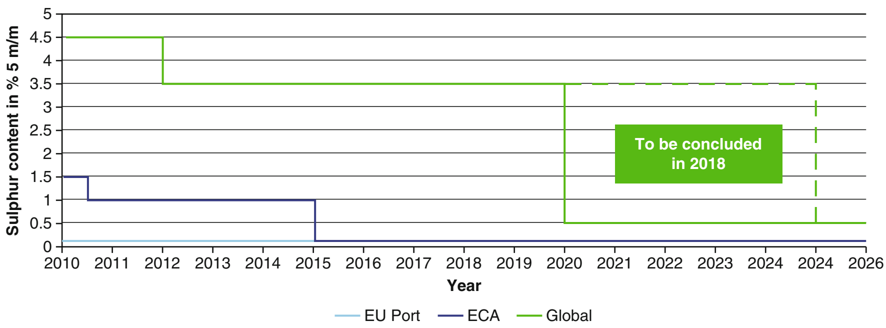


Fig. 10.4 MARPOL Annex VI and European sulfur regulation limits

coastline of Japan, Mexico, and the seas off the main Chinese ports, Singapore, etc., will be eventually declared as ECAs (see e.g. Royal 2017; Schinas and Bani 2012).

The discussion is not complete unless the issue of PM is addressed. In MARPOL, there are no explicit limits for the PM emitted from ships; it is expected that PM will be reduced as a function of reduced sulfur content of fuels. Lack et al. (2009) suggest that combustion emissions from shipping are dominated by fine mode particles, as most particles have diameters from 0.01 to 0.1 μm with very few above 0.25 μm. Moreover, the main components of PM from shipping are either organic carbon or organic matter, such as black carbon (or elemental carbon – the main component of soot, sulfate particles, ash, etc.). Evidence from 200 ships consuming HFO yielded the following results:

Fig. 10.5 The currently declared ECAs

- 46% sulfate particles,
- 39% *O*rganic *M*atter (OM), and
- 15% black carbon.

While sulfate emissions are dictated by fuel sulfur content, it should be noted that OM is emitted as a function of both fuel sulfur and the engine type. Finally, the same source also addresses the following question: *What is happening to PM emissions from ships that switch their fuel from HFO to MDO or MGO?*

In brief, the PM mass has decreased (e.g. to 67%) and their composition is enriched with black carbon, while the effect of MDO particles on human health and the greenhouse effect is still examined.

10.2.2.2 Regulating Greenhouse Gases

The abatement of CO_2 is an overly complicated challenge. Regulations 19, 20, and 21 of MARPOL Annex VI, as well as the resolutions of the *M*arine *E*nvironment *P*rotection *C*ommittee (MEPC), provide necessary information for the implementation of the *E*nergy *E*fficiency *D*esign *I*ndex (EEDI), as expressed in simplified Eq. 10.1, see EC (2014a) and EC (2014b).

$$\text{EEDI} = \frac{CO_2 \text{ from the propulsion} + CO_2 \text{ from the auxiliary} - CO_2 \text{ innovative technol.}}{\text{DWT} \times \text{speed}} \tag{10.1}$$

The concept behind the EEDI is to provide an indication of energy efficiency, based on CO_2 emissions (in g) per unit of transport (in ton-mile). The non-dimensional conversion factor between fuel consumption and CO_2 emissions C_F ranges from *3.114* to *3.206*, depending on the grade of conventional fuel, as per the international classification (see IMO 2014a, par. 2.1). As per the provisos of Annex VI and the above-mentioned resolutions, the attained EEDI will be calculated for each new ship and for all ships having gross tonnage of 400 and above. Then the attained EEDI will be less than the required EEDI:

$$\text{attained EEDI} \leq \text{required EEDI} = \left(1 - \frac{X}{100}\right) \times \text{reference line value} \quad (10.2)$$

where X is the reduction factor specified in Table 1 of Regulation 21 for the required EEDI compared to the EEDI reference line. Figure 10.6 illustrates the reference lines. The attained EEDI measurement should be below the reference line as per Eq. 10.2. Otherwise, measures should be taken to reduce the emission of CO_2 per unit of transport. The reference line will be reviewed by the IMO in the given years, when lower reference lines will be considered, thus pushing ship operators to increase the unit energy efficiency.

The need for updating the reference lines, as well as regional initiatives (European in particular, see Sect. 10.2.2.3), mandated the adoption of a data collection system for fuel oil consumption of ships by the IMO (see IMO 2016). This IMO initiative was preceded in 2015 by the new EU *M*onitoring, *R*eporting, and *V*erification (MRV) Regulation (see EC 2015). Thorough data collection is necessary for the implementation of *M*arket-*B*ased *M*easures (MBMs), as there is evidence that operational and technical provisos considered in the instruments are not sufficient for satisfactorily reducing the amount of GHG emissions from international shipping (see IMO 2019b).

In the 72nd Session of the MEPC in April 2018, the Member States adopted an initial strategy on the reduction of GHG emissions from ships, setting out the ambition to drastically reduce GHG emissions from international shipping. It is the

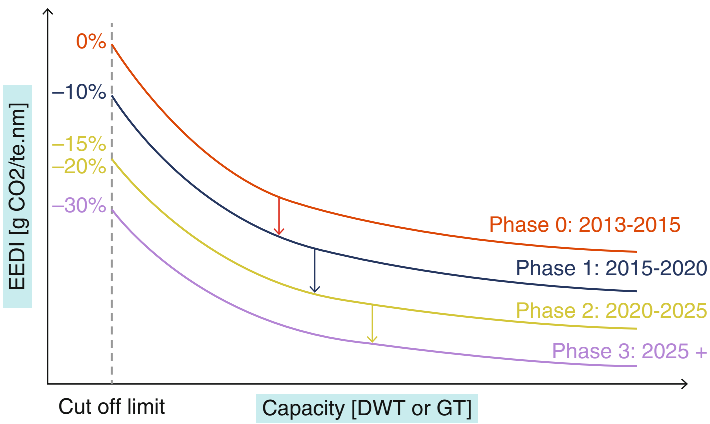


Fig. 10.6 Required EEDI against existing and proposed reference lines (DWT: *D*ead *W*eight *T*ons, GT: *G*ross *T*onnage)

first time a clear goal for the reduction in total of GHG emissions from international shipping is set and boils down to reducing the total annual GHG emissions by at least 50% by 2050 compared to 2008 levels, "... while, at the same time, pursuing efforts towards phasing them out entirely" (see IMO 2018b).

MBMs are needed as part of a comprehensive package of effective regulation of GHG emissions from international shipping. This is to provide an economic incentive for the maritime industry to reduce its fuel consumption by investing in more fuel-efficient ships and technologies, to operate ships in a more energy-efficient manner (in-sector reductions), and to offset growing ship emissions in other sectors (out-of-sector reductions). These measures include proposals leading to CO_2 trade, funds (charge per ton of fuel), caps, and levies. Nevertheless, the IMO has to consider the *no more favorable treatment*[4] of MARPOL and the *Common But Differentiated Responsibility* (CBDR) of *U*nited *N*ations *F*ramework *C*onvention on *C*limate *C*hange (UNFCCC).[5] Thus, the MBM issue is puzzling and calls for intense political negotiations. Two (groups of) concepts are considered:

1. *E*mission *T*rading *S*ystem (ETS), and
2. Levy scheme.

Kosmas and Acciaro (2017) and Psaraftis (2008, 2012) present these measures as well as proposals leading to CO_2 trade, funds (charge per ton of fuel), caps, and levies.

10.2.2.3 Regional Approaches

There is regional pressure for stricter rules related to environmental issues. Most commonly, it is the pressure from local stakeholders that policy-makers at international level do not feel but forces local or regional measures to deal with serious problems. Therefore, these measures are stricter, have shorter grace periods, and are different from international standards. The term *Gold Plating*[6] is widely used, especially in the European literature.

An instrument that had a clear impact on ports and terminals in the EU is the "Sulphur Directive." Originally introduced in 1999, the directive was amended in 2005 and 2012 (see EC 1999, 2005, 2012). Schinas (2015) provides a detailed

[4] As in many IMO instruments, ships must not be placed at a disadvantage because their country has ratified the new convention. MARPOL Regulation 5(4) clearly protects the interests of ships registered under Members of the Convention: *With respect to the ships of non-Parties to the Convention, Parties shall apply the requirements of the present Convention as may be necessary to ensure that no more favorable treatment is given to such ships.*

[5] The instruments of the IMO as a specialized agency of the UN should be streamlined with the decisions of the UNFCCC.

[6] As per Boci et al. (2014) *Gold Plating* refers to ... *obligations that go beyond EU requirements – an excess of norms, guidelines, and procedures accumulated at national, regional, and local levels interfering with the expected policy goals.*

analysis of the directive, and the following points highlighted in his analysis could be further considered in the current work:

1. The directive streamlines European law with the provisos of MARPOL Annex VI, practically accelerating the implementation of the Annex VI regulations in the EU.
2. There is a solid legal foundation justifying the introduction of the Sulphur Directive, which is based on the founding treaties and environmental policies of the EU.
3. In ECAs after 2015, and in the EU ports since 2010, the sulfur limit has been 0.1% (Fig. 10.4). This is an effect of Directive 2005/33/EC amending Directive 1999/32/EC (see EC 1999, 2005).
4. The Sulphur Directive has a direct operational impact and expands legal terms when the ship is in the port or at berth.
5. Compliance with the directive implies either the use of more expensive fuels or investment in scrubbers and relevant abatement equipment. Both options impose a financial burden on the operators. Technical solutions such as cold ironing might be further examined and considered (see also Sect. 10.4.2).

The Sulphur Directive is an interesting instrument from a policy point of view. It is reactive, as it follows the initiative of the IMO but is also proactive as it accelerates the incorporation of the provisos of the IMO into the national legislation of the EU member states. Moreover, it is an example of gold plating that aims to protect the interests of the society through improved and stricter environmental requirements. Finally, due to its complex and demanding application, it generates many operational, financial, and enforcement concerns.

From a GHG point of view, the EU MRV regulation (see EC 2015), which, since the beginning of 2018, has also been an interesting case. The regulation mandates that all ships above 5000 gross tons visiting EU ports collect data about their CO_2 emissions and other relevant operational information and then annually transmit verified data to the authorities. Considering the IMO instrument (see IMO (2016) as well as Sect. 10.2.2.2), the regional requirements are stricter. The aims are as follows:

1. To monitor and annually report the verified amount of CO_2 emitted on journeys to, from, and between EU ports and also when in EU ports,
2. to monitor and annually report additional parameters such as distance, time at sea, and cargo carried to enable the determination of the ships' average energy efficiency,
3. to submit to the European Commission an emissions report containing externally verified annual aggregated data, which will then be publicly available, and
4. to carry a document of compliance issued by an accredited MRV verifier when visiting EU ports. This will confirm that the ship is in compliance with its MRV obligations for its activities during the preceding year for possible inspection by regulatory authorities.

These requirements also reflect the European interest in promoting MBM, as MRV is the prerequisite for referencing and classification of ships according to energy performance. Additionally, the MRV regulation offers a clear sign of the determination of the EU to adopt even unilateral measures in the fields of air quality and of decarbonizing the economy, especially if the IMO fails to address the need for reduction of CO_2 emissions from ships as per *Recital 39* of the MRV Directive of the EU (see EC 2015). The European paradigm is interesting and could pave the way for the decarbonizing of the maritime industry and allied sectors, including port zone activity. In the EU, there are enough policy instruments in place, as well as experience in promoting measures like the *E*mission *T*rade *S*chemes (ETS). This is better exemplified when considering directives focused on decarbonizing the aviation industry that have been temporarily derogated to allow time to market actors and stakeholders to adjust to the new framework and conditions (see EC 2003, 2008, 2013). So, the Commission is signaling its will and determination to decarbonize all sectors of economic activity, but it is at the same time attentive to the markets and fair competition. Finally, these aviation-related instruments could serve as a role model for shipping, as well as for putting pressure on the IMO, to accelerate the procedures and reach an agreement on global measures to reduce GHG.

Apart from the European instruments, significant regional initiatives stem from the *C*alifornia *A*ir *R*esources *B*oard (CARB). All other US states can follow either the Federal *E*nvironmental *P*rotection *A*gency (EPA) or the CARB. The CARB issued Fuel Sulfur and Other Operation Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline on July 24, 2008 (see CARB 2012). Moreover, this regulation requires applicable shipowners to make substantial investments in onboard shore-power equipment, such as shore connections for cold ironing (see Sect. 10.4.2). The CARB rules are more extensive than the European ones, as they also address PM along with NO_x and SO_x emissions from ocean-going vessels – reductions that are necessary to improve air quality and public health in California. Currently, the ECA limits apply along the US coastline (see Fig. 10.5). Moreover, MARPOL Annex VI does not specify the type of fuel to be used other than stipulating sulfur content $\leq 0.1\%$. In contrast, CARB requires the use of distillate fuel oil (not residual fuel oil such as HFO). In this regard, MARPOL allows the use of alternative emission control technologies, such as exhaust gas scrubbers, while CARB does not recognize the use of such technology.

Concluding the brief presentation of the regulation on air emissions, one can only agree with Roe (2013, pp. 20–22) that, in contrast to other regulatory actions, environmental policies seem to be more articulated yet more convoluted. Unilateral actions and initiatives threaten and jeopardize the international maritime policy regime, which is why policy-makers should carefully avoid them.

10.3 The Impact on Ports and Terminals

Considering all international and regional regulation related to air emissions, it appears that ports and terminals are involved in the chain of enforcement policies and functions. *P*ort *S*tate *C*ontrol (PSC), and other enforcement bodies and their officers have the right to make all necessary inspections and ensure compliance with the applicable rules. The pressure on the authorities is high as externalities are mostly endured by the communities living close to the port zones.

To draft, review, and implement the right policy instruments, it is necessary to measure the emitted pollutants. There are two ways to do this – the *top-down* and the *bottom-up*. The former estimates emitted air pollutants based on the reported amounts or marine bunker fuel sales, while the latter considers fuel consumption or truck, rail, and ship movements in the port zone, i.e. it is activity based. Maragkogianni et al. (2016, pp. 11–24) offers a thorough analysis of this subject. The activity-based approach is described in various sources and has been elaborated in detail, showing collective understanding among professionals and researchers. The primary equation used to estimate emissions is as follows:

$$\text{Emissions} = MCR \times LF \times A \times EF \tag{10.3}$$

with

MCR: maximum continuous rating of the combustion engine in use (kW)
LF: engine load factor during the specific activity
A: activity time (hours)
EF: emissions factor (in $\frac{\text{g}}{\text{kWh}}$ or $\frac{\text{kg}}{\text{kWh}}$)

Given the operation of ships in the port zone, which also contributes to the environmental burden, and quoting (Maragkogianni et al. 2016, pp. 27–28), the activity of ships can be divided into the following:

$$E_{total} = E_{\text{cruising}} + E_{\text{manoeuvring}} + E_{\text{hoteling}} \tag{10.4}$$

and determined as:

$$E_i = \sum_{j,k} \left(T_j \times P_k \times LF_{j,k} \times EF_{i,k}\right) \tag{10.5}$$

with

E: amount of ship emissions (tons)
i: specific type of emissions (NO_x, SO_x or $PM_{2.5}$)
j: ship's activity stage (i.e. moving, maneuvering or hoteling)

k: engine type, i.e. main or auxiliary engine

P: engine power (kW); usually the MCR is considered

T: T is the time spent at each of the ship's activity stages (hours), as A in Eq. 10.3. For example, when the ship is maneuvering: $T = \frac{D}{U}$, where D is the distance traveled by the ship in the port before docking, and U is the moving velocity of the ship during maneuvering

National and specialized agencies such as EPA (2000) provide values and information regarding the above-mentioned factors. Other sources provide similar information, and in some cases, with a clear regional interest and focus. For example, Table 10.3 provides indicative load factors for a container ship, while Table 10.4 summarizes the annual average engine load factors used for propulsion and auxiliary engines of different vessel types in the West Coast of the United States (see SCG 2018).

Apparently, a similar approach can be used for rail activity and movements, see Table 10.5, as well as for trucks. Considering the data provided by Mathers et al. (2014, p. 11), the activity of a TEU-mile results in 597.4 g of CO_2 for trucks and 292.8 g in case of rail transport. Hence, the movement of one container in the port

Table 10.3 Indicative load factors for a container ship's main propulsion and auxiliary machinery

Load factor	At sea	Maneuvering	In-port
Propulsion	0.80	0.03	0.00
Auxiliary	0.13	0.50	0.17

Table 10.4 Annual average engine load factors of different vessel types

Type	Propulsion	Auxiliary
Assist and escort	0.31	0.43
Harbor tug	0.31	0.43
Ocean tug	0.68	0.43
Commercial fishing	0.30	0.30
Ferry	0.34	0.43
Excursion	0.42	0.43
Government	0.51	0.43
Pilot boat	0.51	0.43
Tank barge	n/a	0.43
Workboat	0.38	0.32

Table 10.5 Rail emission factors

Pollutant	$\frac{\text{kg pollutant}}{\text{tonne fuel}}$	$\frac{\text{kg pollutant}}{\text{kWh}}$
CO_2	3.164	0.744
CH_4	0.18	0.00004
N_2O	1.22	0.00029

zone by rail results in almost half the burden by truck. Hence, port managers and terminal operators aim to do away with truck miles, as this results in 1.6 metric tons of CO_2 reduced per 10,000 miles, and to shift cargoes from truck to rail, which results in 1.4 metric tons of CO_2 reduced per 10,000 ton-miles.

As already stated, many researchers have identified the actual need or political motive for the promotion of regional regulatory approaches to reduce emissions from ships at ports (see e.g. Thomson et al. 2015). In this regard, Schinas and Butler (2016, p. 93) derived an equation that combines key financial data of the "green" and of the "conventional" ship with the rebate in port dues, that incentives investment in green tonnage, by eliminating some financial benefits of the "conventional" ship, as "green" ships demand higher initial investment. Equation 10.6 considers the following parameters:

$$m = \frac{k \times CAPEX_1 - n \times Fuel_1}{Port_1} \tag{10.6}$$

with

$CAPEX$:	capital expenses of the "conventional" ship (USD/day)
$Fuel$:	price of conventional fuels (USD/day)
$Port$:	port-related expenses, i.e., the usual port dues related to the ship and not to the cargo (USD/day)
k:	premium of the "greener" ship in $CAPEX$, e.g., 0.2 in case of 20% higher initial cost
n:	difference in price of the greener fuel uses, such as LNG, as percentage from the competing conventional fuels (mainly HFO), e.g. 0.15 in case of 15% less cost per ton
m:	discount ports should offer to ships with reduced emission profiles when calling at their facilities

and Index 1 applies to conventional ships. The same source provides a numerical example for a 1500 TEU-slot container ship,

with

$CAPEX_1 =$	4500 USD/day
$Fuel_1 =$	4800 USD/day
$Port_1 =$	1600 USD/day
$k =$	0.2 ("green" ship is higher)
$n =$	0.15 ("green" energy is less expensive)

The discount m in port dues the port can offer is 11.25%, i.e. the port dues $Port_2$ for the green ship should be 1420 USD/day to equalize the financial burden between green and conventional ships. Further analysis of the financial aspects of the topic is provided by Schinas (2018).

Equation 10.6 simplifies real-world business but provides a transparent and solid basis for ports to justify discounts and policies to favor calls of greener ships in their facilities. Schinas and Butler (2016) also suggested the term *regulatory acupuncture*, indicating the need for catalytic local intervention to implement greener solutions. The discount m at ports is a compensation paid by the local authorities (and therefore by the local communities) to the ship for polluting less when calling at the port. This is the rationale for financial incentives provided by many ports (see also Sect. 10.4.3), such as Hamburg, Rotterdam, Singapore, and Seattle, through a reduction of port dues for greener ships (see HPA 2014; Mellin and Rydhed 2011; Merk 2014; Vinkoert 2012). Although it is not possible to generalize the results of a single formula or of an estimation based on given ports and conditions, the results of Schinas and Butler (2016) are conceptually validated by the work of Agnolucci et al. (2014), who claims that only part of the financial savings from energy efficiency accrues to operators. Therefore, it is of outmost importance for ports to derive a methodology for estimating the burden in terms of Eqs. 10.3 and 10.4 when introducing financial incentives, as per Eq. 10.6.

The above metrics and approaches can aid the port management in deriving, monitoring, and accessing policies for regulating ship and cargo activity; however, regulatory initiatives might drastically influence operational and financial decisions. In view of the analysis in Sect. 10.2, the following issues are explored further:

- The impact of ECA in operations,
- the effort of lowering LF in Eq. 10.3, and
- the impact of regional instruments, and particularly of the Sulphur Directive.

The introduction of an ECA has a significant impact on the attractiveness of a port as a nodal point. Operation in an ECA implies higher costs, as desulfurized fuels or *E*xhaust *G*as *C*leaning *S*ystems (EGCS) should be used for complying with SO_x, and *E*xhaust *G*as *R*ecirculation (EGR) or *S*elective *C*atalytic *R*eaction (SCR) – both diesel-engine technologies – should be used for reaching the Tiers of NO_x emissions. In this regard, a ship that uses HFO in the high seas has to switch to MGO or operate the EGCS, and this cost is practically absorbed by the ship operator. All options above imply investment, operational complexity, and risks, and it is possible that older tonnage will be phased out. Should the cost of transport increase, the affected ports and hinterland connections will have to pay the toll. This issue is discussed thoroughly in Psaraftis and Kontovas (2016) from a ship-operator's perceptive.

The attempt at lowering the load factors of the main and auxiliary engines, especially in high seas, is closely related to slow steaming. As explained in Sect. 10.2, a lower speed means a lower consumption of fuel and thus a lower CO_2 emission. So, a reduction in the operational speed by Δs knots has a significant impact on consumption based on the cube law (ΔConsumption $= f(\Delta s^3)$). Many researchers, such as Cariou (2011), Psaraftis and Kontovas (2015), Yin et al. (2014), Sødal et al. (2009), have explored the impact of slow steaming. It should be noted that the positive results of slow steaming is evident if only the supply of ton-miles (i.e. of ships) is elastic. If the supply becomes inelastic, the freight rates will increase and the demand may not be satisfied and be shifted to other means if possible, resulting in a spill over. Slow steaming also involves safety concerns, as ships should have enough power for maneuvering in restricted waters and operations in adverse sea and weather conditions. Underpowered ships, because of myopic application of environmental rules, pose threats to navigation and life at sea.

Finally, the application of the Sulphur Directive introduced many legal and operational concerns for operators when calling EU ports. Schinas (2015) provides a detailed analysis from the ship operator's perspective. Nevertheless, the need for desulfurized operations encouraged and stimulated the demand of LNG-fueled ships and also sparked investments in cold ironing, i.e. on-shore power supply, facilities at ports.

10.4 Effective Solutions

Considering the regulatory requirements and policy instruments as presented in the earlier section, the effective abatement of air emission in port zones is possible through:

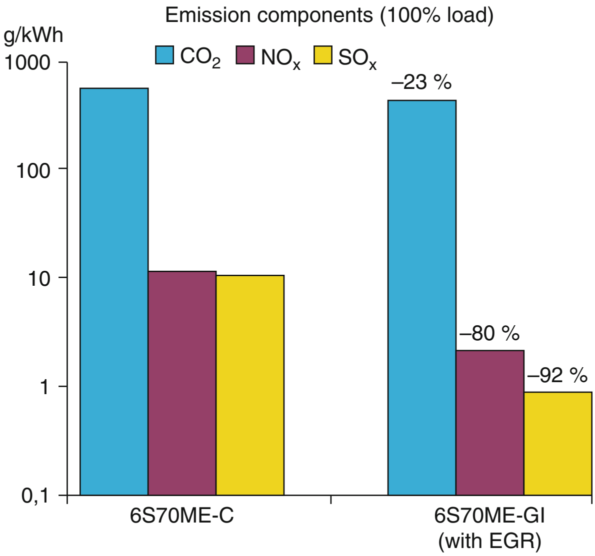
1. The use of desulfurized fuels, such as LNG, in ocean-going ships,
2. introducing and mandating cold ironing for all ships at berth,
3. introducing financial incentives for ships to become "greener,"
4. applying smart technologies in the port zone to reduce emissions from the port and cargo handling equipment.

Apparently, the use of LNG as a bunker provides a wider political and business option, and cannot be dictated by port authorities or terminal managers. Nevertheless, the introduction of ECA and the strict regional regulation on sulfur promotes LNG and other desulfurized fuels as a possibility. The three other options are closely related and determined by the capacity and the decisions of the port and terminal managers: Cold ironing and smart technologies are based on the assets of the port and the terminal. The award of financial incentives also reflects wider community and stakeholders' interests, especially in city-ports, such as Hamburg and Singapore.

10.4.1 LNG as Marine Fuel

Ship operators can use LNG as a marine fuel. LNG provides significant reductions in SO_x and NO_x emissions, thus enabling compliance with existing and proposed regulatory limits. The benefits of using LNG are clearly presented in the logarithmic graph of Fig. 10.7. SO_x and PM are eliminated from the emissions, while the NO_x emissions are reduced close to 85%, meeting in many cases the *Tier III* requirement. In Fig. 10.7, the same engine, MAN 6S70ME, an engine of established technology and market acceptance, is tested in the same operational conditions with HFO (left bars) and LNG (right bars). As expected, the reduction in SO_x is remarkable (-92%) and the regulatory requirements are satisfied. To address NO_x requirements, the engine was fitted with EGR; in this case too, the

Fig. 10.7 HFO vs. LNG emissions (Andersen et al. 2011, p. 2)



achieved reduction of 80% of NO_x meets the expectations of regulators. Thus, even existing engines can technically reach the nGHG requirements, subject to retrofit. Nonetheless, the carbon footprint is only marginally reduced (−20%) and skepticism is further fueled.

The supporters of LNG as marine bunkers highlight the reduction of carbon footprint, justifiably claiming that it contributes positively to the EEDI performance. The carbon footprint benefit is attributed to the lower C_F, which for LNG is 2.75, offering a nominal reduction potential of around 14%. However, LNG is not a panacea, as methane CH_4 might slip in the atmosphere due to the imperfect combustion of LNG in the engine. This raises concerns and sparks interest in technical innovation (see Brynolf et al. 2014; Corbett et al. 2015; Howarth 2014; IPCC 2015a,b,b; PHS 2018; Thomson et al. 2015). It is reminded that CH_4 is 28 times more harmful than CO_2 (see Table 10.1).

The issue of LNG-fueled ships has attracted the interest of researchers, policy-makers, and industry leaders. Many researchers have examined and considered the technical viability of LNG-fueled ships (see e.g. Cockett 1997 or Thomson et al. 2015) estimated the differential of fuel prices[7] (see Schinas and Butler 2016). Some have examined the willingness of investors to support such projects (see Leete et al. 2013), or even suggested different uses of the available assets and resources, such as by promoting port-pairing (regional initiative) with hydrogen-fueled ships (see Farrell et al. 2003). Likewise, policy-makers and stakeholders promote LNG technology (see DNV-GL 2014, 2016; EC 2014), or conclude, based on arguments not relevant to shipping, that LNG is a transitional fuel (see CEA

[7]Differential is understood as the difference between LNG and HFO prices.

2014; GT 2009). Reservations and criticisms about LNG-fueled ships concern the following arguments:

1. Bunkering infrastructure,
2. availability of LNG as a fuel,
3. after market, and
4. regulatory uncertainty.

The issue of infrastructure is serious in regions that are not confined by an ECA. In the EU, there is a political decision to make LNG available in the main ports and LNG bunkering infrastructure should be available till 2025 at ports of the core of Trans-European Transport Networks and till 2030 for all inland ports (see EC 2014), while in North America, there are already many sufficiently equipped terminals (see ABS 2015). Many sources suggest that the risk of availability of LNG is overestimated, and that there is sufficiency at least in all major hubs and ECA ports (see LR 2014). The price differential and the statistics of the LNG price can further support the optimism in using LNG as marine fuel (see Schinas and Butler 2016). The risks of a lack of an aftermarket as well as regulatory uncertainty should be further explored, assessed, and addressed.

10.4.2 Cold Ironing

As presented in Sect. 10.2.2.3 on regional instruments, the Sulphur Directive (Regulation 4b) and the CARB regulation designated the use of cold ironing as a possible means to reduce emissions at port. CARB regulations require that auxiliary diesel engines must be shut down and grid-based power must be used for specified percentages of fleet visits. Merk (2014, p. 14, Table 6) provides indicative data on ports that offer shore-based supply.

The issue of cold ironing deserves some further discussion. There are clear benefits for the population living and working in or close to the port zone. The main benefits of cold ironing are fuel savings and reduction, if not elimination, of air emissions and noise levels. Nevertheless, there are technical and legal challenges, which are briefly outlined below:

1. Incompatibility of connectors and cables as they are still not internationally standardized.
2. Incompatibility of technical – mainly electrical – parameters: There is no uniform voltage and frequency requirement, so many ships use 220 V at 50 Hz, some at 60 Hz, some others use 110 V. Moreover, land-based facilities may distribute voltage that varies from 440 V to 11 kV.
3. There are substantial and wide variations in load requirements: A cargo ship may need few hundred *kW*, while a passenger ship, especially a cruise ship, may require many *MW*.

4. There are legal implications for many ports, such as when power supply should be subcontracted or provided by third parties. There might be competition issues as well as conflicts among stakeholders.

Assuming that technical incompatibilities are addressed – i.e. a rather soft assumption as there is work in progress toward this direction – the main issue is the variation of demand, i.e. of ships' calls and their average requirement in load, as well as the "lumpy" character of the investment.[8] Thus, port managers are confronted with variations in demand that could also be extreme, so there is an issue of dimensioning the technical solution, while at the same time they are challenged with lumpy investments, which call for sufficient planning, security, and commitment, and their success depends on the demand levels. Wrong dimensioning of the investment implies not only dissatisfied demand in terms of power availability and pricing but also load factors of the facility that might deviate from the design or optimum levels. The following example illustrates the dimensioning dilemma: Assuming that a container ship at berth needs 1–1.5 MW from the local grid or the dedicated facility of the port, e.g. LNG barges in the port of Hamburg (see Becker Marine Systems 2019), then a system of 10–15 MW would suffice for the simultaneous service of 10 similar ships. However, the need to serve a cruise ship with an average load of say 40 MW would render the system inoperable. On the other side, lower traffic levels would make the system under-utilized. The need for servicing lumpy loads conflicts with the rationality of the design of such systems. Any stepwise approach is suboptimal, as cabling, switchboards, and transformers designed for parallel operation cost more than a system designed for a given, i.e. less variable, level of loads. Therefore, flexible and independent systems, such as floating power stations (barges), might solve the problem of fluctuating demand. Power-supply systems on barges might be fueled with LNG and cover demand that the grid cannot serve. Still, it is the forecasting capacity of demand that determines the project viability before any subsidy or state subvention.

Regardless of the technology used, either shore- or barged-based systems, there is a significant cost burden for the ports or the terminals as well as for ship operators. It is also a typical "chicken or egg" problem: Should the port invest in cold ironing technology first while no regulatory requirement is in force, or should it focus on a policy initiative first, even a local one, and distort the current practice? This is another critical dilemma, as any regulatory initiative that deteriorates the commercial attractiveness of the port might lead to an exclusion of the port from the schedules of ships. Moreover, the challenge of compatibility of the ship-

[8]Investments in ports and port facilities can be very expensive, usually costing many millions (and sometimes even more). One cannot offer a new service based on a new facility for a small investment. Hence, when port managers make investments in new facilities, these are exceptionally large investments that do not happen every year. That is what lumpy means in this context. There is not a series of small annual investments but few much larger ones happening at the end of longer periods, say 5 or 10 years. In brief, a port might invest X million USD this year, then another X million USD 5 years later. This is a lumpy series of investments, as opposed to $\frac{X}{5}$ million USD every year, which would be a "steady" investment.

shore systems should be considered. Many technologies are available, and yet the *I*nternational *O*rganization of *S*tandards (ISO) has not developed a prototype for global application. Eventually, the port and the shore power providers should offer an assurance for the adequate supply of power at a reasonable cost. In most cases, power from barges or shore-based systems is higher than the onboard power produced by auxiliary engines. A total burden of over 450 million USD is reported for shore power retrofit in the US west coast, while the cost of retrofit for ships is estimated to be 0.5–1.1 million USD. Ships that call often these ports should undergo retrofit to achieve technical compatibility (see Anderson et al. 2015, pp. 171–172).

10.4.3 Financial Incentives

Other ports encourage reducing GHG and nGHG emissions with operational and financial incentives, such as the reduction of port dues. These incentives boil down to the form of compensations to operators for additional fuel costs due to timely fuel switch, or lower port dues and tariffs. For example, the ports of Hamburg (see HPA 2014), Hong Kong, Shenzhen, Seattle, and Houston give reimbursements to ship operators based on the volume of low-sulfur fuel burned during each port call (see Merk 2014, pp. 15–16), while the port of Singapore gives a 15% rebate on port dues for vessels that switch to clean fuel or use relevant abatement measures and technologies.

Overall, many incentives might be linked to the *E*nvironmental *S*hip *I*ndex (ESI), a measurement derived by the *W*orld *P*ort *C*limate *I*nitiative (WPCI) of the *I*nternational *A*ssociation of *P*ort and *H*arbors (IAPH). The ESI identifies seagoing ships that perform better in reducing air emissions than required by the current emission standards of the IMO and evaluates the amount of NO_x and SO_x emitted by a ship. Moreover, an estimation on CO_2 is included in the reporting scheme per ship. The idea is to provide a special tariff or scheme of benefits to seagoing ships that outperform the current emission standards. Nevertheless, it should be noted that currently the ESI is completely voluntary. On the basis of publicly available formulas,[9] the amount of NO_x, SO_x, and CO_2 emitted by a ship is evaluated and the result is compared using a scale. Should a ship that emits none of the above pollutants visit the port, then it scores the maximum of 100 points. More than 30 ports in the USA and the EU offer discounts on port dues; however, the discount scheme varies significantly from port to port. The rationale of the ESI is explained better when considering the numerical example provided by WPSP (2019).

[9]In this regard, more detailed information is available at www.environmentalshipindex.org.

Table 10.6 Input for nitrogen oxides ESI NO_x

Key figure	Main engine(s)	Auxiliary engine(s)	Unit
NO_X limit value	17	11.5	g/kWh
NO_X rating	13	11	g/kWh
Δ Emission	4	0.5	
Rated power	9480	970	kW
Number of engines	1	3	

Table 10.7 Input for sulfur oxides ESI SO_x

Consumption	High	Mid	Low	Unit
Baseline	3.5	0.5	0.1	% S (m/m)
Actual	1.5	0.3	0.04	% S (m/m)

Assume a ship which is equipped with cold ironing equipment and engines as per Table 10.6 consuming fuel as per Table 10.7 in percent by mass (m/m),[10] as well as reporting fuel consumption and distance sailed every half year. At ports, an *O*n-shore *P*ower *S*upply (OPS) installation shall be available.

Then – as per the formula provided by WPSP (2019) – the total ESI Score is calculated as follows:

$$12.68(\text{ESI } NO_X) + 19.50(\text{ESI } SO_X) + 5(\text{ESI } CO_2) + 10(\text{OPS}) = 47.18$$

Basis for ESI SCORE calculation:

$$\text{ESI SCORE} = \text{ESI } NO_X + \text{ESI } SO_X + \text{ESI } CO_2 + \text{OPS (max. 100)} \tag{10.7}$$

NO_X points are calculated by

$$\begin{aligned}\text{ESI } NO_X = & \frac{100}{\text{Rated Power } \sum \text{of all Engines}} \\ & \times \frac{(NO_X \text{ limit value } - NO_X \text{ rating}) \times \text{ Rated Power}}{NO_X \text{ limit value}} \\ & \times \sum \text{of all Engines}\end{aligned} \tag{10.7a}$$

SO_X points are calculated by

$$\text{ESI } SO_X = k \times 30 + l \times 35 + m \times 35 \tag{10.7b}$$

[10]Percent by mass (m/m) is the mass of solute divided by the total mass of the solution, multiplied by 100%.

CO_2 points depend on the reporting interval (see notation below)
with

cm	ESI NO_X = x,	where x is 2 × NO_x points, ranging between 0 and 100 and divided by 3
cm	ESI SO_X = y,	where y is SO_X points, ranging between 0 and 100 and divided by 3
cm	k, l, m	relative reduction of the average sulfur content of *High*, *Mid*, *Low*; see Table 10.7, e.g. input for k is: $3.5 - 1.5 = 2.0$
cm	ESI $CO_2 = 5$,	for reporting (every half year) of fuel and distance efficiency increase in % is added as points; total capped at 15
cm	$OPS = 10$,	if OPS installation is fitted

This numerical example illustrates the direction the regulation dictates, and the IAPH through WPCI supports further ports and terminals. Should in the previous example the NO_x rating be 10 for all (main and auxiliary) engines, then the ESI score would be 51.80. Clearly, NO_x as pollutant attracts more interest and priority. Should the actual content of sulfur be less than 0.05 of the limit, say 0.04, then ceteris paribus, the score would be 59.0. Should both conditions apply, then the score would be 75.37. In other words, the index is sensitive to NO_x and SO_x, while the GHG approach is still not fully considered. Finally, the index could cluster ships on historical and reported data and link their environmental performance with discounts in port dues. However, such a policy might be controversial, and as the ship's environmental performance depends on the operational pattern, the comparison conditions are not fair. As an extreme example, consider a ship that operates continuously in an ECA vis-à-vis a ship that does not.

Other financial incentives are closely related to specific regional or national goals. The Swedish "differentiation of fairways dues," a rebate scheme of port dues for ships, is aimed at reducing NO_x and SO_x emissions in the Baltic Sea (see CSI 2019). Interesting incentives provided in Swedish ports are reported by Mellin and Rydhed (2011); some concepts and ideas could be effortlessly generalized and used in other ports too. In Norway, a NO_x fund is set up, and affiliated companies pay €0.5 per ton of NO_x to the fund, instead of tax. Companies subject to NO_x tax are the ones that have energy production from propulsion machinery with a total installed capacity of over 750 kW, and have motors, boilers, and turbines with a total installed capacity of more than 10 MW. The fund will then support retrofitting and relevant projects (see NOx Fund 2019). Finally, other EU ports make use of European funding, such as the port of Rotterdam, and financially support the construction of an LNG terminal (see EIB 2014).

The incentives in other significant international maritime fairways might be different. In the USA, various ports, such as the ports of Long Beach, New York, and New Jersey, have adopted the *V*essel *S*peed *R*eduction (VSR) incentive. Ships arriving at a lower speed get a financial discount on port dues. The cost of the discounts amounts to almost 1.5–2.0 million USD annually (see Anderson et al. 2015, p. 59). Furthermore, the USA provides funding for infrastructure that increases shore-side power availability.

Finally, some incentives are linked to the *C*orporate *S*ocial *R*esponsibility (CSR) plans of operators. Programs are financed, and awards are given for greening. The port of Singapore finances the green ship, port, and technology program. Emissions are linked to the reduction in port dues and other benefits. Singapore has invested about 100 million USD in the program and awarded many operators. Last but not least, a CSR-focused approach is adopted by the port of Rotterdam that awards the "Green Trophy" (see Vinkoert 2012).

10.4.4 Smart Terminal Technologies

In contrast to the previous measures, where the ship technology is in focus and related options and decisions depend on them, there are port and terminal-related technologies that may increase operational efficiency and can contribute the most toward the alleviation of the total air emission burden in the port zone. As per Anderson et al. (2015), such technologies are mainly classified as:

1. Automated mooring systems,
2. electric shore-side equipment, including pumps for liquid bulks,
3. off-terminal transloading, and
4. optimization of cargo handling at terminals.

Automated mooring systems emerged almost 20 years ago and enable faster turnaround times, saving almost 1–2 h of maneuvering. Such systems are remotely controlled and can be combined with other technologies. By using electric vacuum pads mounted on the quayside, emissions from the main and auxiliary engines are avoided. Therefore, the load factor in Eq. 10.3 becomes zero as the resulting burden. A critical factor for the implementation of such a system is the total time saved. Although the technology has matured enough, the associated installation cost discourages from implementing these solutions widely in ports and terminals, as the capital cost is practically for the account of the terminal.

Similar to the automated mooring systems, shore-side equipment, such as cranes and *A*utomated *G*uided *V*ehicles (AGV), as well as pumps for liquid bulks and bunkers, could be further electrified. In liquid bulk terminals, the electrification of steam- or diesel-powered systems ashore, or of barges and ships, could improve local air quality. In most ports across the world, cargo handling systems provided by the port are used and in only few cases, is necessary to use the gear of the ship. However, there is still cargo-handling equipment in ports that is diesel-driven, such as straddle carriers. Therefore, any effort to electrify this equipment and operation will benefit positively the local air quality. Along with the source of energy LF, one should also consider the activity time A (see Eq. 10.3). Any time saved from the diesel-engine port-handling equipment, as well as from the auxiliary engines of the ship (e.g. by offering and demanding cold ironing), is translated into less environmental burden, assuming that shore power has a greener footprint. Such technologies and policies are gradually adopted in many terminals worldwide. Finally, besides environmental benefits, many operational advantages are associated with automation and control technologies, increasing efficiency, productivity, and planning capabilities.

Off-terminal transloading or mid-stream operation is the practice of unloading cargo – mainly containers – between ocean-carriers at anchor in generally non-berth locations. In the past, mid-stream operations were allowed or even promoted by ports, e.g. in Hong Kong, due to capacity constraints ashore. Cost and time, in terms of handling movements, are saved, as container ships are simultaneously served and lightened by two or even more barges and smaller ships. Experience suggests that mid-stream operations address cargo handling needs of ships with capacity of more than 6000 TEUs; however, there are many operational limitations and considerations. Safety is the main concern, as lightening is a dangerous operation per se. Mid-stream requires calm seas, effective anchoring, and probably dynamic positioning technologies so as to permit highly automated and fast cargo handing operations. Assuming electric- or LNG-driven tugs and electric supply for the visiting ship, the footprint of operations might reduce significantly, as significant part of Eq. 10.4 is lowered or eliminated. Mid-stream could be an option worth examining, especially when a first sorting of containers is feasible or demanded.

There is no international regulatory initiative focusing on ports, although there are many instruments that apply horizontally in ports and inland waters. The quintessence of Eq. 10.3 lies in optimizing operations and minimizing the burden of emissions. Therefore, the optimization of cargo-handling procedures and technologies lead to less movements, higher efficiency, and productivity, thus unit reduction of all externalities. Optimization is not necessarily synonymous to automation, though as concepts they are highly related. Hence, automation can improve the environmental profile of the terminal and of the port, as distinct operations and procedures, such as pre-arrival communication of information, passage, maneuvering, mooring, loading and unloading of cargo, shore cargo handling, etc., can be better scheduled, minimizing parameters LF and A in the equations and leading to lower emissions. Finally, the re-engineering of all processes and the higher degree of automation imply less volatility of loads and occupancy, i.e. more stable, efficient, and environmentally friendly operating conditions, but also less flexibility when deviating from the "optimized" path or sequence of procedures.

10.5 Concluding Remarks

The issue of air emissions poses a huge challenge from a technical, regulatory, and financial point of view for the port and terminal managers, as well as for all actors involved along the maritime logistics chains, yet mainly for the shipowners. First, there is an international set of rules that addresses some pollutants. This international framework is also evolving, but it is the product of consensus, hence not as effective as possible. Stricter regional or national rules might apply, addressing the needs of local stakeholders, but such measures distort competition and might deteriorate the commercial attractiveness of ports. Much research has shed light on the adverse impacts of local stricter rules on local traffic. In both cases, the burden of enforcement and that of providing technical options and alternatives is on the port and/or terminal management.

Since much of the effort is directed to the abatement of emissions from ships engaged in international voyages, the owners and operators of ships are confronted with the risks and challenges of compliance. When the ships are in the port zone, enforcement through national means yet based on international rules is possible, under the regulatory framework of the IMO and the provisos of the UN. In this regard, fuel change, investment in modern technologies, and change in operational procedures, including slow steaming, are of ship-owners' account.

At the same time, port and terminal managers are not confronted with the challenge of following a global and universal regulation. Their motives are regional or local, and in some cases also purely commercial, as in the case of offering LNG bunkering facilities to attract LNG-fueled ships and their cargoes. However, the local pressure or wider policies that apply to all sectors of the economy, such as the AQD and NEC Directives of the European Commission (see EC 2011, 2016), justify effort and investment in the port zone.

This effort and investment boils down to the reduction of load factors and of the time of activity of diesel engines at sea and ashore, as well as to the optimization of operations, to avoid unnecessary movements or use of diesel-driven assets. Electrification is another challenge along with automation. But both options should be examined in a holistic way, as they impact the financial performance, operational profile, and capabilities of the terminals.

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Part III
Planning Area: Seaside Access and Terminal Quayside

Chapter 11
Cost and Performance Evaluation Impacts of Container Ships on Seaport Container Terminals: An Update

Axel Schönknecht

Abstract The subject of this chapter is a method of evaluating costs and performance of container ships as means of transport in the main part of the intermodal transport chain for ISO containers. The rational is the continuous development in the size of container ships, the infrastructure development to cater for them and the strong variations in bunker prices over the past years. Furthermore, the complete transport chain development with pre- and on-carriage cannot be seen as risk-free. The method described will make clear that the factors for success or lack of success for large container ships can be found almost exclusively in the ports and their hinterland infrastructure in combination with the general loop design.

11.1 Introduction

Due to the continuously increasing transport volume in sea container traffic in the past, the call for bigger and bigger container ships was greater from many sides and has not stopped so far. Independently from the current over capacity there are still open orders for more than 3.5 million TEU fleet slot capacity which is approx. 17% on top to the already existing fleet (see Alpha 2016). Around the half of the ordered new capacity is for ships of a size equal or above 14,000 TEU according to Damas (2016). With ever bigger container ships more and more containers could be shipped per round trip, the turnover increased and with it the profits. That the latter occurs was already stated in theory at the beginning of the 2000s, see e.g. Ihlwan (2003). So far, the theory seems to become a reality as the costs have developed sub-proportionally to the size of the ships, and the number of container ship round trips remain almost the same. The combination of the criteria "income," "cost," and "ship round trips" in a particular time period, in short the *tonnage* or *slot productivity* (i.e. the profitability per slot and day), is hardly ever considered in the discussion on

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the development of the size of the ships. This economic key indicator depends on many logistics influencing factors. If, at some point in time, the slot productivity will not continue to increase as the ships become bigger, or even reduces, then, the giant container ships will achieve a lower return on investment as expected. If this happens, a similar development as with the giant tankers in the 1970s is to be feared, which were scrapped almost overnight. Infrastructure created for these ships, mostly with public funding, proved to be useless.

The size development of container ships until today has been enormous. Was the average size of a container ship in 2006 about 4000 TEU (with a maximum of 13,000 TEU, see Pawellek and Schönknecht (2011)), in 2016, the average size was already 8000 TEU (with a maximum size of over 19,000 TEU (see Damas 2016) and, in 2019, two (of nine) ships are expected to be delivered with a capacity of significantly more than 22,000 TEU. They will be the first ever LNG-powered container ships of this size (see Visser 2018).

This development is requesting even more a check of the sustainability of container ship growth by a method that shows container ships' typical *operating performance*. This method is the main content of the following chapter and should show which major factors influence container the ship profitability and productivity and what feedback the continual growth in ship size has on the transport chain and its interfaces. Initially the correlation between the transport chain and a container ship loop should be explained briefly in Sect. 11.2.

11.2 Role of Container Ships in the Transport Chain

An intermodal transport chain is defined as the transportation of goods in the same transport box using at least two different means of transport. The transport chain considered here is divided into pre-, main, and on-carriage. The use of at least three means of transport is necessary to go through transport chains, where a container ship is the consolidating main means of transport (see Fig. 11.1).

The service mode for container ships in liner shipping operation is primarily the *round trip* or *loop*, respectively. *Round trip* is here a shipping term that includes several calls of a ship at different ports – sometimes multiple calls at the same port during one round trip can be found as well. It should be noted that the starting port and the final port of a round trip are always identical. Round trips in liner shipping are usually between two continents. In this regard, Asia–North America, Asia–Europe, and Europe–America are the most important trade routes. Every loop port has the job of consolidating cargo from different transport chains for loading on container ships and allocating cargo to different transport chains for distributing across the port's hinterland.

Figure 11.2 illustrates the influence of the size of the container ship on the task and the number of transport chains to be connected. As bigger a container ship is as more pre- and on-carriages needs to be handled per call.

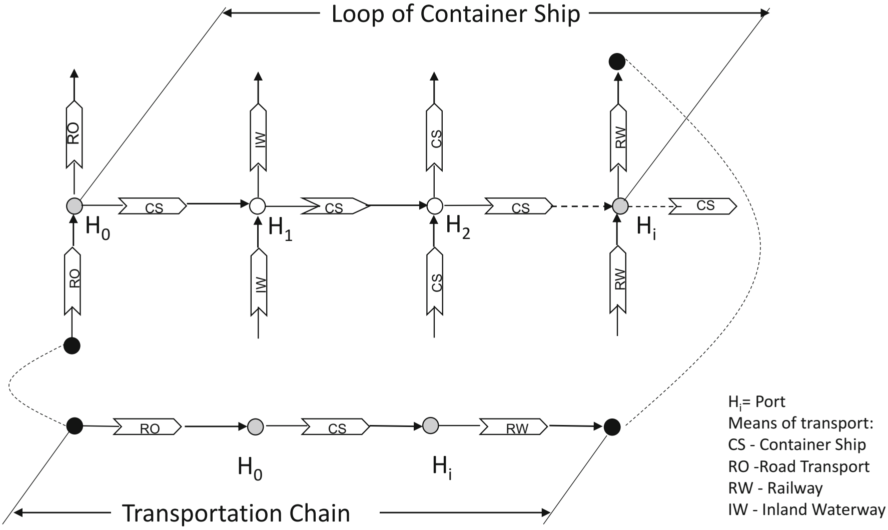

Fig. 11.1 Correlation between transport chain and a container ship round trip

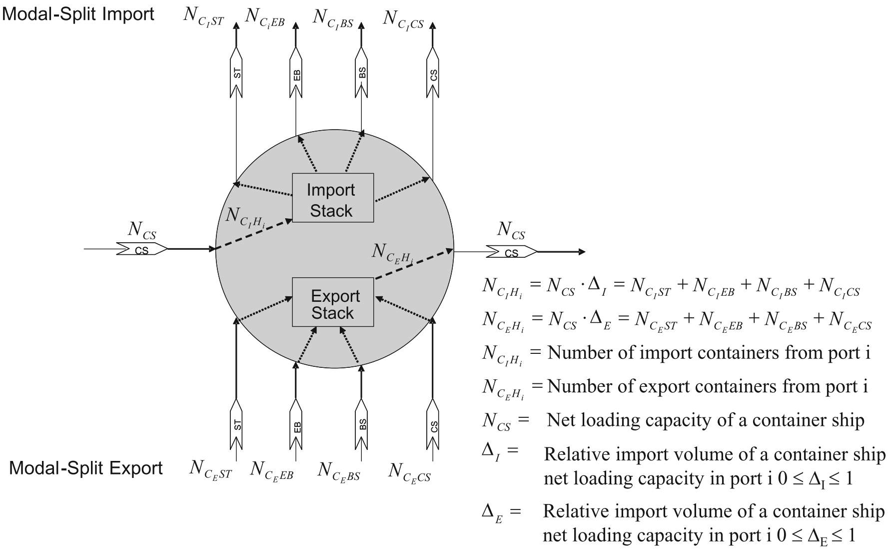

Fig. 11.2 Influence of the size of a container ship on the number of transport chains to be served in port *i*

The container volume of each ship to be handled at a port can be expressed by the ship's net loading capacity N_{CS}[1] and the factor Δ. Factor Δ represents how many containers are to be handled in proportion to the ship's (net) loading capacity. This can vary between import and export containers. Assuming only two ports in a round trip and full utilization of capacity this factor turns towards 1 for imports as well for exports. Here, all incoming containers are discharged every time a ship reaches a port and all slots are re-allocated by outgoing containers before the ship leaves again.

The slot capacity and the net loading capacity N_{CS} of container ships have been grown constantly since the beginning of container shipping. This is well known. It is unknown whether this development will further continue or end abruptly similar to the mentioned giant tankers of the 1970s, of which the largest had a comparatively short operating time before scrapping.

Furthermore, there is a need for further research to see how the factor Δ develops depending on container ship size and whether it affects or makes demands on the modal split of means of transport in pre- and on-carriage in the ports. In order to estimate the cost efficiency of various sizes of container ships, a model of the cost and revenue parameters of a container ship's round trip is necessary and is introduced below.

11.3 Cost and Revenue Model of a Container Ship in Liner Shipping

It is required to develop a model that can compare the profitability of various sizes of container ships in a given (general) round trip. Ships taken into consideration in this investigation have been chosen in the following size clusters from various sources (see Table 11.1).

11.3.1 Cost Model

Subsequent explanations focus on the development of a cost model for round trip operations in container shipping. Determining the round trip ports or regions, respectively, the model allows for application to different container ship sizes. First, Sect. 11.3.1.1 introduces a case-based modeling approach that represents the round trip costs by using the parameters of the related loop ports. Afterwards,

[1]The *net loading capacity* of a ship is usually smaller than the *slot capacity* of a ship. For the former, an average weight of 14 tons must be taken into consideration per used slot (see Cullinane and Khanna 1998). Therefore, the deadweight capacity of a ship is reached before all slots are filled.

Table 11.1 Definition of the ship-size clusters for model development

Cluster	Deadweight capacity (dwt)	Container capacity (TEU)	Net container capacity (TEU)	Reference capacity (TEU)	Speed (kn)	Engine power (kW)	Length (m)	Registered tonnage
TEU 0–1000	7673	645	548	548	17	5833	116	6452
TEU 1000–2000	22,575	1400	1613	1400	19	10,763	169	17,315
TEU 2000–3000	40,336	2761	2881	2761	21	22,760	225	34,649
TEU 3000–4000	46,510	3595	3322	3322	24	31,670	251	39,698
TEU 4000–5000	66,327	4848	4738	4738	23	36,877	288	57,898
TEU 5000–6000	76,622	6289	5473	5473	25	64,713	292	70, 552
TEU 6000–7000	87,943	6744	6282	6282	25	60,173	306	80, 420
TEU 7000–8000	101,429	7523	7245	7245	25	63,990	330	89,717
TEU 8000–9000	104,203	8546	7443	7443	25	68,387	334	92,583
TEU 9000–10,000	108,956	9216	7783	7783	25	70,346	346	103,498
TEU 10,000–11,000	152,000	12,670	10,857	10,857	23	70,000	390	150,000
TEU 11,000–12,000	157,000	11,989	11,214	11,214	25	91,537	400	142,418
TEU 13,000	175,000	13,640	12,500	12,500	23	77,941	400	150,000
TEU 18,000	242,800	18,154	17,343	17,343	25	116,588	400	239,380

the approach is generalized in Sect. 11.3.1.2 leading to a cost model that includes the same parameter characteristics for all (or certain groups of) round trip ports (e.g., regarding handling volumes or quay tariffs). Generalization simplifies model application and extends options for exploration without diminishing the quality of model results or considering analysis objectives insufficiently.

11.3.1.1 Round Trip Cost Model

The approach for the cost model will initially be made from a round trip out of k ports, where the ports H_0 and H_k are qualitatively identical and between each port a distance s_i is to be covered (see Fig. 11.3).

The sum of all segment distances s_i is the same length as the round trip s_R. In each port H_i, there is a number of export containers to be loaded N_{C_E} and a number of import containers to be unloaded N_{C_I} (see Fig. 11.4); the containers can be of 20 or 40 ft. The number of containers moved between ports $N_{C_s i}$ cannot be bigger than the net loading capacity of a ship N_{CS} potentially reduced by the utilization factor α. The number of containers per port is calculated as follows:

$$
\begin{aligned}
N_{C_s i} &= N_{C_s i-1} - N_{C_I i} + N_{C_E i} \\
N_{C_I i} &= N_{C_{I_{20}} i} + N_{C_{I_{40}} i} \\
N_{C_E i} &= N_{C_{E_{20}} i} + N_{C_{E_{40}} i} \\
N_{C_s i} &\leq N_{CS} \times \alpha \\
0 &\leq \alpha \leq 1.
\end{aligned}
$$

The net loading capacity N_{CS} of a ship in containers depends on the split of 20 and 40 ft containers. This split is expressed as the TEU factor F_{TEU}. The relation between container quantity and container volume N_{TEU} is as follows:

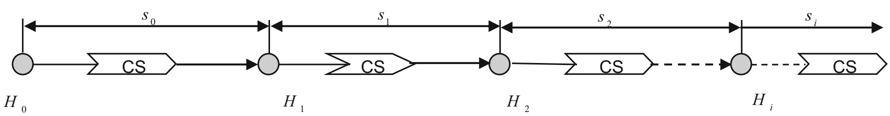

Fig. 11.3 Illustration of a round trip in container liner service

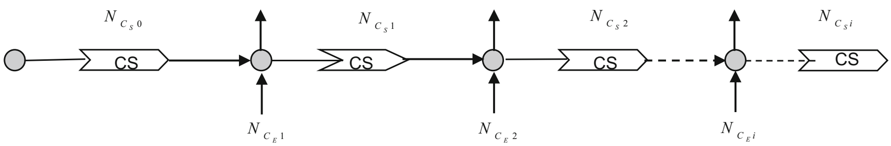

Fig. 11.4 Number of containers handled in a round trip

Fig. 11.5 Time components of a round trip

$$F_{TEU} = \frac{N_{TEU}}{N_C}; 1 \leq F_{TEU} \leq 2$$
$$N_{TEU} = N_{C_{20}} + 2 \times N_{C_{40}}$$
$$F_{TEU} = \frac{N_{C_{20}} + 2 \times N_{C_{40}}}{N_c} = 1 + \frac{N_{C40}}{N_C}$$
$$N_{C_{40}} = N_C \times (F_{TEU} - 1)$$
$$N_{C_{20}} = N_C - N_{40}.$$

Accordingly, the ship's net loading capacity can be expressed as:

$$N_{CS} \leq \frac{NTEU_S}{F_{TEU}},$$

where $NTEU_S$ is the ship's capacity in net TEU.

With this framework the round trip time T_R of a container ship can be calculated with a certain degree of accuracy as the sum of sea-times T_{s_i} and port lay times T_{L_i} (see Fig. 11.5). It should be noted that times for canal passages, unforeseen stops, etc. are not taken into account.

The time at sea per segment distance s_i is simplified here and calculated as follows:

$$T_{s_i} = \frac{s_i}{V_s}.$$

The port lay time is made up of a consistent arrival and clearance time T_{H_i} as well as the total handling time. The latter depends on the number of containers T_{U_i} to be loaded and unloaded, the number of quay cranes N_{CB} used for ship processing, and the specific handling time T_{UM} for a loading or unloading action of a quay crane. This time can vary from port to port and is also a function of the ship size. The influence of poor stowage planning shall not be taken into consideration. Furthermore, only single lift moves are being considered for quay crane operations. A container ship's lay time in port i can therefore be expressed as:

$$T_{L_i} = T_{H_i} + (N_{C_I}i + N_{C_E}i) \times \frac{T_{UM_{H_i}}}{N_{CB_{H_i}}}.$$

With the definition of the time components and handling volumes of a round trip, different cost types can be calculated and added up to the total round trip costs K_R. Within the total scope, there are five cost types being considered per round trip.

$$K_R = K_{FR} + K_{VHR} + K_{VSR} + K_{UR} + K_{sonst}$$

with:

K_{FR}= Fixed costs
K_{VSR}= Variable costs at sea (e.g., bunker costs)
K_{VHR}= Variable port costs (e.g., port and pilto dues)
K_{UR}= Variable handling costs
K_{sonst}= Additional costs e.g., Suez Canal

Each cost component has a specific daily or transaction oriented cost factor. For example, the specific fixed costs per day K_{FS} [EUR/day] are being multiplied with the round trip time T_R to calculate the fixed costs per round trip. K_{FS} depend on the size of the ship (often similar to the charter rate incl. crew) and reflect the economy of scale (see Fig. 11.6).

$$K_{FR} = K_{FS} \times T_R.$$

Although the numbers of the specific fixed costs per day K_{FS} were investigated in 2009 only the capital costs of a ship could be different in comparison to today. In dependency of the order date there can be some differences to older ships of the

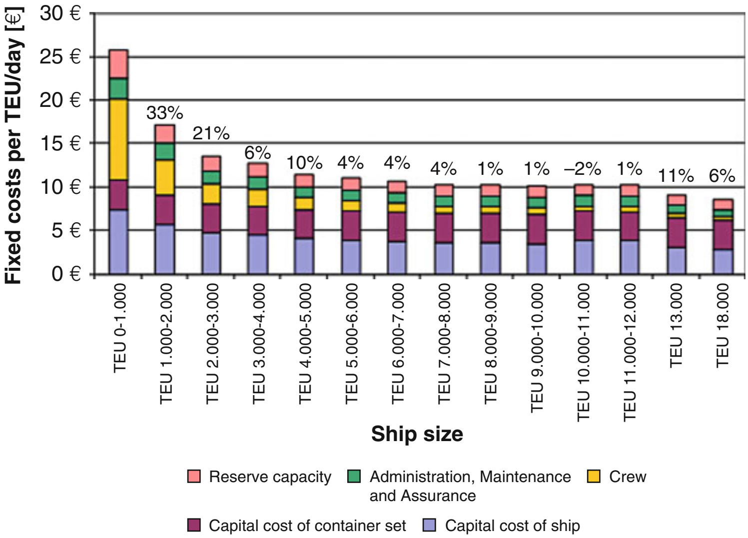

Fig. 11.6 Distribution of fixed costs ship size – relative change to its predecessor on the top of the columns. Calculation based on the NTEU capacity (see Schönknecht 2009, p. 46)

same size. Especially, the cancelation of ship orders – as Maersk it did for some Triple E-class ships (see WMN 2015) – creates some pressure on the new build prices for container ships. However, the new build price had – already on the higher price level of 2009 – only a cost impact of less than 20% on the total fixed cost, so that the potential changes in new build price can be neglected in the context of this investigation.

The variable port costs K_{VHR} are being based on the specific costs per port day K_{HS} and the time T_{L_i} staying in a port. The result K_{VH_i} is added up for all round trip ports. The specific costs per port day are usually calculated with the begin of each 24-h period staying in a port and are posted in the terms and conditions of port operators:

$$K_{VH_i} = K_{HS} \times T_{L_i}$$

$$K_{VHR} = \sum_{1}^{k} K_{VH_i}.$$

For the variable costs at sea K_{VSR} the specific cost factor K_{VS} [EUR/day] is being multiplied with T_{s_i}, the time at sea per round trip segment, and the result is added up for all segments:

$$K_{VS_{s_i}} = K_{VS} \times T_{s_i}$$

$$K_{VSR} = \sum_{1}^{k} K_{VS_{s_i}}.$$

The variable costs at sea mainly depend on the fuel consumption. Fuel consumption is defined by the utilization of the installed engine power which results in a corresponding speed. It is well known that small speed variations of ships have a significant impact on the engine power needed. Engine power and consumption are linear connected. Gudehus (2010) made a measurement for a 5000 TEU ship where he found following relation between fuel consumption per *n*autical *m*ile (nm) C_{nm} and speed V in *kn*ots (kn):

$$C_{nm} = 58 + 0.00013 \times V^{4.5}.$$

Ships of the same size but different service speed (or installed engine power, respectively) can therefore have significant differences in fuel consumption. This makes the identification of a large-scale effect in variable costs at sea difficult. Furthermore, in dependency of the chosen service speed bigger ships can have a significant higher fuel consumption per slot or vice versa. Comparing a speed variation from 23 to 25 kn approx. 35% more engine power for the same ship would be needed. A benchmark of installed engine power per slot is therefore only meaningful when the service or design speed of the ships is similar – but that is not given. However, the strong non-linear development of fuel consumption can be considered in the frame of the so-called *slow steaming*. Slow steaming is an acronym for operating a ship below its design speed. On the one hand, the fuel consumption per ship will significant drop with lower speed, on the another hand, additional ships need to be added in a container service for keeping the same departure frequency. With regard to these added ships slow steaming is probably only an "adjustment instrument" for temporary over capacities.

The handling costs per container are typically expressed by the quay tariff and split into 20 and 40 ft container. Thus, the handling costs K_{UR} for a round trip can be calculated based on the quay tariffs of the ports involved: $K_{KAI20_{H_i}}$ and $K_{KAI40_{H_i}}$

$$K_{U_i} = K_{U20_i} + K_{U40_i}$$

$$K_{U20_i} = \left(N_{C_{I20}}i + N_{C_{E20}}i\right)\ K_{KAI20_{H_i}}$$

$$K_{U40_i} = \left(N_{C_{I40}}i + N_{C_{E40}}i\right)\ K_{KAI40_{H_i}}$$

$$K_{UR} = \sum_{1}^{k} K_{U_i}.$$

Considering a specific round trip between Europe and Asia, the costs for various ship types are calculated and compared (see Fig. 11.7). The costs per slot and round trip drop with increasing ship size. However, the round trip time per ship is significant different.

The model so far developed can be used for different round trip cost simulations, for example, to show how events in ports (like various handling procedures) can affect a round trip. The varying parameters, e.g. handling volume, quay tariffs, etc., must be applied to the dedicated ports in the model. But the requested data volume is enormous and in dependency of the region not always public available. On top, it is practically impossible to simulate all variations of a round trip that exist between several continents for all ship sizes. The cost model must be abstract enough so that no specific round trip is necessary for benchmarking several ship sizes. In order to come to general conclusions regarding the commercial behavior of different ship sizes a general cost model will be proposed in the next section.

11.3.1.2 General Cost Model

The number of containers handled per round trip N_{CR}, like in Fig. 11.8, can be expressed for each ship as:

$$N_{C_R} = \sum_{1}^{k} (N_{C_I}i + N_{C_E}i).$$

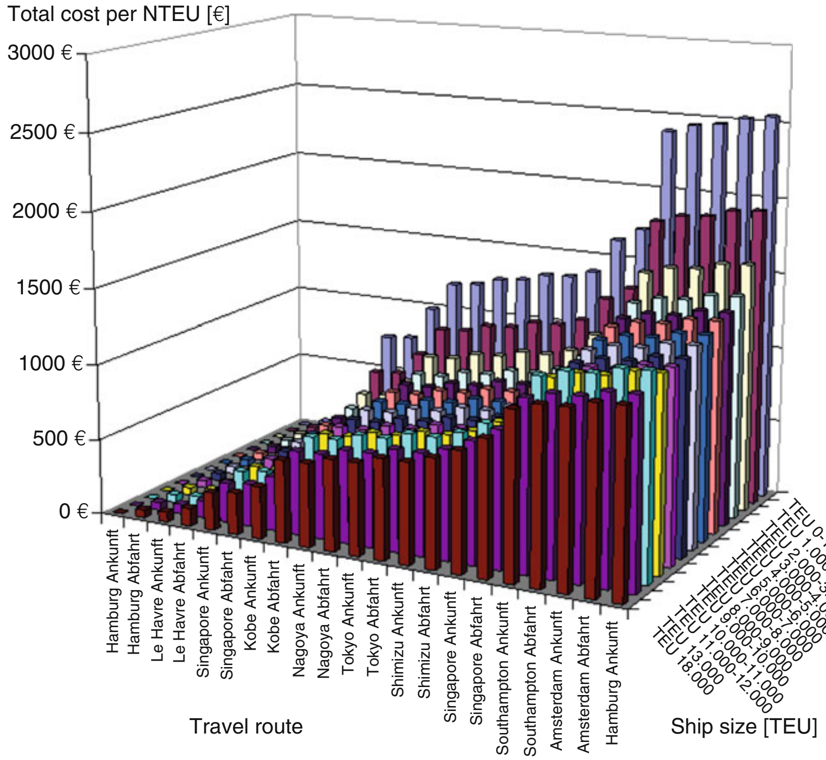

Fig. 11.7 Example of cost development of a round trip per slot for various container ship sizes in the ship-size clusters. Fixed costs from Fig. 11.6, ship data according Table 11.1, assumption of engine utilization for service speed 90%, specific fuel consumption 171 g/kWh, bunker price 250 EUR/t, container handling speed according to empiric data per TEU of Port of Hamburg, handling volumes 25–50% of ship net loading capacity in each port, handling charges 95 EUR per TEU in Europe and 80 EUR per TEU in Asia, port dues according to the average of Port of Hamburg and Rotterdam

The following can be stated per port:

$$N_{C_I i} + N_{C_E i} = \Delta_i \times \frac{NTEU_S}{F_{TEU}} \times \alpha,$$

where Δ_i is the amount of containers in port i measured in proportion to the ship's total capacity.

By using α, the already mentioned reduced capacity utilization (due to a reduced amount of cargo) can be modeled, and so the number of containers handled per

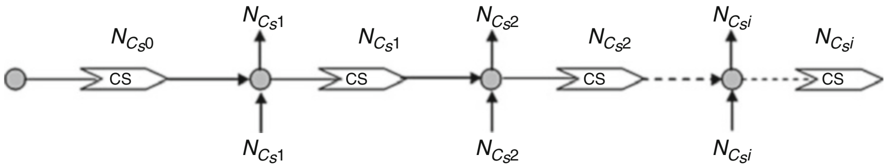

Fig. 11.8 Determining full container volumes

round trip is as follows:

$$N_{C_R} = \sum_{1}^{k} \Delta_i \times \frac{NTEU_S}{F_{TEU}} \times \alpha = \frac{NTEU_S}{F_{TEU}} \times \alpha \sum_{1}^{k} \Delta_i.$$

The proportion of handlings totaled per port and slot can be defined as re-use W_R of a slot per round trip:

$$\sum_{1}^{k} \Delta_i = 2 \times W_R.$$

One re-use per slot means that in the course of a round trip one container is being unloaded and another loaded. If a ship within the scope of a round trip sails, e.g. only between two ports, re-use can happen twice max. Four handling procedures would be necessary for this. Thus, the number of containers N_{C_R} handled per round trip and the handling operations necessary to achieve this, through the ship's net loading capacity in TEU, the utilization factor α and the assumed slot re-use W_R can be determined:

$$N_{C_R} = \frac{NTEU_S}{F_{TEU}} \times \alpha \times 2 \times W_R.$$

Each move will be charged at a quay tariff. These rates are different for 20 and 40 ft containers and between different continents. The breakdown of moves N_{C_R} for 20 and 40 ft is expressed as follows:

$$N_{C_R} = N_{C20_R} + N_{C40_R}$$

$$N_{C20_R} = \left(\frac{2NTEU_S}{F_{TEU}} - NTEU_S\right)\alpha \times 2 \times W_R$$

$$N_{C40_R} = \left(NTEU_S - \frac{NTEU_S}{F_{TEU}}\right)\alpha \times 2 \times W_R.$$

In terms of distribution of handling operations between continents, it is being assumed that half of the movements in a round trip occur on one continent. To simplify things, the same quay tariffs are assumed for one continent. The different quay tariffs can be expressed using a factor β, e.g.:

$$K_{KAI20_{Asien}} = \beta \times K_{KAI20_{Europa}}.$$

Based on these assumptions, the time components[2] of a round trip of k ports can be calculated as follows, without knowing them exactly:

$$T_R = T_{s_R} + T_{L_R}$$
$$T_R = \frac{s_R}{V_S} + k \times T_H + \frac{NTEU_S}{F_{TEU}} \times 2 \times \alpha \times W_R \times \frac{T_{UM}}{N_{CB}}.$$

Building on this, the cost components can be generated:

$$K_{FR} = K_{FS}\left(\frac{S_R}{V_S} + n \times T_H + \frac{NTEU_S}{F_{TEU}} \times 2 \times \alpha \times W_R \times \frac{T_{UM}}{N_{CB}}\right)$$
$$K_{VSR} = K_{VS} \times \frac{S_R}{V_S}$$
$$K_{VHR} = K_{HS} \times k$$
$$K_{UR} = \alpha \times W_R \times (1+\beta) \times \left(K_{KAI20_{Europa}}\left(\frac{2NTEU_S}{F_{TEU}} - NTEU_s\right) + K_{KAI40_{Europa}}\left(NTEU_S - \frac{NTEU_S}{F_{TEU}}\right)\right).$$

Other costs are unchanged in this calculation.

11.3.2 Earnings Model

The explanations of the following subsections refer to the earnings model for ship round trips developed here. The model enables the calculation of earnings for ships of different size operating in pre-defined regions of the word. Initially, Sect. 11.3.2.1 describes the earning components which are considered for this purpose. Analogously to the cost modeling approach, a generalized earnings model for round trip operation of container ships is developed in Sect. 11.3.2.2. The related model includes the same parameter characteristics for all (or certain groups of)

[2] Handling times are based on empiric data of the average berthing time per TEU of the Port of Hamburg (see Schönknecht 2009, p. 55).

round trip destinations (e.g., regarding freight rates or terminal handling charges) making the procurement of specific port information superfluous.

11.3.2.1 Earnings Model for a Round Trip

Every container transported creates costs. But only full containers can generate earnings. When calculating earnings, worldwide imbalances Q_R are to be taken into consideration. Imbalances are differences in goods flows between continents. For 2013, these imbalances in full container flows are shown in Fig. 11.9 (basis: WSC 2016).

In Trans-Pacific and Trans-Atlantic trades, the imbalances are typically between 50% and 60% and caused by trade differences between the regions. These imbalances not only create differences in the flow of full containers, they impact freight rates per direction as well. In the fully utilized direction, a considerably higher freight rate can be achieved than in the other direction.

Imbalances must be taken into consideration when ascertaining the volume of full containers for a round trip N_{CV_R} and also the appropriate freight rates. The volume of full container traffic for a round trip is made up of the sum of full containers for export $N_{C_{EV}}$ per port (Fig. 11.10).

$$N_{C_{SV}i} = N_{C_{SV}i-1} - N_{C_{IV}i} + N_{C_{EV}i}$$

$$N_{C_{SV}i} \leq NTEU_S \times \alpha\ (100\% - Q_{Ri})$$

$$0 \leq \alpha \leq 1\ ;\ 0 \leq Q_{Ri} \leq 100\%$$

$$N_{CV_R} = \sum_{1}^{k} N_{C_{EV}i}.$$

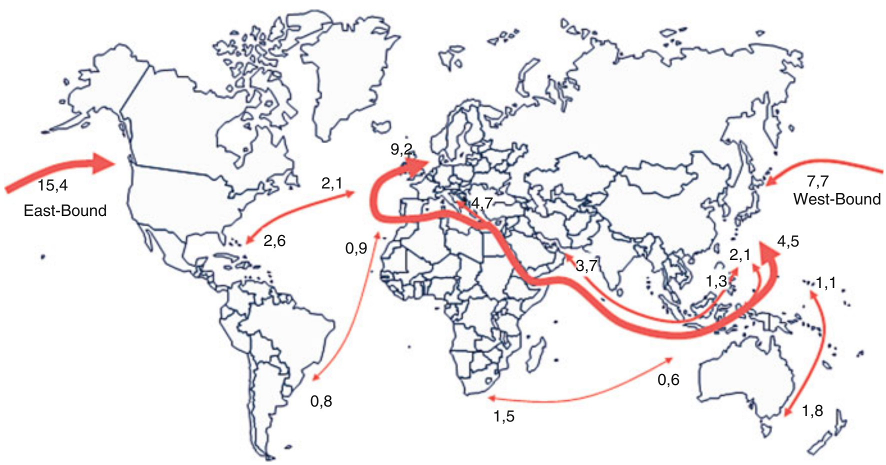

Fig. 11.9 Distribution of full container flows in million TEU in 2013 between Europe, Asia and North America

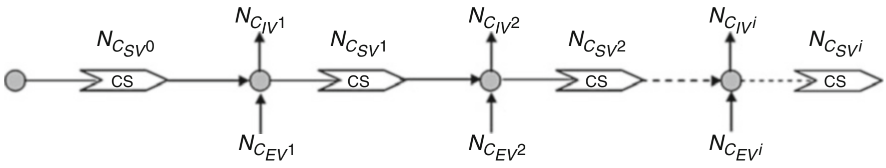

Fig. 11.10 Full container volume for a round trip

When considering earnings, the difference between 20 and 40 ft containers is to be taken into consideration:

$$E_{H20i} = N_{C_{EV20}i} \times E_{C_{20}}$$
$$E_{H40i} = N_{C_{EV40}i} \times E_{C_{40}}$$
$$E_{Hi} = E_{H20i} + E_{H40i}$$
$$E_R = \sum_1^k E_{Hi}.$$

Earnings per container E_C are made up not only of freight rates but also of surcharges such as the bunker adjustment factor BAF_{TEU},[3] the currency adjustment factor CAF_{TEU}, and the terminal handling charges THC which are different for 20 and 40 ft containers and for dispatch and receiving ports. As it is very difficult to allocate possible earnings to specific ports (just like the costs), the model is being adjusted to a general earnings model.

11.3.2.2 General Earnings Model

Freight rates for one direction are in relation with the opposite direction as follows:

$$E_{C\ Asia-Europe} = \delta \times E_{C\ Europe-Asia} \quad \in \ [0, 1].$$

The number of full containers per direction is the same as half the amount of handling movements in the round trip, when the imbalance is 0%. In an area with an imbalance, full container volume is reduced by the difference of imbalance volume and full capacity.

$$N_{CV_R} = \frac{NTEU_S}{F_{TEU}} \times \frac{\alpha}{2} \times W_R + \frac{NTEU_S}{F_{TEU}} \times \frac{\alpha}{2} \times W_R \ (100\% - Q_R).$$

[3]Container shipping lines collect an additional and variable extra charge in the form of this factor for compensation of bunker price variations.

When calculating earnings, the differing freight rates[4] for 20 and 40 ft containers are to be applied. In areas of imbalance, freight rates are reduced by the factor δ mentioned above. Earnings from full 20 ft containers per round trip can be calculated as:

$$E_{R20} = E_{C_{20}Europe-Asia}\left(\frac{2 \times NTEU_S}{F_{TEU}} - NTEU_S\right) \times \frac{\alpha \times W_R}{2}\,(1 + \delta\,(100\% - Q_R)).$$

Earnings for 40 ft containers can be calculated using:

$$E_{R40} = E_{C_{40}Europe-Asia}\left(NTEU_S - \frac{NTEU_S}{F_{TEU}}\right) \times \frac{\alpha \times W_R}{2}\,(1+\delta\,(100\%-Q_R)).$$

The sum of earnings of the two container types are the total earnings per round trip.

11.3.3 *Evaluating Profitability and Performance of Ship Operations*

Based on the models developed in the previous sections, the overall costs and earnings of the container ship clusters mentioned in Table 11.1 are calculated for a round trip of ten ports and typical parameters of the Asia–Europe route. Costs and earnings resulting from model application are aggregated to sound profitability and performance figures of container ship operations. For each ship cluster, the profitability is measured by the *R*eturn *O*n *I*nvestment (ROI) to be expected for the total round trip (see Sect. 11.3.3.1) and the performance is measured by the ROI based on a single a round trip day. The latter is also referred to as *ship productivity* (see Sect. 11.3.3.2).

11.3.3.1 Evaluating Ship Profitability

The ROI of a round trip is a simple measure of the round trip profitability (see Müller and Schönknecht 2005). It is defined as the relationship between profit and cost.

$$R_R = \frac{E_R - K_R}{K_R}.$$

[4]Freight rates include all elements, e.g. BAF, CAF, and THC.

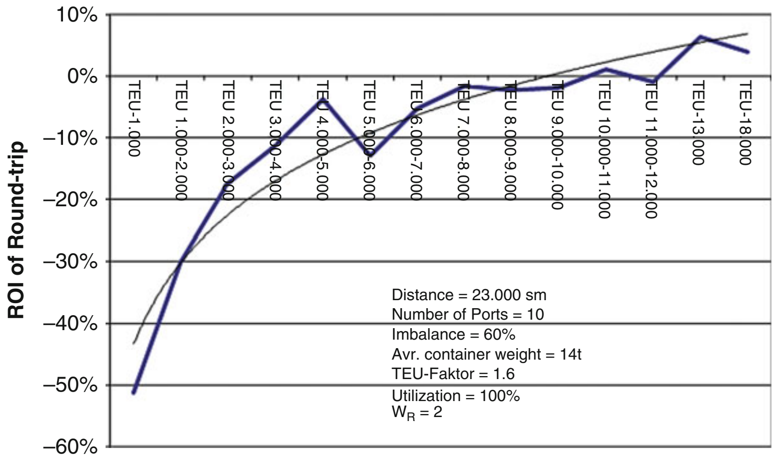

Fig. 11.11 Profitability comparison between the ship clusters of Table 11.1 based on the ROI of a round trip on the Asia–Europe route in 2016

The ship clusters defined in Table 11.1 and typical parameters[5] of an Asia-Europe round trip have been used for calculating the ship profitability (see Fig. 11.11). For the investigation, the speed at sea assumed for the ships of a cluster is typical for the related ships. This leads to different times at sea and thus to cluster-specific round trip times (see Fig. 11.12). Slowly ships have lower fuel consumption, however, needs more time for the same travel distance. Faster ships have higher fuel costs but are able to transport more containers per time unit. They make more round trips per year and increase by this effect the earnings.

Today (2016) smaller vessels up to approximately 9000 TEU are apparently no longer able to carry out profitable trips on the Asia-Europe route. In 2009, this limit was at around 3000–4000 TEU (see Schönknecht 2009). Above a size of about 9000 TEU, a low positive ROI is possible if the utilization is at 100%. This 7-years comparison shows the dramatic commercial situation of the container shipping industry.

For the calculation of the port lay time, first, a representative loop port of a region is selected. Ship dwell times at this port are assumed for all other loop ports of the region based on the actual number of TEU handlings considered for a ship cluster on the round trip. For European ports, for example, a statistics analysis of the Port of

[5]Fixed costs from Fig. 11.6, ship data according Table 11.1, assumption of engine utilization for service speed 90%, specific fuel consumption 171 g/kWh, bunker price 330 EUR/t, container handling speed according to empiric data per TEU of Port of Hamburg, handling volumes 200% of ship net loading capacity over all ports, average handling charge 108 EUR per TEU, port dues according to the average of Port of Hamburg and Rotterdam in each port, freight rate A-E 20 ft 720 $, freight rate A-E 40 ft 1271$, freight rate E-A 20 ft 280 $, freight rate A-E 40 ft 460 $, BAF 420 $/TEU, CAF 8%, THC 143 $/TEU, $/EUR 1.15.

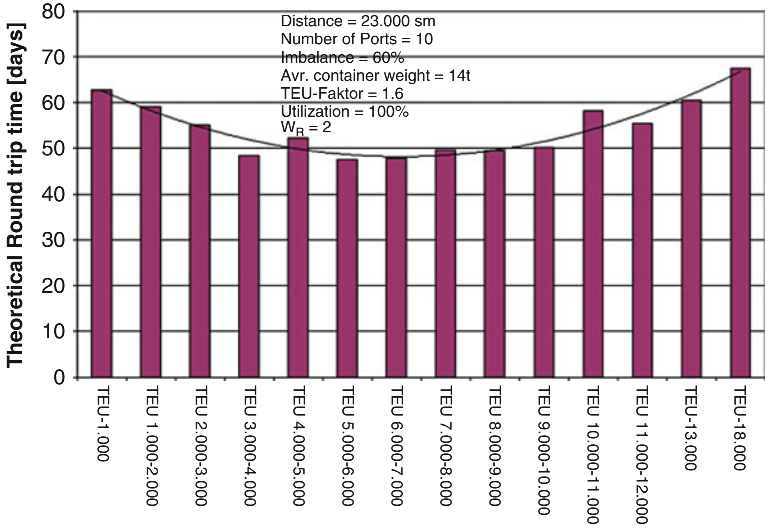

Fig. 11.12 Distribution of the round trip time for a loop of 23,000 nm with 10 ports (Asia–Europe route)

Hamburg from 2009 is used, where the port lay time was measured in comparison to the handled container volume (i.e., un-/loaded TEU per ship). According to these figures, a large container ship above 10,000 TEU is taking approx. 25 s per handled TEU in a port. This includes all needed activities such as berthing, bringing quay crane in position, the real handling time with all used quay cranes, etc.

As today, more or less the same quay cranes and handling technologies are working as in 2009 – except some few new cranes with minor innovations – it will be assumed that the port lay time is still in the same range. According to Fig. 11.12, the round trip time for the approx. 23,000 nm on the Asia-Europe route is in the range of 67 days for ships larger than 10,000 TEU. A spot check of the current sailing plan of Hapag-Lloyd is underlining this calculation.

Alternatively, theoretical calculation models for container handling times exist which consider, e.g., the optimal number quay cranes per ship. In planning practice, they are often being used for dimensioning container terminals. However, compared to reality, these models frequently calculate the (overall) port lay time as too short, which is confirmed, e.g., by experiences in the Port of Hamburg. Accordingly, for the present analysis, empiric port data is used and not theoretical handling times being generated by related models.

Considering the different components of the cost model (see Sect. 11.3.1.2), the time needed to go through a round trip has significant impact on the round trip costs and with that on the profit. As already mentioned, the same applies to the annual earnings of a container ship since the round trip time directly determines the number of trips per year and thus the annual shipping volume. As the round trips of the ship clusters considered have all different times, for a correct comparison of the profitability, the ROI of a ship per equal time unit needs to be considered. Hereinafter, this is referred to as *ship productivity*.

11.3.3.2 Evaluating Ship Productivity

A ship's productivity can be operationalized in various ways. In the scope of this study, the productivity is defined as the ship's profitability per round trip divided by the round trip time.

$$P_R = \frac{R_R}{T_R}.$$

The ship profitability of the Asia-Europe round trip results in the productivity shown in Fig. 11.13.

For the present round trip example, the productivity between 13,000 and 18,000 TEU seems to drop or is pretty much the same. It seems that with the chosen parameter and market input data the optimum is achieved or short before to be achieved. Profitability and productivity of ship operations can be additionally influenced by the following (non-monetary) parameters:

- Average container weight affects net slot numbers $NTEU_S$
- TEU factor F_{TEU} affects stowage structure and therefore the number of handling moves
- Imbalance Q_R affects full container volume

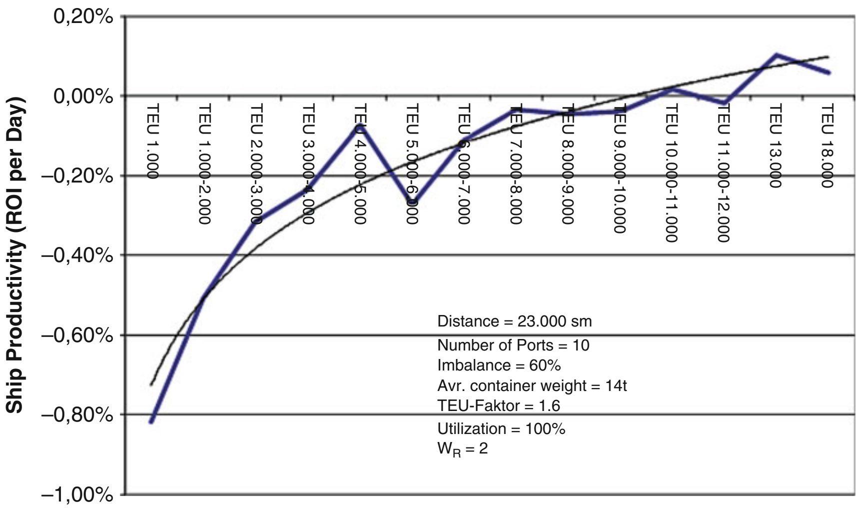

Fig. 11.13 Productivity comparison between the ship clusters of Table 11.1 using data of Figs. 11.11 and 11.12 from 2016

- Utilization α affects total container volumes
- Reactivation W_R affects total container volumes
- Length of the handling process T_{UM} per quay crane affects port lay time
- Number of quay cranes in use N_{CB} affects port lay time
- Speed chosen for a service

A detailed discussion of all these parameters is shown in Schönknecht (2009). Except for the first parameter none of the others have anything to do with the size of the ship. Even the first parameter is determined by trade and cargo development and is not within the influence radius of a shipping line or shipyard. In so far, the discussions on the profitability or unprofitability of a ship must more include than the discussion of the right ship capacity in slots.

A parameter not mentioned explicitly up to now is the number of ports of call in a round trip. The number of ports of call does not affect handling time. It does not matter if all containers are loaded and unloaded in one port or spread between five, for example. Pure handling time is theoretically identical. Merely through arrival time and port charges a slight time delay and added costs can arise, although these work out considerably lower than handling time and quay tariffs.

Admittedly, by far not all ports in the world are equipped to handle large container ships. With increasing size of ships, the number of ports in the world which can operate these big ships will be less and less. Limiting factors are, in particular, the port draft and the outreach of quay cranes over the container bays. Furthermore, due to the punctual handling of large container volumes in comparison to the timewise more distributed container handling of smaller ships, the hinterland connections are coming more and more in the focus (see Sect. 11.4).

11.4 Feedback of the Development of Ship Size on the Transport Chain

In the light of research done up to the present time, it can be said that factor Δ from Fig. 11.2 needs to develop over-proportionally to the ships' growth when large container ships shall have similar or significant better profitability and productivity than smaller ships. That is, beside technical reasons (see Sect. 11.3.3.2), economic reasons as well lead for large container ships to the necessity to use (turn) their slots in less ports than smaller ships. This helps to limit the round trip time of larger ships which is longer than that of smaller ones (assuming the same speed at sea) due to the higher number of container handlings to be carried out on a round trip.

The consequence is that container ships handle more containers per port in comparison to their capacity with increasing size. Rodrigue (2017) supports this statement. When larger container ships need to reduce the number of ports per round trip the peak load in container handling will increase inside the ports of call. This development will not remain as isolated phenomenon for a few ships. If the larger ships replace the current fleet and will be the dominating ship class, then the ports and port terminals will deal or deal already with stronger peak volumes. These high volumes of containers will set new challenges on the storage areas as well as on the technical and organizational design of container flows from/to the port hinterland.

The storage conditions in many ports of the world are already adapted. But the hinterland situations suffer and cannot be improved easily due to competing use of urban infrastructures. In this regard, the much discussed hinterland terminals could relax the situation. More traffic concentration for the container pre- and on-carriage is probably the only possibility for improving the traffic situation around port areas and can be on top a differentiation criteria for port regions in the international competition.

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Chapter 12
Ensuring Navigational Safety and Mitigate Maritime Traffic Risks While Designing Port Approaches and Ship Maneuvering Areas

Hans-Christoph Burmeister

Abstract Safety of ships is of major importance when approaching a port and berthing at a terminal. Continuously increasing ship sizes raise the pressure on proper design of new waterborne infrastructure, but also on safety and risk assessment methodologies when applied to ships of the new generation for existing infrastructure. The chapter introduces international accepted approaches on how to design waterborne infrastructure (especially port approaches and related maneuvering areas) for ensuring safe ship navigation and maneuvering. Moreover, basic methods and guidelines of safety and risk assessment used for this purpose in the maritime world are presented.

12.1 Introduction and Basics

12.1.1 Port Approaches

Port approaches are the infrastructural links allowing ships to sail from the shore-side interface at the quay to the open, freely navigable sea. As seabed rises the closer you are to shore, port approaches are normally characterized by narrow navigable waterways, which concentrates maritime traffic to certain tracks on the so-called channels and fairways. For the mariner, approaching represents the phase of transition from coastal to port navigation (see IALA 2014).

Thereby, a fairway is in principle navigable water which is indicating the way from and to open waters. Fairways are often marked by the so-called aids-to-navigation, being “any device or system [. . .] which is provided to help a mariner determine position and course, to warn of dangers or of obstructions, or to give advice about the location or a best or preferred route” (see IALA 2014). Typical

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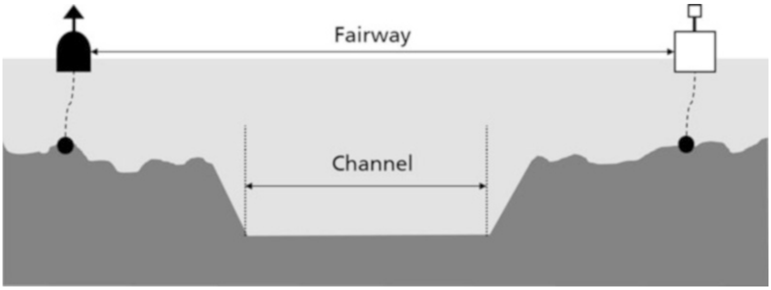

Fig. 12.1 Relation Fairway to channel (own drawing based on PIANC (2014))

representatives are buoys (lateral marks) or lighthouses (with e.g., leading or sector lights).

Indeed, channels are normally specific parts of fairways providing a certain “width and depth that is sufficient to allow safe passage of the design ships” (see PIANC 2014). As depicted in Fig. 12.1, the marked fairway is intended to be used by a wider range of ships, while those with the maximum dimensions, the so-called design ship, stick to the channel part of it. In general, this is the only area, where water depth is constantly monitored and maintained.

The objective of the contribution is to give an overview of

– how an initial design of the main fairway parameters can be derived by empirical approaches,
– how it can be further refined and how its safety level for one ship can be assessed by means of ship-handling simulation, and
– how the overall traffic risk can be assessed by means of frequency models.

12.1.2 Safety of Navigation

Navigation is “the process of planning, recording, and controlling the movement of a craft from one place to another” (see IMO 2001). Safe navigation is of major importance to many maritime stakeholders and participants. However, around 100 total losses of ships are accounted for each year, fortunately with a declining trend. The majority of the total losses are related to bad weather and foundering accidents that occur far away from ports and terminals. However, approximately 20% of all total losses can be assigned to grounding accidents that normally happen closer to shore or during port approaches (see Dobie 2016).

Besides the category of total losses, less severe maritime accidents occur even more frequently, as, e.g., demonstrated by the German Federal Bureau of Maritime

Casualty Investigation.[1] While the Federal Bureau normally lists less than 10 very serious marine casualties per year in German waters and for German vessels, the number of less severe marine causalities is more than 20 times the size, with more than 200 events. This is especially the case in the accident categories "grounding" and "collision with ship and object" that includes port and approach-related accidents (see BSU 2016).

Studies show that a wide majority of these accidents involves human failures (see Blanding 1987; Rothblum 2002; Sandquist 1992). Approaching and maneuvering in ports are thus very challenging operations, as restricted fairways and turning basins are less fault tolerant than the operation in open seas, which is also why, e.g., higher position accuracy and more real-time information are required in this phase (see IALA 2014).

Aiming at sufficient safety margins, guidelines have been developed to ensure proper channel design for the development of fairways, with PIANC (2014) being internationally the most prominent one. Hereby, PIANC provides both empirical methods and guidelines for the early concept design phase to develop an initial layout and recommendations regarding simulation and physical test methods for detailed design studies in the later design phase when the final layout is derived. Especially the empirical approach for safe fairway design will further be detailed in Sect. 12.2.

After port construction is completed, widening and deepening of channels do not always keep pace with the increase in ship sizes, especially in Western Europe. Thus, for existing infrastructure and newer, larger ships, safety assessments are indeed in the focus of interest to ensure safety even once operating ships' dimensions are outside the PIANC guidelines' limits. Here, assessing safety is normally done by ship-handling simulations, which are touched at the end of Sect. 12.2.

While the above-mentioned approaches are primarily designed for analyzing and assessing the safety of individual ships, Sect. 12.3 introduces the concept of frequency modeling as the basis of the IALA iWrap MkII framework developed by the *I*nternational *A*ssociation of Marine Aids to Navigations and *L*ighthouse *A*uthorities (IALA). This framework represents a tool to assess ship traffic risks in certain areas.

12.2 Design of Fairway Channels and Port Basins

Designing a fairway's channel according to PIANC (2014) initially requires defining a design ship, which represents a ship that shall be capable to navigate safely on the fairway's channel. As a minimum, the definition of the design ship

[1]The Federal Bureau of Maritime Casualty Investigation is a department of the German Ministry of Transport and Digital Infrastructure and translated into German the *B*undesstelle für *S*eefall*U*ntersuchung (BSU).

should contain the main dimensions length, width, draught, and air draught as well as an indication regarding the ship type and/or its maneuverability capabilities. Based on these characteristics and given certain environmental statistics and data being available (e.g., about prevailing wind or swell directions and strength), the guideline then allows to empirically determining the following core attributes of channel elements:

Vertical dimensions

- Water depth
- Bridge height

Horizontal dimensions

- Straight channel (width and length)
- Bends (width, angle, and radius)
- Maneuvering basin (radius)

In both dimensions, the design guideline distinguishes between outer and inner channels, basically meaning if the channel is exposed to waves or protected by breakwaters or within river estuaries.

12.2.1 Water Depth

Regarding fairway navigation, it is important to consider that water depth is not fixed, but mostly a time-dependent value. This is due to the fact that both seabed level and water level constantly change over time, e.g., by tide or silting. Thus, the available water depth at the same position can differ substantially, especially due to changes in the water level height, mostly due to tide. For navigation, reference is therefore normally made to the specific water depth at *L*owest *A*stronomical *T*ide (LAT), which is the "lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions" (see IHO 2009).

The required water depth is of course basically determined by the design ship static draught, meaning the maximum vertical immersion of the ship in the water at zero speed measured from the water line (see also Fig. 12.2). However, there are further factors influencing the necessary water depth that can be attributed to three main categories:

- Water level factors, meaning additional safety margins due to, e.g., tidal changes in the water level;
- Ship-related factors, meaning additional safety margins mainly due to dynamic changes in the ship draught, e.g., because of squat and heeling effects;
- Bottom-related factors, meaning additional safety margins between the nominal channel bed and the dredged channel, e.g., to account for silting during dredging;

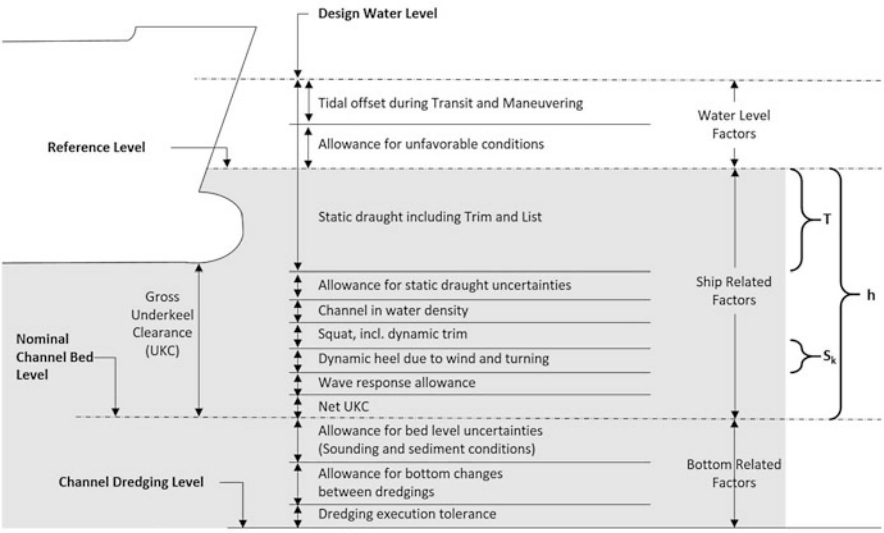

Fig. 12.2 Water depth design factors (see PIANC 2014)

As it can be seen indicatively in Fig. 12.2, ship-related factors have the most dominant influence on water depth requirements. PIANC's empirical approach allows determining the required water depth h as a function of the design ship's static draught as follows:

$$h = F_s + S_k \tag{1}$$

with

h: water depth required for design ship
F_s: ship-related factors
S_k: additional sinkage

F_s should of course be determined individually for all the above-mentioned components, but in early design phases an initial estimate for the inner and outer channel depth can also solely be based on the critical factors ship's speed and wave height, respectively:

$$F_s = \begin{cases} F_{speed} \times T + h_{bottom} & \text{in inner channel} \quad (2.1) \\ F_{wave} \times T + h_{bottom} & \text{in outer channel} \quad (2.2) \end{cases}$$

with

F_{speed}: ship's speed factor
F_{wave}: wave height factor
T: static draught of design ship
h_{bottom}: safety margin due to grounding risks

The safety factor for waves (F_{wave}) ranges from 1.15 to 1.40 depending on the environmental conditions, while that for the ship's speed (F_{speed}) is in inner channels less wide from 1.10 to 1.15. Additional a safety margin h_{bottom} for hard and thus grounding-risky bottom types can be up to 1.0 m.

While choosing wave height as critical factor for the outer channel might be obvious, one needs to dig a bit into hydrodynamics to understand the selection of ship's speed as critical factor for inner channels. In shallow waters, ships get closer to the seabed when their speed increases. This is due to the so-called *squat effect* meaning a low pressure zone below the ship induced by the decreasing cross section of the water by the ship's body that consequently increases the ship's dynamic draught.

Indeed, S_k takes into account the additional sinkage of the ship due to wind-induced heeling for a certain roll angle ϕ_{WR}, which is normally between 1.0° and 2.0°. Given the geometry of the keel curve, S_k is calculated by:

$$S_k = F_k \times \left(\frac{B}{2} \times \sin \phi_{WR} \right) \tag{3}$$

with

S_k: sinkage by wind-induced heeling
F_k: keel curve geometry
B: design ship width
ϕ_{WR}: roll angle

Using the empirical method described above, an initial estimate of the water depth required for the considered design ship can be already given at an early development stage of new fairway channels. For more details on the approach and further methodical aspects, it is referred to (see PIANC 2014).

12.2.2 Straight Channels

The next step concerning channel design is to draw up the horizontal dimensions. The ideal channel is short and straight, needs no dredging, is protected from wind, current, and wave and has basins at either end of the channel (see PIANC 2014). Thus, the main design parameter to be determined is the channel width. Of course, the required width is basically determined by the design ship's breadth. However, there are further factors within the conceptual design determining this dimension of a one-way channel. Related factors can again be attributed to the three main categories:

- Ship-related factors, specifically the basic maneuverability, which means a special safety margin to take into account the ship's swept path, which normally exceeds its breadth also in perfect environmental conditions, e.g., due to the ship's inherent maneuverability and the ship's latency to react on commands;
- Environmental and traffic-related factors, meaning, e.g., safety margins for prevailing wind and wave conditions as well as existing aids-to-navigation;
- Channel-related factors, meaning safety margins for bank clearance;

Within the conceptual design of PIANC (2014), the width W_{one} of a channel is given by (see also Fig. 12.3):

$$W_{one} = W_{BM} + \sum W_i + W_{BR} + W_{BG} \quad (4)$$

with

W_{one}: total bottom channel width of a one-way fairway
W_{BM}: width of the basic maneuvering lane
$\sum W_i$: additional safety margins for environment and traffic to determine the width of the full maneuvering lane
W_{BR}, W_{BG}: needed bank clearances on the channels (red) port side and (green) starboard side, respectively

The *basic maneuvering* lane width on a conceptual level is solely determined by the design ship's assumed maneuverability. Considering the defined ship type, the related lane width ranges from 1.3- to 1.8-times the design ship's width (B). As this is normally given, the factors allowing for optimizing the channel width are primarily environmental- and traffic-related and can be attributed to the following sub-categories (in descending order based on their importance):

Major factors (safety margins of more than $1.0 \times B$ per category possible)

- Expected maximum cross current,
- Expected maximum cross winds, and
- Expected maximum wave height.

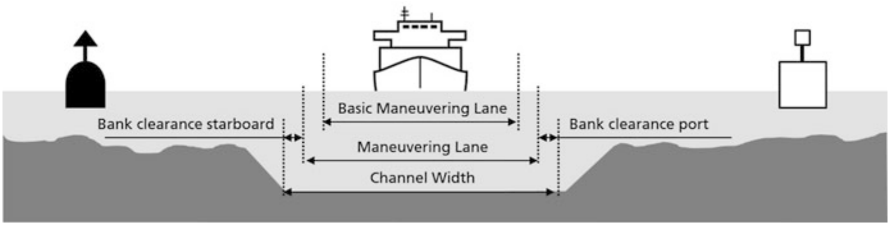

Fig. 12.3 Channel characteristics and clearances of a one-way fairway in the horizontal dimension

Minor factors (usually safety margins of less than $0.5 \times B$ per category)

- Expected longitudinal current,
- Prevailing aids-to-navigation,
- Expected water depth,
- Bottom type, and
- Expected speed through water.

Furthermore, additional safety margins for bank clearances of up to $1.3 \times B$ per channel side might be required, in case of steep embankments in combination with high passing speeds. This is required to minimize *bank effects*, which can be seen as the horizontal counterpart to the *squat effect*. That is, due to pressure difference at the bank's side, the ship tends to laterally move towards the bank and turn its bow towards the middle of the channel. The higher the ship's speed and the steeper the bank increases, the higher this pressure difference will be requiring the described additional safety margin to reduce its effect on ship safety.

In case of one-way fairways, the approach presented above enables an early estimate of a channel's necessary width for the intended design ship. It is worth noting that a combination of bad circumstances can result in a width increase of nearly up to 10.0-times the design ship's breadth, highlighting the importance of proper environmental-related design to minimize dredging and maintenance effort later on. Analogously to one-way channels, a two-way channel's width W_{two} is given by

$$W_{two} = 2W_{BM} + 2\sum W_i + \sum W_p + W_{BR} + W_{BG} \quad (5)$$

with

W_{two}:	total bottom channel width of a two-way fairway
W_{BM}:	width of each of the basic maneuvering lanes
$\sum W_i$:	additional safety margins for environment and traffic to determine the width of each full maneuvering lane
$\sum W_p$:	additional safety margins for passing distance
W_{BR}, W_{BG}:	needed bank clearances on the channels (red) port side and (green) starboard side, respectively

The formula above basically reflects the need for two maneuvering lanes due to encountering ships (assuming that both ships belong to the same design ship class) as well as an additional safety margin $\sum W_p$ as passing distance, which ranges between 1.0- and 2.5-times the design ship width depending on ship's speed and traffic density (see Fig. 12.4). For further details, it is referred to (see PIANC 2014).

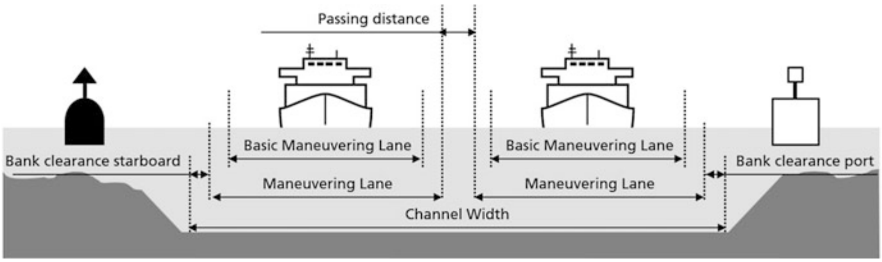

Fig. 12.4 Channel characteristics and clearances of a two-way fairway in the horizontal dimension

12.2.3 Bends

Besides the ideal situation of a sole straight channel, local circumstances as well as the bathymetry often require more meandering port approaches. To keep related channels safely navigable, a proper design according to PIANC (2014) should at least provide a certain straight leg between two bends of ideally 3.0- to 5.0-times the length of the design ship. In the horizontal dimension, the conceptual bend design comprises the following two main characteristics:

– Bend radius and
– Bend width.

Bends should provide constant radii that the design ship can manage to steer without using hard rudder, but only 15–20° of rudder angles to maintain a certain safety margin. Depending on the design ship's ability for course changing as well as the depth-draught-ratio, bend radii range between 4.0- and 7.0-times the related ship length. The width of a bend is primarily defined by the same concept as for straight channels, but with an additional factor to take into account the increasing effective ship width during the turn. This additional safety margin depends strongly on the depth-draught-ratio, as course stability increases in shallow waters and thus can be between 30% and 40% in shallow and 100% and 160% in deep waters.

12.2.4 Turning Basins

The turning basin's main characteristic is its diameter. Compared to the conceptual design of bends and channels, PIANC (2014)'s recommendation regarding turning basins is rather simple: Consider a turning basin diameter of at least 2.0-times the design ship's length for tug-assisted turns and 3.0-times in the absence of tug assistance.

Based on simulator studies, McCartney et al. (2005) suggests even smaller minimum diameters with 1.2- to 1.5-times the design ship's length for low (<0.5 kn) and medium-strong (<1.5 kn) current flows. For high currents or special windy areas, he indeed suggests more detailed simulation studies instead of empirical formulas as well as elongated turning basins instead of pure circles.

12.2.5 Ship-Handling Simulation

Applying an empirical approach to determine a port's waterside infrastructure enables "quick" design results. Nevertheless, there are (two) negative implications for future-proof design:

- First, as related methods and guidelines are primarily based on simple empirical models, they contain big safety buffers to cover a variety of not further analyzed effects. This may result in over-dimensioning and thus high dredging and maintenance costs.
- Secondly, an empirical approach is frequently not directly applicable again after port construction is completed, since ship sizes increases beyond the intended design ship's limits. As infrastructure is in that case already settled, supplementary changes might result in high costs or might even not be possible at all due to legal or environmental constraints.

Thus, ship-handling simulation is applied to make a more detailed appraisal of the navigational situation within a port approach. Actually, ship-handling simulators have been primarily designed for nautical education. The simulator use in training is internationally governed by the STCW[2] convention (see IMO 2011). They allow for executing scenarios in real-time by providing a mock-up of the bridge systems like ECDIS (*E*lectronic *C*hart *D*isplay and *I*nformation *S*ystem), conning and radar as well as a 3D visualization, e.g., for the view from the bridge. These bridge systems are connected to the main simulation core that primarily calculates the ship movements by hydrodynamic maneuvering models with six degrees of freedom (for details, see, e.g., Fossen 2011).

Besides the application of ship-handling simulators in training, real-time ship maneuvering simulation is also a recommended approach for detailed fairway assessment (see PIANC 2014). This is especially true in case of existing structures. In short, those assessments consist of four logical tasks:

1. Assessment scenario definition,
2. Modeling of simulation environment,
3. Real-time simulation as well as
4. Analyzing and assessing simulation results.

Within the scenario definition, the area of investigation as well as the design ship and operational circumstances (environment, accident scenarios, tug usage, etc.) are defined to derive a simulation matrix. Pre-analytics by empirical formulas

[2] *S*tandards of *T*raining, *C*ertification and *W*atchkeeping for Seafarers.

like PIANC (2014) can help to limit size and complexity of the scenarios to be investigated, as real-time simulations are normally quite time- and resource-intense.

Additionally, the simulation environment must be prepared, which especially requires proper physical modeling of the ship's and environment's hydrodynamic characteristics. Compared to the regular nautical training, which is generally more about bridge processes and less about precise ship maneuvering, the accuracy requirements for simulation-based fairway assessment are much higher. In Germany, for example, this even resulted in external quality assessment requirements (see BAWiki [Hydraulic Engineering Methods] 2011) to be considered for such simulation studies.

While the simulation and hydrodynamic experts are responsible for generating an adequate simulation environment, nautical experts (in many cases the pilots) usually control the simulated ship during the scenario runs. This competence split allows for both a methodological proof by means of reproducible simulation environments and an in-depth knowledge-based assessment of the navigational situation and ship safety. Generally, this proceeding leads to the successful optimization of a fairway's channel dimensions compared to the empirical limits resulting from (see PIANC 2014).

12.3 Risk Assessment of Maritime Traffic Layouts

While the ship's individual safety especially results from the interaction of the ship with the respective waterway conditions, building new terminals also has an effect on safety on a ship traffic level, e.g., due to new crossing traffic volumes or the increasing use of a fairway layout by more ships. Thus, besides if it is safe for an individual design ship to navigate the intended path, it shall also be assessed the impact on traffic safety by several ships using a waterway in the same area. Necessities for this especially arise if considerable changes in the fairway traffic are recorded or expected, respectively. In such cases, resulting effects on the overall traffic safety are normally quantified by the so-called *maritime risk assessment*.

According to IMO (2007), the term "risk" is defined as *the combination of the number of occurrences per time unit and the severity of their consequences.* The occurrence might, e.g., be a collision or a grounding event. Its consequence is, e.g., an oil leakage or a sinking ship, which is mostly measured in monetary values. Thus, it implies the common risk definition as *probability of a collision multiplied by its expected damage* (see Pedersen 2010).

To quantify the risk on fairways or at sea, the International Association of Marine Aids to Navigations and Lighthouse Authorities IALA recommends a probabilistic methodology based on *frequency modeling* – the IALA iWrap MkII framework (see IALA 2009). Thereby, frequency models are easy to apply to different fairway designs and traffic forecasts allowing a quick comparison of risk levels for alternative fairway designs and operations, as they can also assess, e.g., effects of one-way regulations or overtaking restrictions. Thus, they assist in identifying high risky areas of current fairway designs and in assessing infrastructural or operational risk mitigation measures during the planning process to keep risk *A*s *L*ow *A*s *R*easonable *P*racticable (ALARP). ALARP "refers to a level of risk that is neither negligibly low nor intolerable high [and] is actually the attribute of a risk, for which further investment of resources for risk reduction is not justifiable" (see IMO 2007). The exact level of ALARP does however differ between different projects, national practices and recommendations and need to be clarified beforehand in interviews with the respective regulating authorities. Frequency models are based on the work of Macduff (1974), Fujii (1983) as well as Pedersen (1996). The methodology has been applied in several analyses, e.g., in the Canary Islands (see Otto et al. 2002), in the Øresund (see Rambøll 2006), in the Gulf of Finland (see Kujala et al. (2009) as well as Hänninen et al. (2012)) or the river Weser (see Jahn et al. 2013).

In this context, "frequency" corresponds to the expected number of collision events N_c during a specific time. In principle, this number is calculated by multiplying the expected value of the number of collision candidates N_a with the causation probability P_c:

$$N_c = P_c \times N_a \tag{6}$$

A collision candidate represents an encounter situation that would result in a collision, if "blind navigation" of the encountering vessel(s) is assumed, ergo neither detection of the situation nor any action by any officer of the watch. Furthermore, the causation probability reflects the share of these situations that really results in a collision. Thus, it is the inverse probability with that the officer of the watch detects the uprising critical situation and is able to take proper action to avoid it.[3]

To assess the overall risk change in a spatial area, this area is divided into different individual risk situations. Basically, the methodology distinguishes collisions between *ships underway* (see Sect. 12.3.2) and between a ship and an *object* (see Sect. 12.3.2). Grounding events are considered as "collisions," since they are methodologically similar to collisions with fixed objects.

[3]Whenever a ship operates in a (defined) spatial area the ship may encounter with other ships or "fixed objects" which are in this area as well. Based on a great many observations, an average number of specific encounter situations (e.g., characterized by a maximum passing distance) is to expect in a time slot. These situations may be subdivided into three categories:

Two ships (or a ship and a fixed object)

[I] safely pass each other and the ship(s) involved do not change their course and/or speed or

[II] threaten to collide but avoid each other due to human detection and appropriate countermeasures or

[III] collide with each other due to missing human detection, with human detection but inappropriate countermeasures or technical failures during the encounter.

The sum of the situations of category [II] and [III] accounts for the number of collision candidates.

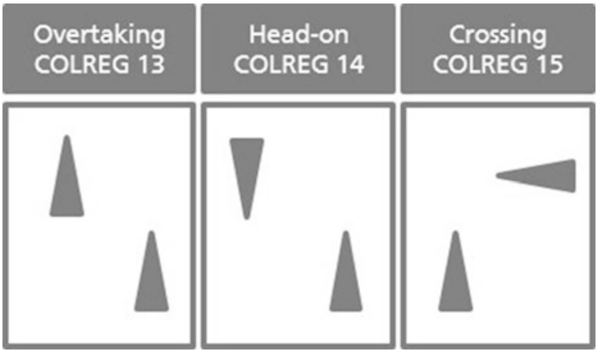

Fig. 12.5 Generic types of encounters in risk assessment

12.3.1 Ship-to-Ship Collisions Risk Assessment

With regard to ship-to-ship collisions, *frequency modeling* differs for three categories based on the encounter angle of the ships, see Fig. 12.5[4]:

1. Head-on encounter (encounter angle $<10°$),
2. Overtaking (encounter angle $>170°$) and
3. Crossing.

Ships do not sail on rails, so the chosen path of the ship in the fairway varies slightly from voyage to voyage. This variation is described by a lateral distribution, which is a statistical function describing the probability for a certain cross-track distance of the ship from the leading (center) line of the fairway, which forms the essential input into risk assessment. For ship-to-ship encounters, an integrated integral of the two encountering ships' lateral distribution can thus be used to determine the probability of a collision candidate:

$$P_{a\,i,j}^{enc} = \int_{-\infty}^{\infty} \int_{z_i-\overline{B}}^{z_i+\overline{B}} f^{(1)}(z_i) \times f^{(2)}(z_j)\, \mathrm{d}z_i\, \mathrm{d}z_j \qquad with\ \overline{B} = \frac{B_i^{(1)} + B_j^{(2)}}{2} \tag{7}$$

with

$P_{a\,i,j}^{enc}$: probability that an encounter between the two ship groups i and j takes place on this fairway

$f^{(1)}(z_i)$, $f^{(2)}(z_j)$: lateral distribution of the ship tracks travelling in the two directions (1) and (2) of the fairway

[4]COLREGs are International *REG*ulations for Preventing *COL*lisions at Sea which are derived from a multilateral treaty from 1972 called *Convention on the International Regulations for Preventing Collisions at Sea*.

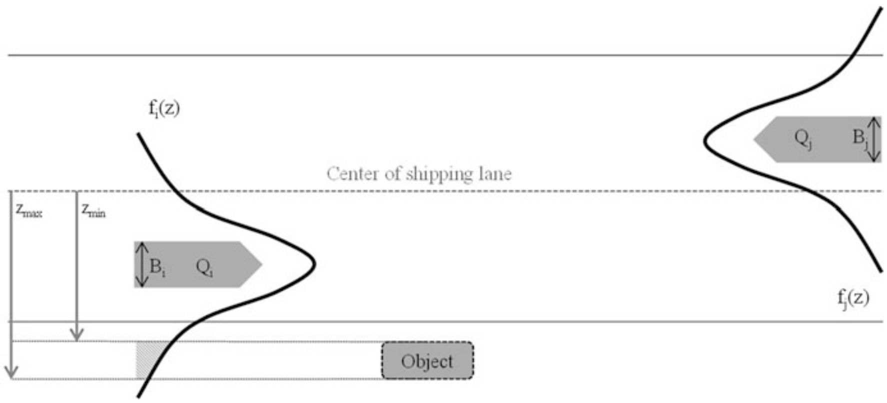

Fig. 12.6 Head-on encounter type based on Pedersen (1996)

z_i, z_j: distance from the middle of the fairway
$B_i^{(1)}, B_j^{(2)}$: ship's width

Assuming on a fairway $Q_i^{(1)}$ ships of type i in one and $Q_j^{(2)}$ ships of type j in the opposite direction within the time investigated and given the lateral distribution $f^{(1)}(z_i)$ and $f^{(2)}(z_j)$ of the two encountering ship types with a speed $v_i^{(1)}$ and $v_j^{(2)}$ on the fairway of length L_W, the expected value of the number of collision candidates can be derived based on standard statistics as follows, see also Fig. 12.6:

$$N_a^{front} = L_W \times \sum_{i,j} \frac{v_i^{(1)} + v_j^{(2)}}{v_i^{(1)} \times v_j^{(2)}} \times Q_i^{(1)} \times Q_j^{(2)} \times P_{a\ i,j}^{enc} \tag{8.1}$$

with

$Q_i^{(1)}, Q_j^{(2)}$: number of ships of type i and type j
$v_i^{(1)}, v_j^{(2)}$: ship's speed
L_W: length of the fairway
N_a^{front}: number of head-on collision candidates (expected value)

Hereby, the width of ships ($B_i^{(1)}$ and $B_j^{(2)}$) determines the critical overlap necessary between the two encountering lateral to be considered as a collision candidate (see Fig. 12.6). It represents at least the width of the two ship types, but sometimes even a value representing the width of the safety area around the ship (the so-called *ship domain*) is taken, as a violation of it would normally require the officer of the watch to intervene. Similarly to the head-on encounter category, the expected value of the number of collision candidates for overtaking situations (N_a^{over}) can be derived by

$$N_a^{over} = L_W \times \sum_{i,j} \frac{v_i - v_j}{v_i \times v_j} \times Q_i \times Q_j \times P_{a\,i,j}^{enc} \qquad \forall v_i > v_j \tag{8.2}$$

With regard to crossing the number of collision candidates (N_a^{cross}) depends rather on the crossing angle θ than on the specific lateral distributions:

$$N_a^{cross} = L_W \times \sum_{i,j} \frac{Q_i^{(1)} \times Q_j^{(2)}}{v_i^{(1)} \times v_j^{(2)}} \times D_{ij} \times v_{ij} \times \frac{1}{\sin\theta} \tag{8.3}$$

Here, v_{ij} represents the relative speed between ship i and j and is given by basic trigonometry as:

$$v_{ij} = \sqrt{(v_i^{(1)})^2 + (v_j^{(2)})^2 - 2\,v_i^{(1)} \times v_j^{(2)} \times cos\theta} \tag{8.3.1}$$

D_{ij} is, furthermore, the theoretical collision diameter which indicates the area of the circle where collisions may happen under the assumptions made. Assuming rectangular bodies of ships with length L_i and width B_i it is

$$D_{ij} = \frac{L_i^{(1)} \times v_j^{(2)} + L_j^{(2)} \times v_i^{(1)}}{v_{ij}} \times \sin\theta + B_j^{(2)} \times \sqrt{1 - (\frac{v_i^{(1)}}{v_{ij}} \times \sin\theta)^2} + B_i^{(1)} \times \sqrt{1 - (\frac{v_j^{(2)}}{v_{ij}} \times \sin\theta)^2} \tag{8.3.2}$$

Further details to these analytical methods are given by Pedersen (1996).

12.3.2 Ship-to-Object Collision Risk Assessment

About ship-to-object collisions (including grounding), frequency modeling generally differs for the two categories based on the encounter angle:

1. Straight leg, fixed object
2. Bend, fixed object

Situations of the first category are to handle straightforward – given the lateral distribution as well as z_{min} and z_{max} determining the position of the object or potential shallow waters in relation to fairway, see also Fig. 12.6:

$$N_a^{object} = \sum_i Q_i \times \int_{z_{min}-\frac{B_i}{2}}^{z_{max}+\frac{B_i}{2}} f_i(z)\,\mathrm{d}z \tag{9.1}$$

with

N_a^{object} :	number of ship-to-object collision candidates (expected value)
$f_i(z)$:	lateral distribution of the ship tracks
Q_i:	number of ships of type i
z_{min}, z_{max}:	distance of the outer object limits from the middle of the fairway
B_i:	ship's width

During a bend, the risk of collision is related to the fact that the officer of the watch fails to initiate a turn in proper time. Even though the *human element* is normally modeled in the *causation probability* and not within the collision candidate determination, the specific case of bends is a slight exception. Accordingly, for determining the bend-related collision candidates, not just the geometrical descriptions, like the distance d of the object to the bend's waypoints as well as the outer limits z_{min} and z_{max} of the object regarding the original course line are considered, but also the officer's regular (ship) position checks are taken into account by assuming them to follow a Poison process with the average time λ between two checks. Thus, the expected value of the number of ship-to-object collision candidates (N_a^{bend}) is given by

$$N_a^{bend} = \sum_i Q_i \times e^{-\frac{d}{\lambda v_i}} \times \int_{z_{min}-\frac{B_i}{2}}^{z_{max}+\frac{B_i}{2}} f_i(z)\,\mathrm{d}z \tag{1a}$$

For specific determination of collisions with temporary objects, it is referred to Burmeister et al. (2014).

12.3.3 Risk Simulations

Frequency models are quick to set-up, but suffer some drawbacks, e.g. that ship movements are not taken into account and that information about the exact collision situations is missing. Also, while the number of collision candidates can be objectively derived, the accuracy in determining the causation probability can be more questioned. Thus, there are also more simulation-oriented risk assessment methodologies for further detailed analyses. On the one hand, those are discrete-event oriented simulations like, e.g., in Goerlandt and Kujala (2011) delivering more details on the exact collision situation. On the other hand, there are activities like the European Maritime Simulator Network aiming at providing a large-scale risk assessment environment specifically covering the "human element" (see Rizvanolli et al. 2015 and Burmeister et al. 2020).

12.3.4 Summary and Conclusions

This chapter gives a rough intro into general approaches (including related methods and guidelines) to assess and ensure ship safety while designing port approaches and maneuvering areas. While especially the empirical approach from the PIANC Guideline is an accepted way to provide enough space for individual ships to navigate, the IALA iWrap MkII Frequency model is a recognized (analytical) approach to assess risk changes in ship traffic. However, both approaches are rather high level and might be best in earlier phases of port or terminal development projects, respectively. Furthermore, more in-depth simulation-based assessment methods have been touched as well. Their detailed description is, however, out of the scope of this general introduction and it is referred to the relevant literature.

Most ports do only provide one approach from port to seas, making the approach itself a critical infrastructure for the port without redundancy. Thus proper planning and maintaining a safe approach for current and future vessels is key for a long-term success of commercial port operations, as incident and accidents in the port approach can directly lead to a temporary or long-term closure of the whole port. Without enabling safe and efficient flow of ships from and to the terminals, those are directly limited in their operational capability by design.

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Chapter 13
ITSS: The Integrated Terminal Ship System

Direct Loading and Unloading of Transshipment Containers Between Ultra Large Container Vessels and Feeder Vessels

Johannes March

Abstract *U*ltra *L*arge *C*ontainer *V*essels (ULCV) with high trade volumes per port are making fewer calls per round trip with more transshipment cargo and more port times at higher costs. Innovations which increase handling productivity and streamline handling operations of feeder vessels (in short: feeders) are required to avoid inefficient long stays in ports as well as to reduce the costs resulting from ULCV processing. The patented "*I*ntegrated *T*erminal *S*hip *S*ystem" (ITSS or ITS system) satisfies these requirements by the innovation of direct container handling between ULCV and feeder vessels. Basically, there are two technical solutions possible: Transshipment containers are simultaneously handled on both ULCV sides using two finger piers (first alternative) and im-/export containers are un-/loaded at the ULCV quayside while transshipment containers are directly handled between ULCV and feeders at the ULCV waterside using one finger pier (second alternative). Both ITSS system alternatives use traction engines which move on the finger pier(s). The engines facilitate direct handling of transshipment containers by shifting the feeder vessel(s) alongside the pier(s) to the respective container bays required as per stowage plans.

13.1 Introduction

The development of sea trade and sea cargo shipping from conventional general cargo vessels to the container transport with full cellular container vessels at the end of the 1960s can be regarded as one of the most – perhaps the most – important innovations in modern sea shipping. The reduction of transport costs

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by about 90% enabled the worldwide division of labor and thus globalization (see Levinson 2006). Despite all the improvements in vessel engineering and design, port and terminal technologies, operating procedures, IT implementations, etc., over the last 40 years this innovation remains one of the few essential innovations, as far as systems in both sea cargo shipping and terminal operations are affected equally. Another innovation in this regard being also of fundamental importance for container transport is the development of ULCV with (among others) considerable impact on the infrastructure of ports and the suprastructure of terminals. Due to economies of scale, the use of such huge vessels leads to appreciably improved financial results. However, it should be noted that the economic potential of the vessels cannot be fully realized in most cases. The ULCV round trip productivity (number of round trips per year) usually does not correspond to that of smaller vessels but is lower (assuming the same travel speed at sea). Ordinarily, the higher number of containers to be handled per call is associated with longer port stays since the productivity of terminal berths has not risen to the same extent as the increased handling volume of these vessels. That is, longer ULCV round trip times additionally limit the annual transport capacity of the vessels and, with that, the possibility to allocate the higher ULCV system costs to an (even) higher number of containers.

In the past four decades, the vessel capacity has grown 28fold from 740 TEU to about 21,000 TEU. However, the (gross) handling productivity of most terminal berths has only doubled from 60–70 to 130–150 moves per hour (see Hollmann 2006, Tirschwell 2014, p. 4, p. 6–7, p.14, p.17 as well as March 2015, pp. 77–79). Besides various other determinants, the number of simultaneously used quay cranes for vessel processing is one of the most important for berth productivity but limited by the length of the vessel. Based on literature and author's experiences, Table 13.1 shows the number of quay cranes used on average for processing different vessel sizes. Depending on the quay construction a minimum of 50–60 meters is required to enable smooth operations of a single quay crane.

For various reasons, it is not uncommon that terminals underperform and cannot provide the above-mentioned figures, in particular, in case of larger vessels. Moreover, ULCV call at fewer ports per round trip which is associated with an increase of transshipment volume and, thus, a higher cost share attributed to transshipment cargo.

To overcome existing problems and to improve the viability of ULCV in a very competitive shipping market, innovations are required that speed up processing

Table 13.1 Average number of simultaneously used quay cranes depending on vessel size (see Brett 2015 as well as March 2015, pp. 80–83)

Ships' size [TEU]	Length [m]	Number of bays	Quay cranes
8000–10,000	325	20	5
12,000–14,000	366	22	5–6
16,000–18,000	400	23	5–7

of related vessels at ports and reduce the costs for handling of transshipment containers. The invention "Integrated Terminal Ship System" meets these requirements. The ITSS represents an advanced, environment friendly system solution for accelerated container handling which is both highly productive and cost-effective.

13.2 Objectives and ITSS Requirements

The ITS system is characterized in particular by the direct exchange of transshipment containers between ULCV and feeder vessels without twofold handling of related containers at the quay wall. Currently, transshipment containers are being moved in 6 steps at modern seaport terminals using *S*hip-*T*o-*S*hore (STS) gantry cranes:

- unloading from the mainliner vessel (ULCV)
- container transport to the yard stack
- container stacking
- container retrieving from the stack
- container transport to quay
- loading on the feeder vessel and vice versa (if transshipment containers arrive with the feeder vessel)

With regard to the ITS system these activities are being replaced by one direct move between the ULCV and the feeder ship. The implementation of the ITS system will considerably increase the berth productivity and reduce operational costs for transshipment container handling at comparatively low investments. Considering ULCV operation itself, the ITS system enables significantly shorter port stays and, thus, greater round trip productivity or economic viability, respectively.

The ITS system requires the construction of a new container terminal or the adaptation of an existing one as well as sufficient transshipment volumes and feeder connections. There are two types of system alternatives with the corresponding operation processes:

- ITSS handles almost only transshipment container like the terminals in Singapore, Malta, Tangier, Algeciras, Kingston, etc. (with transshipment shares between 85 and 100%, see Table 13.3)
- ITSS handles domestic cargo (i.e., import and export containers) and transshipment cargo like the terminals in Hamburg, Rotterdam, Antwerp, Shanghai, Busan, etc. (split of 50%/50% up to 30%/70% between transshipment and domestic containers, see Table 13.3)

Following investments in civil engineering measures and handling equipment are required for the ITS system alternative exclusively dealing with transshipment cargo (see Fig. 13.1 and Table 13.2):

- 2 × finger piers
  - approx. 400 m long each (aligned to maximum vessel length)
  - parallel to each other in a distance of 60–70 m (depending on the vessel size to be expected in maximum)
  - approx. 20 m wide each (to buffer hatch covers and to position the ITSS cranes as well as the mooring systems)
- 5 × ITSS portainers
  - running on rails which are installed on the finger piers
  - with two lifting gears and trollies for container handling on both sides of the vessel

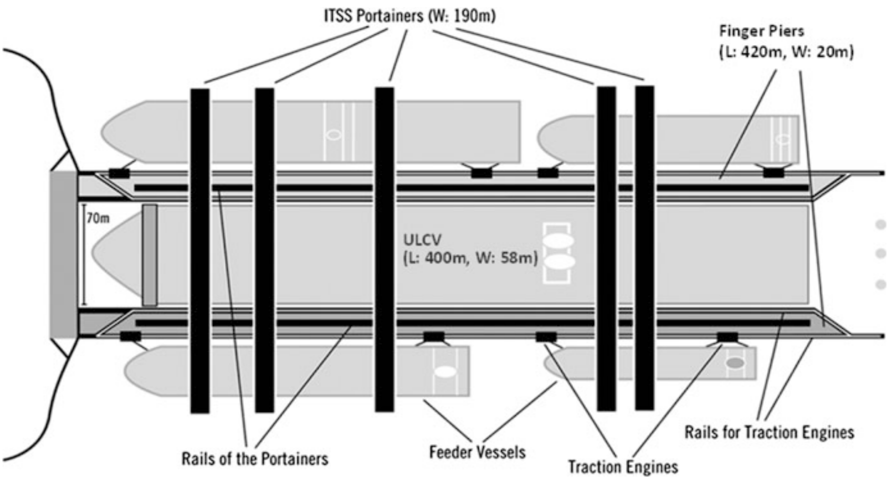

Fig. 13.1 ITS system alternative with two finger piers and 5 portainers exclusively handling transshipment cargo (see March 2004, p. 17)

Table 13.2 ITSS investments for calculation purposes and subject to actual negotiations in million EUR

System elements	Per unit	ITSS alternative domestic and transshipments	ITSS alternative transshipment only
Finger piers	55	1 × 55 = 55	2 × 55 = 110
Portainers	12	5 × 12 = 60	5 × 12 = 60
Traction engines	0.5	6 × 0.5 = 3	8 × 0.5 = 4
Total investment		118	174

  - the height is depending on the vessels' draft and corresponds to the maximum of traditional Post-Panamax STS cranes to handle the upper container tier on deck. It is not necessary to pass the height of the masts and superstructures by higher ITSS portainers as the superstructures of the ULCV are located on the foredeck and the containers in front of the bridge can be handled in the conventional manner by a STS crane to the shore side only not applying the ITSS. To pass the funnel the lifting gear and spreader can be moved lateral of the funnel
  - 190 m wide to span the ULCV, two finger piers, and two feeder vessels
  - assumed productivity of 30 moves per lifting gear hour and $2 \times 30 = 60$ moves per portainer hour by two lifting gears and simultaneous both side handling, which results by 5 ITSS portainers $\times$ 60 moves per hour in an overall productivity of 300 moves per berth hour

- 8 × rail mounted traction engines comparable to those operating in the locks of the Panama Canal
- 4 × mooring systems (as an alternative to traction engines)
  - replacing two or four traction engines
  - working on the basis of vacuum technique

The ITS system alternative for handling transshipment and domestic cargo requires the following investments in civil engineering measures and handling equipment (see Fig. 13.2 and Table 13.2):

- one finger pier (instead two as above)
- 5 × ITSS portainers (as above)

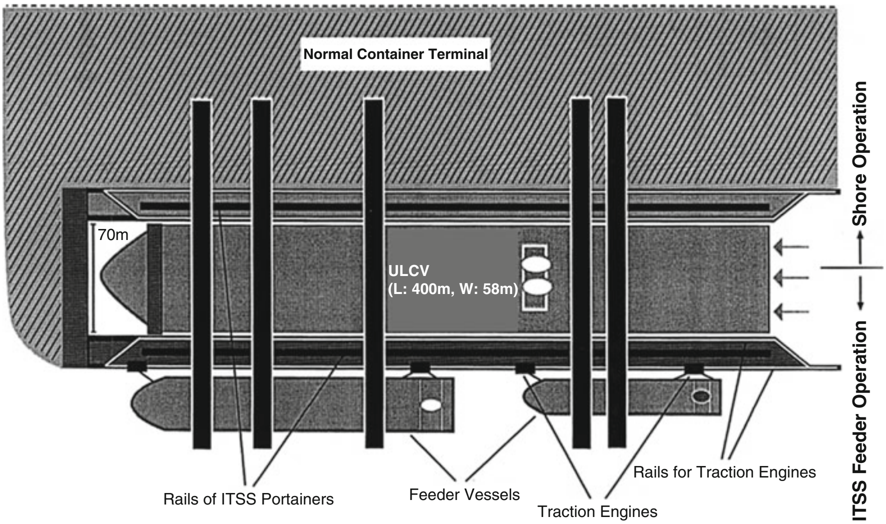

Fig. 13.2 ITS system alternative with one finger pier and 5 portainers handling domestic cargo at the quay wall and transshipment cargo at the finger pier (see March 2004, p. 17)

- 6 × rail mounted traction engines (instead 8 as above)
- 4 × mooring systems as an alternative to traction engines (as above)

13.3 ITSS Operation

Fast docking of ULCV is being achieved by 6 traction engines (three on each side), which enable precise movements of the vessel to the final position as used in the locks of the Panama Canal. Five ITSS portainers (each fitted with two trollies and cantilevers) spanning the ULCV as well as

- the feeder vessels being moored alongside the finger piers (system alternative "pure transshipment"),
- the feeder vessels being moored at the finger pier and, on the quayside, a container handover area on the terminal quay with a depth of about 40 m (system alternative "transshipment and domestic").

This allows for simultaneous handling operations on both sides of the ULCV.

Once an ULCV has been moored, the traction engines are moved to the outer rails of the finger pier(s). They enable direct container handling (ship-to-ship) by precisely shifting the feeder vessels to specific pier positions so as to match individual container bays of the ULCV and feeder vessels as per stowage plans. In case of the system alternative "transshipment and domestic," this goes hand in hand with domestic container handling which is simultaneously carried out on the vessel quayside analogous to traditional STS operation.

The ITSS operation requires simultaneous berthing of the ULCV and the feeder vessels allowing some flexibility in the overall port time of the ULCV (see Fig. 13.3). To prevent or minimize delays, it is a prerequisite that all involved processes (especially ULCV and feeder operations as well as terminal activities) can be coordinated including slight adjustments of stowage planning. Nevertheless, schedule reliability represents the basis for smooth ITSS operation and, therefore, must be top priority for operational planning.

Following obstacles to the ITS system have been questioned and discussed with practitioners and researchers:

(a) The feeder vessel has to match the schedule date of the ULCV

Feeder schedules vessels have to be kept for effective ITSS operation, which is feasible. The analysis of monitoring data from feeder line operation clearly shows that individual lines keep their vessels on schedule, while others suffer considerable delays. Without doubt the most reliable vessel is also the most economical one, while vessels that are subject to delays and have to be brought back to schedule are the most expensive. To calculate too short round trip times and to run the risk to fall behind the schedule generates far higher cost by recovering schedules and speeding up vessels or even phasing in and out vessels.

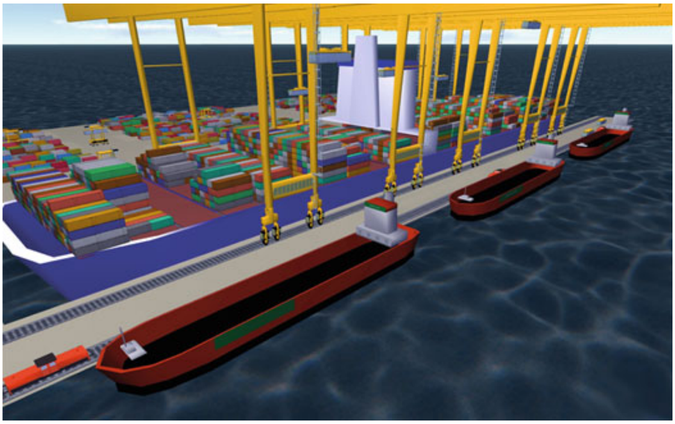

Fig. 13.3 ITSS operation with one finger pier

(b) To coordinate feeder schedules

In former times, most of the independent feeder services did not operate reliably as per their schedule. This has been changed, as most of the large shipping lines operate their own dedicated feeder services. With regard to independent feeder services the large carriers have such a market power that they can enforce their requirements on the market and independent services are compelled to comply with them.

(c) The height of ITSS portainer cranes

At a first glance it was assumed that ITSS portainers have to be far higher to pass the height of the masts and superstructures on the foredeck and the funnel. But this is not necessary as the containers in front of the bridge can be handled without the ITS system and the funnel can be passed by lateral move of the lifting gear (see Sect. 13.2).

(d) Assumed stowage difficulties

Concerns from practice that stowage difficulties might occur are unfounded. Five to seven port calls in the Far East and 5 in Northern Europe (plus 3–5 sub-destinations for exchange of feeder cargo to be stowed separately) do not generate any stowage problems due to the high number of bays and stowage possibilities in case of ULCV. The individual port imbalances of export and import containers, existing imbalances between container weights, as well as the imbalances of transshipment container flows at hub ports allow sufficient stowage possibilities even on fully loaded vessels. Nevertheless, the stowage of the ULCV and the feeder vessels being connected with the mainliner service has to be coordinated carefully. Regarding the "up and down" effect it is true that at first light containers will be unloaded from the feeder vessels and loaded on the ULCV and vice versa. However, contrary to smaller vessels, e.g., with a Panamax width of 32 meters, and less stability container sequences like the mentioned above are appreciated for ULCV due to their higher stability resulting from widths of 40–60 meters, respectively. The "up and down" effect when occurring at very stiff ULCV is sometimes very helpful to solve stability problems.

(e) Reactivated dual cycle moves

Handling operations based on dual cycle moves mean that a quay crane moves containers in both directions, i.e., onto the vessel (loading) and from the vessel (discharging) in one full crane cycle avoiding empty movements. Dual cycle moves are difficult to plan for the handling operation of traditional STS cranes due to frequent disturbances in the horizontal transport from and to the cranes. By comparison, the ITS system enables dual cycle moves between the ULCV and feeders without difficulties as the stowage of the transshipment containers on the vessels is planned well, i.e., in advance for fixed positions. Here, dual cycle moves can (usually) be carried out without any disturbances different from operations at the quayside.

The ITS system can be implemented worldwide. Nevertheless, certain preferences have those ports with a high transshipment share. Table 13.3 exemplarily provides the transshipment share of several transshipment dominated container ports in different regions of the world (see ISL 2009).

Table 13.3 Selection of transshipment ports worldwide (approximate values)

Mediterranean Sea		
Malta	Marsaxlokk	96%
Southern Italy	Gioia Tauro	95%
Southern Spain	Algeciras	95%
Morocco	Tanger	96%
Egypt	Port Said	90%
Far East		
Singapore	Singapore	85%
Malaysia	Tanjung Telepas	95%
Caribbean and Central America		
Jamaica	Kingston	85%
Bahamas	Freeport	99%
Panama	Balboa	95%

13.4 Economical Results

The productivity gains and cost reductions resulting from the use of the ITS system generate considerable advantages for all involved parties and lead to positive economic results.

13.4.1 Terminal Productivity Triples (ITSS-Terminal with one finger pier for quay and transhipment cargo)

Assuming a split of domestic and transshipment cargo in a proportion of about 50% and single lift operations, the following considerations show that the quay throughput can be tripled by using the ITS system.

In case of traditional STS crane operation, the quay is occupied by the following activities:

Domestic cont. moves via quay at ULCV	50%
Transship. cont. moves via quay at ULCV	50%
Transship. cont. moves via quay at feeders (frequently not at the ULCV berth)	50%
Summing up cont. moves	*150%*

In case of ITSS operation, the number of cranes moves can be reduced by one-third due to the possibility of direct transshipment container handling between ULCV and feeders:

Domestic cont. moves via quay at ULCV	50%
Transship. cont. moves via quay at ULCV	0%
Transship. cont. moves via quay at feeders	0%
Direct moves of transship. cont. (ULCV $\leftrightarrow$ feeders)	50%
Summing up cont. moves	*100%*

Considering the quay occupancy time caused by the containers discharged/loaded from/on an ULCV (with a split of 50% domestic and 50% transshipment), the time is reduced by another third. This is due to the possibility of the ITS system to execute domestic and transshipment container moves at the same time. Assuming, for example, 48 h discharging and loading an ULCV by traditional STS cranes the resulting overall occupancy time by container handling operations (compared to ITSS) is as follows:

	STS Operation	ITSS Operation
Domestic cont. handling at ULCV	24 h	24 h
Transship. cont. handling at ULCV	24 h	0 h
Transship. cont. handling at feeders	24 h	0 h
Direct handling of transship. cont. (ULCV ↔ feeders, simultaneously Executed with domestic cont. handling)	0 h	24 h
Total quay occupancy time	*72 h*	*24 h*

A more detailed consideration shows that the reduction of berth occupancy time to one-third leads to a threefold increase of the quay throughput if you count the "container units" and a twofold increase if you count the "container moves" in case of ITSS.[1]

Furthermore, the reduction of the quay occupancy time by two-thirds means the quay throughput triples. In other words, one ITSS berth replaces three conventional terminal berths with investment savings of about 300–400 million EUR (see March 2015, pp. 142–143).

13.4.2 Terminal Productivity Quadruples (ITSS-Terminal with two finger piers for transhipment cargo only)

Assuming 100% transshipment share, two finger piers, and single lift operations, the resulting numbers show that the quay throughput can even be quadrupled by the ITS system.

Again 48 h crane operations are to be supposed for discharging/loading an ULCV which leads to the following results:

	STS Operation	ITSS Operation
Transship. cont. handling at UCV quay	48 h	0 h
Transship. cont. handling at feeders' quay	48 h	0 h
Direct handling of transship. cont. (ULCV↔feeders, simultaneously Executed on both ULCV sides)	0 h	24 h
Total berth occupancy time	*96 h*	*24 h*

In this case, the ITS system replaces 4 conventional berths and leads to savings of about 600–700 million EUR (see March 2015, pp. 142–143).

[1]This consideration shows that the occupancy time to one-third leads to a threefold increase of quay throughput and terminal productivity. One ITSS-berth replaces three conventional container terminal berths with investment savings of about 300-400 millon EUR (see March 2015, pp.142–143).

13.4.3 Ship Operating Costs Are Halved per Port Stay as Berth Productivity Doubles

Due to simultaneous handling operations on both sides of the ULCV the berth productivity doubles.[2] Consequently, the port time and, with that, the ship operating costs are halved per port stay.

13.4.4 Container Handling Costs Are Reduced Up to 80%

By means of traditional STS cranes, handling operations of transshipment containers are performed in six steps (see Sect. 13.2). According to the ITSS operation these steps are replaced by one move which is directly carried out between the ULCV and the feeder vessel. Based on practical experiences, for STS operation, the author assumes a cost share of about 60% for container discharging/loading from/on the vessel and about 40% for container transport and stacking on the terminal area. If you additionally assume that the costs of a full loading/discharging move (i.e., container handling by quay crane plus transport and stacking on the terminal) will be

- 100 EUR for an ULCV and
- 80 EUR for a feeder vessel

the handling operation of STS cranes, on the one hand, and ITSS, on the other hand, generate the following costs for a transshipment container:

	Percentage	costs (EUR)
Full discharging/loading move (ULCV)		100
Full discharging/loading move (feeder)		80
Total terminal handling costs (STS crane operation)	100%	180
Average costs for a full discharging/loading move		90
Total terminal handling costs (ITSS operation)	*thereof 40%*	*36*

The calculations above show that the total terminal handling costs for a transshipment container can be reduced to 20% (36 EUR) by using the ITS system.

[2]Continued moves per berth hour.

13.4.5 Environment Protection

The reduction in energy and emissions and the respective costs are estimated to be 40%.

13.4.6 Round Trip Cost and Savings

The basis for analyzing the impact of ITSS on the round trip costs (and possible savings) forms a cost comparison study for a mainliner service running between ports in Far East and Northern Europe. The study considers the liner service with 10 vessels in two capacity variants (13,400 TEU and 16,000 TEU) based on a round trip time of 70 days and a transshipment share of 35%. With regard to Northern Europe three operational alternatives for feeder services are included in the cost comparison.

- conventional transshipment operations via Hamburg
- transshipment operations via Hamburg into the Baltic Sea and Scandinavia with ITSS transshipment operation in Hamburg
- transshipment operations via a Baltic seaport close to Rügen or the Belt

The cost comparison study provides results for vessels of a capacity between 13,400 TEU and 16,000 TEU (see Table 13.4). All assumptions and calculations of the study are described in March 2015, pp. 176–181 in detail.

Table 13.4 Cost comparison for a Far East – Northern Europe mainliner service with operational alternatives for feeder services in Northern Europe (cost per round trip in million EUR)

	Conventional transshipments via Hamburg	ITSS operation transshipments via Hamburg	ITSS operation transshipments via a Baltic Sea Port
Ship sizes in TEU	13,400–16,000	13,400–16,000	13,400–16,000
Ship system costs	11.5–12.4	11.5–12.3	11.4–12.3
Feeder costs	0.9–1.0	0.8–0.9	0.4–0.4
Transshipment handling costs	0.6–0.7	0.2–0.3	0.2–0.3
Total round trip costs	13.0–14.1	12.5–13.5	12.0–13.0
Annual cost savings (10 vessels)		*153.4–179.4*	*287.0–337.8*

13.5 ITSS Floating Feeder Terminal

Some port areas might not be suitable for the construction of an ITSS terminal with fixed finger piers because of narrow fairways and not sufficient operational water draught or access. In those ports, the finger piers could be replaced by floating pontoons with ITSS cranes or special swing cranes traveling on rails along the pontoons. The pontoons might also be stabilized by erected movable pillars as used by jack-up systems.

On both sides of each pontoon, there are two or even more mooring systems, e.g., based on vacuum technique. For handling operations, the ULCV is being moored between the pontoons. At the outside of the pontoons the feeder vessels are moored and shifted alongside as per the ITSsystem. The floating feeder terminal offers the flexibility to operate in different port areas. Additionally, it could also be combined with short-distance water transport systems such as the port feeder barge.

13.6 Conclusions

ULCV requires a higher handling productivity to reduce their port times and thus the related costs for vessel processing. The ITS system meets these requirements:

- Berth productivity doubles and ship system costs are halved per port stay
- Reduction of investments by 50–80%
- Up to fourfold increase in quay throughput depending on the transshipment share
- About 40% reduction in emissions

The development and implementation of the ITS system as innovation is still impeded by several innovation barriers (see March 2015). For the individual application case, the given barriers have to be analyzed and overcome by appropriate management measures.

In a critical review, this might remain difficult as using inventions in daily practice accompanied by effective innovation management is not yet firmly established in the transport industry and especially not in container shipping. Frequently, different economic and political interests still prevail. In addition, the shipping crisis, overcapacities, idle vessels, the dramatic deterioration of freight rates, surviving in the market, requirements for higher operating margins, etc., put pressure on the managements of the big shipping lines, who do not set priority on innovations but would like to avoid any risk.

The ITS system represents an effective invention that could increase productivity and reduce costs in global (transshipment) container transport to a significant extent. It has to be seen whether the potential of this system can be made accessible for operational practice.

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Chapter 14
Planning Approach for Quayside Dimensioning of Automated Traffic Areas and Impact on Equipment Investment

Michael Ranau

Abstract In this chapter, the author first provides an overview of the quayside activities of a modern seaport container terminal. On this basis, he compares the space requirements of two different operations systems for horizontal container transport and derives reasonable planning assumptions for dimensioning their terminal layout: The focus is, on the one hand, on automated guided vehicle systems which perform quayside container transport, e.g., at several terminals on the Maasvlakte (Rotterdam) and, on the other hand, on automated straddle carrier systems being in operation, e.g., at the Brisbane Container Terminal on Fishermans Island or the TraPac Container Terminal in Los Angeles. Both system alternatives are investigated in combination with semi-automated cranes at quay wall and automated (rail-mounted) yard cranes working perpendicular to quay. Noting that in practice, only pure automated SC systems can be met until today taking both the quayside container transport and the stacking operations within the yard. Main areas for analysing planning assumptions are the quay crane portal and backreach as well as the traffic area in front of the yard blocks. Based on the findings gained by the analysis, for both systems, the author provides a viable quayside layout and an investment comparison of the equipment required for operating a mainliner berth.

14.1 Introduction

With the commissioning of the Delta/Sea-Land terminal in Rotterdam in 1993 the first robotized container terminal started its automated operation with unmanned transport equipment at terminal quayside and unmanned stacking equipment within the container yard (see ECT 2019). In the year 2002 the HHLA *C*ontainer *T*erminal *A*ltenwerder (CTA) in Hamburg followed this trend of automation (see CTA 2019). In the subsequent years also other terminals have been starting with high degree

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of automation of operational processes. Due to the development of manpower costs it is expected that even in the high wage countries the number of automated terminals will increase in the future. Furthermore, the curtness of terminal space in combination with automated high stacking density is another reason for terminal automation.

In case of evaluation and planning of automated terminals one question arises very often. *Why are the traffic areas between quay wall and the storage yard so large?* On the first view these thoughts seem to be entitled as on conventional terminals – like pure *S*traddle *C*arrier (SC) terminals – the related traffic areas are much smaller. Due to this question the dimensioning of the quayside handling areas within an automated container terminal shall be evaluated in the following. Considering the variety of options for automation only two system variants for horizontal transport are compared and evaluated in detail, namely the *A*utomated *G*uided *V*ehicle (AGV) system and the automated SC system. Both variants are investigated in combination with *A*utomated *S*tacking *C*ranes (ASC) in the yard area operating container blocks arranged perpendicular to the quay wall. The ASC shall be rail-mounted and the assumed block width comes to 10 containers.

The remainder of this paper is organized as follows. Section 14.2 provides a brief overview of the operational functions which occur on the quayside of a container terminal. In Sect. 14.3, the main planning assumptions for dimensioning of the quayside traffic area are described and layout results for two system variants of horizontal container transport are presented (AGV operation vs. automated SC operation). Finally, Sect. 14.5 concludes the paper with a summary of main insights gained in the sections before. In addition, the section provides some specific indications for quayside layout planning and an investment comparison considering the automated vehicles of both system variants required for smoothly serving a common berth.

14.2 Operational Functions of Quayside Works

Before looking more closely on the possibilities for automation, the different operational functions of a container terminal should be illustrated. As the main focus will be drawn on the quayside areas, just the quayside functions will be named in here. All the functions mentioned afterwards have to be fulfilled at the quay wall (discharging/loading of vessels) as well as in the area between quay cranes and container yard (horizontal container transport and handover). Some of these functions might be suitable for automation, some not. For this reason the integration of these functions within both areas should be evaluated in detail.

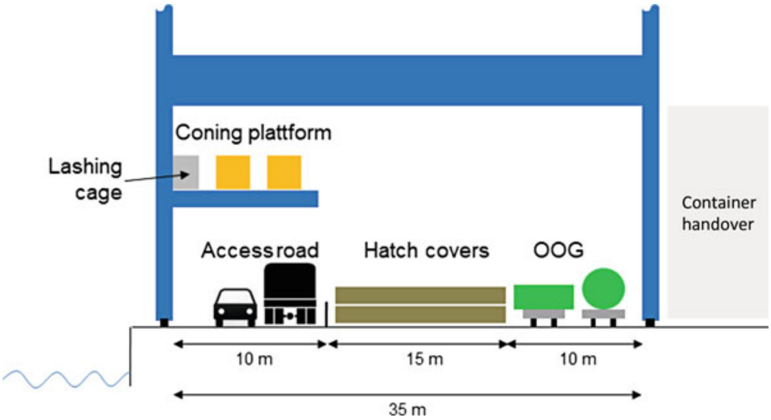

Fig. 14.1 Cross section of a quay crane portal

14.2.1 Twist Lock Handling and Other Materials

Beside the standard operation with standard containers additional operational requirements arise on the quayside. Except for the boatmen after mooring of vessels the first operational thing to be done is the handling of materials like twist lock cages, etc. between vessel and quay. By way of example, the quay crane driver has to move the lashing people (by use of lashing cages) from the quay wall on board of the vessel and vice versa. Furthermore, the twist lock cages have to be placed on the crane lashing platform or within the quay crane portal (see Fig. 14.1). Handling functions of this type are hardly to automate – what can be assumed for future as well. However, for standard coning and de-coning of twist locks several suppliers appeared with advanced technologies during the last years (see Kalmar 2019).

14.2.2 Handling of Out-of-Gauge Cargo

On almost every container terminal cargo must be handled which does not fit in a standard container due to the measures of commodities or oversize, respectively. This *O*ut-*O*f-*G*auge (OOG) cargo has to be handled manually on the quayside and is moved by means of special container types like *flat racks*, *platforms*, or *open top containers* (see Fig. 14.2). After unloading from a truck or another vessel the OOG cargo has to be placed and stored in a dedicated non-automated yard area.

OOG cargo handling and positioning within the OOG area is usually performed by reachstackers, the transport to/from the quay cranes by tractors and different kind of trailers. It is not expected that OOG cargo can be handled in an automated way of transport now and in future.

Fig. 14.2 OOG example: Harvester machine on flat rack

14.2.3 Quayside/Vessel Access and Additional Services

On a container terminal variable persons for different purposes need access to the quay wall or just even the quayside. Vessel suppliers, linesmen, agents, police, customs, boatmen, ambulance, terminal personnel, etc. have to get access to the quayside with vehicles of partly different size. Due to these functions a minimum space for access roads or ways has to be established on the quay wall. All these non-automated functions and persons make a complete automation of the quayside activities impossible.

Additional services – like cargo securing or handling of damaged cargo – also have to be done by manual actions at quayside. Nowadays all these operational functions are not automatable and it may not to be expected that automation becomes possible in future.

14.2.4 Preparing of Break Bulk Cargo

Non-containerizable break bulk cargo, e.g., railway engines or cars, is placed and positioned under the quay crane with tractors and special trailers. As this kind of freight – also termed as *project cargo* – requires specific handling tools, procedures and care, a manual interference is needed (see Fig. 14.3).

Special handling preparations of project cargo are usually fulfilled in the portal of quay cranes right before loading. In contrast to OOG cargo, break bulk is stowed on vessels without using any kind of container; cargo securing is primarily ensured by

Fig. 14.3 Break bulk example: Locomotive loaded on vessel

Fig. 14.4 Storage position for over-height frame at the CTA in Hamburg

chains and ropes sometimes in combination with poles or crate constructions made of wood or steel, respectively.

Furthermore, the handling of project cargo requires an over-height frame. Either this frame has to be moved manually from another place on the terminal or it will be stored on the quay crane. The figure below shows the over-height frame storing position at the HHLA Container Terminal Altenwerder. The frame is stored between the both landside quay crane legs (Fig. 14.4).

14.2.5 Transportation of Standard Containers to/from the Container Yard

At container terminals, the major amount of cargo is packed into standard containers, i.e., containers of 20 ft or 40 ft length. Due to this high quantity of standardized cargo size, an automation of this cargo is reasonable. This relates in particular to the horizontal transport of containers between quay wall and the yard area, but also to parts of vertical transport activities being necessary at quayside for vessel loading/discharging and the storage of incoming/outgoing containers in the yard area.

14.3 Dimensioning of Quayside Traffic Area

In this section, the planning assumptions for the quayside layout of two different container transport systems are described more closely considering alternatively AGV or automated SC as transport equipment between quay cranes and terminal yard. In both system variants, the area between the quay wall and the automated stacking yard can be divided into 4 main functional terminal areas being partly or fully automated (see Sects. 14.3.2–14.3.4). Before planning assumptions and results for quayside layout are presented the potential of terminal automation is basically specified in respect of quayside operation.

14.3.1 Fields of Automation

As mentioned above not all functions on the terminal quayside can be automated. Due to this the areas from the quay wall towards the container storage are to be investigated in detail. Generally, there are following functional areas in which automation could be installed (see PEMA 2016):

- Partial automation at quay wall by quay cranes using double trolley technology for container handling as at the CTA in Hamburg or, in addition, by remote controlled crane operations, e.g., applied by APM Terminals on the Maasvlakte II in Rotterdam (see ABB 2019);
- full automation within the traffic area between quay cranes and container yard by means of AGV as in operations at several terminals in Hamburg, Rotterdam and Busan (see PEMA 2016) or by means of automated SC used for quayside transport operations, e.g., at the Patrick Container Terminal on Fisherman Islands in Brisbane (Australia) or the TraPac Terminal in Los Angeles;
- full automation within the storage area by implementing an automated stacking crane system being usually rail-mounted nowadays as at several terminals in Hamburg, Rotterdam and Busan or by using automated SC as at the abovemen-

tioned terminals of Patrick and TraPac where related SC take both the transport operations between quay cranes and container yard as well as the stacking operations in the yard area itself.

14.3.2 Quay Crane Portal

The operations procedures of quay cranes towards the vessel have to be done manually. Either quay crane drivers directly execute the related operations in the driver's cabin of the crane (standard case!) or – a more recent development – operators monitor and control crane operations via remote control, e.g., from the terminal administration building (see ABB 2019). However, redconsidering the development of quay crane technology in the past, it is not expected that these activities will be fully automated within the next years.

On the other hand, container handling operations towards the terminal yard offer options for automation. As already mentioned the terminals in Rotterdam and Hamburg are working with automated horizontal handling equipment, namely the AGV, for a couple of years. In Hamburg at CTA, the necessary container handover between the manual operated (quayside) crane trolley and the AGVs is realized by a second fully automated trolley. Thus an interface between these two trolleys is required. For this purpose the so-called coning or lashing platforms are installed. By means of buffer positions for two 40 or 20 ft containers the transfer between manual and automated crane handling devices can be realized.

On the ground of quay crane portal a multitude of exercises have to be arranged and most of them – like OOG handling and project cargo – cannot be automated. Hence, an intelligent arrangement of automated and manual areas is necessary. Furthermore, the mode of operation of the quay crane is important. For instance, a tandem lift[1] crane with double trolley technology entails a different design as a semi-automated single or twin lift[2] quay crane. The coning platform requires at least space for checking and buffering four 20 ft (or two 40 ft) boxes in case of a semi-automated tandem lift quay crane noticing that only four (two) positions may be critical from the point of view of time-efficient operation. In principle, tandem lift operation leads to growing space requirements and larger quay crane portals compared to semi-automated single or twin lift cranes.

Figure 14.1 shows a possible design of a semi-automated single or twin lift, double trolley quay crane enabling smooth container flow between vessel and horizontal transport equipment. The coning platform is located on the quayside

[1] Tandem lift operation enables the simultaneous handling of two 40 or four 20 ft containers.

[2] Quay cranes with twin lift operations capabilities are able to shift either one 20 or one 40 ft container or simultaneously two 20 ft containers with a single crane move.

Minimum space requirements of single or twin lift quay cranes for the lashing platform: One 40 or two 20 ft containers plus lashing materials.

of the crane portal and offers space for two 40 or 20 ft boxes. Beside handover operations between both crane trolleys, the container check and twist lock handling activities take place on the coning platform with a width of about 10.0–11.0 m. Thus, twist lock boxes and the lashing cage for the lashing personal must be stored on the lashing platform as well.

The most suitable position for the lashing cage is between the crane legs. Adjacent to the lashing cage the container lashing positions are situated. To guarantee the most suitable access for the lashing personal the twist lock boxes are located between the two container positions. Lashing material is usually moved by small forklift trucks in the quay crane portal. In case of an automated terminal these manual activities are fulfilled in the same area as the storing of hatch covers and the handling of OOG or project cargo. As the lashing material is usually handled by the quay crane itself, necessary pick up and drop down movements cannot be done under the lashing platform.

Underneath this platform the access road for berthing vessels is located. Vessel suppliers, terminal and maintenance personnel are using this road for access and parking purposes. Additional services like OOG cargo or hatch cover handling are executed next to the access road separated by a fence within the quay crane portal. OOG and project cargo is normally positioned in the crane portal by tractors and trailers (see Fig. 14.5).

Most of the OOG and project cargo are stored on deck of a vessel. While handling under the quay crane it is expected that no hatch covers are under the crane at that time. Hence, approximately 25.0 m should be sufficient for the handling of OOG

Fig. 14.5 Quay crane portal at the CTA in Hamburg

or project cargo – enough space to use tractor trailer units or other equipment like heavy forklift trucks. The main preparation of OOG and project cargo is usually done in dedicated areas outside the crane portal. In respect of current operations conditions at container terminals and expected future development, respectively, it is assumed that vessel hatch covers occupy between 15.0 and 18.0 m of the crane portal. Consequently, a passage of 7.0 m remains at the minimum for passing hatch cover positions with OOG or project cargo. Taking into account all these considerations the planning of crane portal width finally ends up about 35.0 m in total (see Fig. 14.1).

Basically, the split up of automated and manual functions guarantees safe and efficient operation on the quayside. If the automated container handling shall take place within the quay crane portal, all manual procedures (including hatch cover stowage) would have to be fulfilled in the backreach, i.e., in an area surrounded by automated operations processes. The crossing of manual and automated handling activities would be mandatory and offset the benefits resulting from process automation.

Furthermore, the automated container exchange between horizontal transport and quay cranes within the portal would lead to the necessity that transport units are to enter/leave this area by passing portals of all vessel operating cranes in the worst case (tunnel effect). All in all, the specific operations requirements of an automated handover area between the quay crane rails would lower the productivity of the horizontal transport units and thus increase the number of required units.

14.3.3 Quay Crane Backreach

The design of the crane backreach or the handover area, respectively, depends on the size and turning radius of horizontal transport units as well as on given peak requirements of vessel handling (i.e., the maximum number of quay cranes simultaneously used for loading/discharging per vessel). Basically, the width of each lane has to be dimensioned in such a way that the transport units must be able to enter driving lanes or waiting/holding positions without collision with any vehicle passing or parking in the nearest lane.

With a length of about 14.8 m (width: approx. 3.0 m) and an outer turning radius of 11.5 m, AGVs require a driving lane width of around 4 m. However, the driving lane towards the waiting/holding area needs a width of 5m. This additional 1 m results from the running radius and from the projecting end appearing by the maximum steering angle. In comparison, automated SCs have a vehicle length of about 11.3 m and a width of approx. 4.9 m. Here, the vehicle length can be disregarded for lane design as the length dimension of some container types exceeds SC extent. The length of the largest loading unit (45 ft box: 13.72 m) in combination with the outer turning radius of 10.1 m of a loaded SC finally ends up with a driving lane width of around 6.4 m.

As mentioned above, the number of lanes in the crane backreach depends also on peak handling requirements of the respective terminal. To serve a quay crane without waiting time the transport units must be able to get direct access to the handover position. Hence, in case of using four quay cranes per vessel call in maximum, four independent driving lanes are required. Two additional metres are needed to ensure clearance from crane machinery.

The backreach of quay cranes in case of the AGV system requires approximately 19.0 and 28.6 m are needed for operation of the automated SC variant. For both variants 2 m of safety distance towards the quay crane were taken into consideration. As mentioned above, the system comparison was calculated with 4 lanes for each variant.

14.3.4 Waiting/Holding Area

Another relevant operations zone at quayside is the waiting/holding area for horizontal transport units. The waiting/holding area is projected for two different reasons. Firstly, it allows parking of transport units or containers, respectively, close to the dedicated quay crane, ensuring quay crane operation without any waiting time and thus a lack in productivity. Secondly, the non-operational transport units are to be placed somewhere. AGVs are partly parked in the handover areas of ASC blocks, since with certain probability an export or transshipment container will require an AGV in the near future anyway. Furthermore, non-operational automated SC cannot be parked in the handover area of ASC blocks as vehicles only get access to the area in case of a loading or discharging order for a dedicated container. Due to this reason all non-operational automated SC have to be parked in a waiting/holding area established for this purpose.

The width of a related area is to be laid out differently for both system variants. AGVs with an inner turning radius of 6.1 m and an outer turning radius of 11.5 m require a total width of the waiting/holding area of 28.0 m (see Figs. 14.6 and 14.7). It has to be mentioned that in particular the total length of the AGV is to be considered for area design as this measure primarily determines the outer vehicle turning radius. In respect of holding positions for automated SC the outer turning radius is defined by the dimension of longest loading unit, (i.e., a 45 ft container) must be moved between quay cranes and ASC yard. With a length of 13.72 m and width of 2.44 m (4.94 m width of automated SC) related boxes induce space requirements for the SC waiting/holding area that ends up with a maximum width of around 18.5 m (see Fig. 14.6 based on CTA information for AGV and Kalmar 2017 for SC).

In both variants additional space towards the landside and towards the waterside has to be considered. The handling devices require a minimum speed before starting the steering process. Basically, it has to be stated that the outer turning radius of transport units is of vital importance for the layout of their traffic areas and

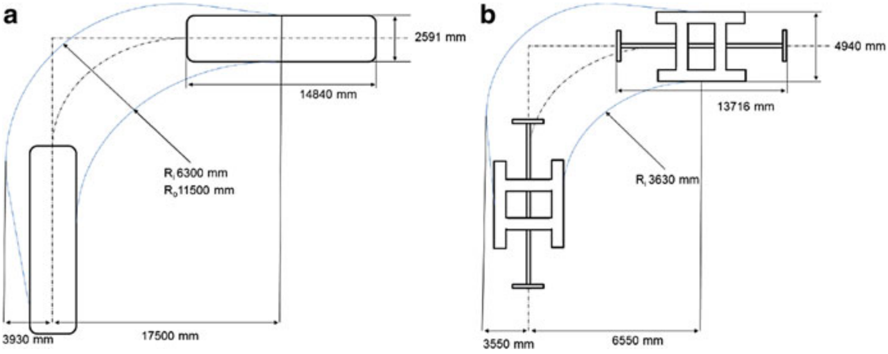

Fig. 14.6 Sample turning radius of (**a**) an AGV and (**b**) for an automated SC

Fig. 14.7 AGVs in the waiting/holding area at the CTA in Hamburg

that decreasing values of this vehicle characteristic directly lead to increasing manoeuvring capabilities and finally to diminishing space requirements.

The waiting/holding area fulfills an additional operational task; namely the buffering of vehicles and containers. In respect of the operations systems considered by this paper horizontal transport connects two different logistics systems for container handling – the quay cranes at quay wall on the one hand and the ASC within the yard on the other hand. The use of transport units decouples both systems basically differing in their operations mode and logistic performance capabilities. Thus, idle times and clogging due to disharmonious (direct) system interaction can be reduced or ideally avoided (see, e.g., Schwab 2015, p. 1). In this context, the implementation of waiting/holding positions for horizontal transport units additionally increases the degree of system decoupling since possibilities for container and vehicle buffering are basically extended. Due to less operational flexibility of automated system components decoupling gets momentous importance in case of automation.

14.3.5 Main Driveways

Next to the waiting/holding area towards the terminal yard the main driveways are located. Subject to the quay length and the expected transport volume, the number of driveways has to be implemented. At the CTA in Hamburg-Altenwerder, six main driveways with a quay length of about 1400 m are established (see CTA 2019). These driveways shall ensure a smooth operating without any congestion or waiting of transport units between the ASC blocks and the waiting/holding area. Hence, a waiting position close to the handover lane of the ASC block assigned for container exchange is of prime importance as well. The width of an AGV lane has to be considered with 4.0 and 5.0 m for inner lanes towards the waiting/holding positions. In respect of the elaborated sample layout five driveways are considered within the AGV traffic area. The width of the automated SC lane is about 6.4 m or 7.4 m, respectively (see Sect. 14.3.3). For the AGV system, a distance of 8.0 m between the (outer) main driveway and the quayside end of ASC rails are taken into consideration.[3] By comparison, the SC variant requires in the same area 5.0 m. This distance is required to guarantee a safe "run-in" and "run-out". Thus, the AGV system finally ends up with a driveway proportion of 29.0 m. However, the automated SC variant needs in case of five main driveways 38.0 m.

As already mentioned, it is obvious that the width and length of the (loaded) transport units or their outer turning radius, respectively, determine the dimensioning of the traffic area between quay cranes and container yard decisively. Depending on the part to be configured the length and width dimension of transport units differ in their influence on the layout. For instance, the scale of vehicle width is of less interest for dimensioning of the waiting/holding area (see Sect. 14.3.4) but becomes more important for the crane backreach and main driveways if four or five parallel vehicle lanes are to be considered (see Sect. 14.3.3). All in all, the use of almost 5 m wide automated SC and an around 3.0 m wide AGV results in a substantial difference regarding the total width and partitioning of the quayside traffic area.

[3]In this regard it should be noted that the dimensioning of the ASC handover area can be assumed as similar when considering *lift AGV* in combination with steel racks as an alternative to *standard AGV* for horizontal transport (see Kone 2019).

Fig. 14.8 Main driveways in front of ASC blocks at the HHLA Container Terminal Altenwerder

14.3.6 Planning Results

Based on the planning assumptions described in the preceding sections the design of the entire traffic area is subsequently presented for both horizontal transport systems. Figure 14.8 shows the sample of the AGV layout that ends up with space requirements of about 76.0 m with regard to the distance between landside quay crane rail and the quayside end of ASC rails. The main basis for this calculation forms the assumption of the AGV width (approx. 3.0 m) and the outer AGV turning cycle (approx. 11.5 m) (Fig. 14.9).

The automated SC system investigated as second transport variant results in a different total area width. The distance between quay cranes and the quayside end of ASC rails amounts to around 85.0 m. In spite of the smaller outer turning radius and thus smaller waiting/holding area the SC variant requires a larger traffic area taking account of given planning assumptions. This is mainly induced by wider transport units leading to increased space requirements for driving lanes. The automated SC comes to a width of almost 5.0 m that considerably exceeds AGV width with about two additional metres (Fig. 14.10).

14.4 Investment Comparison for Transport Equipment

For the comparison of necessary equipment investment, the number of vehicles must be elaborated for automated transport system guaranteeing smooth operation in case of regular system use. Considering the present handling requirements of modern

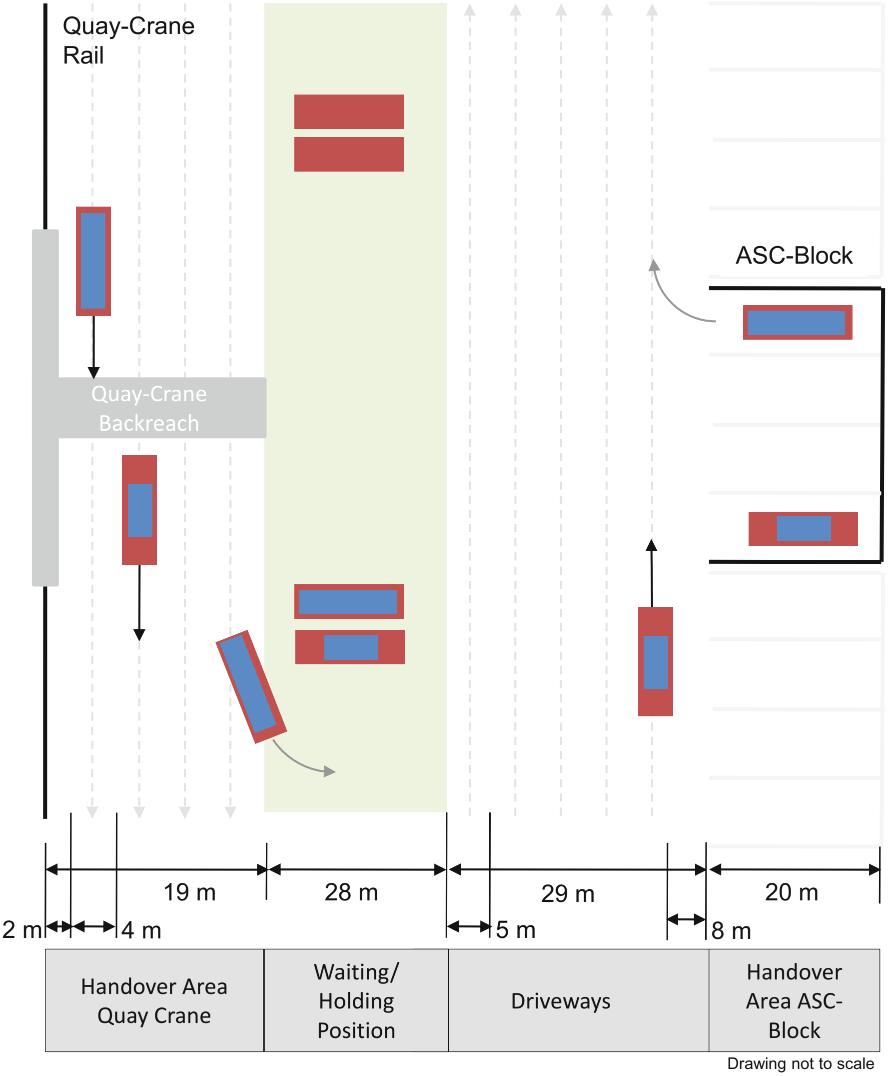

Fig. 14.9 Top view on the AGV layout (stylized illustration)

container terminals the calculation shall be based on an average berth productivity of 150 boxes per hour (bx./h).

Due to terminal optimization aspects (especially regarding needless empty runs and transport paths) the calculation is based on the assumption that no assignment of vehicles to a specific quay crane is made. On the basis of experiences collected at the CTA in Hamburg, an average quayside productivity of 5 bx./h per AGV can

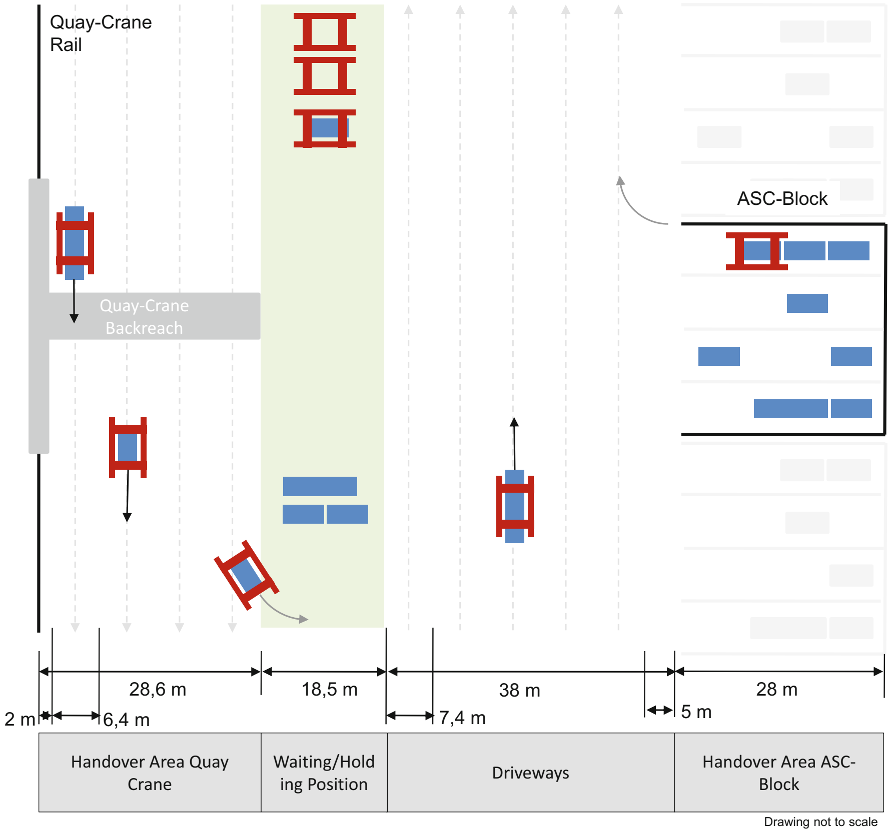

Fig. 14.10 Top view on an automated SC layout (stylized illustration)

be expected. Conversely, this means that on average 30 AGVs are required to fulfill the abovementioned berth handling requirements (of 150 bx./h).

However, looking at the performance of automated SC an average productivity of 6 bx./h shall be assumed for container transports between quay wall and quayside ASC handover areas. The experiences made at terminals with manually controlled (standard) SC show that the vehicle productivity is about 7–8 bx/h on average. According to Kalmar information the performance of an automated SC is a little bit lower than the performance of a standard SC. Due to this, it shall be calculated with an average productivity of 6 bx./h for automated SC. For smoothly meeting the berth handling requirements (of 150 bx./h), this productivity assumption leads to average equipment needs of 25 vehicles.

Table 14.1 Investment comparison (electric) AGV vs. automated SC

Berth productivity requirements [bx./h]	*150*
AGV	
Avrg. vehicle productivity [bx./h]	5
Avrg. number of required vehicles	30
Vehicle investment [million EUR/unit]	0.65
Total investment AGV fleet [million EUR]	***19.50***
Automated SC	
Avrg. vehicle productivity [bx./h]	6
Avrg. number of required vehicles	25
Vehicle investment [million EUR/unit]	0.85
Total investment automated SC fleet [million EUR]	***21.25***

Assuming a price of 0.65 Mio. EUR for an electric AGV[4] and 0.85 Mio. EUR for an automated (diesel-electric) SC a rough calculation results in the following figures for total equipment investment: 19.50 million EUR for the AGV variant and 21,25 million EUR for the automated SC variant (see Table 14.1).

The (extra) equipment to be procured for compensating the vehicle failures due to *M*aintenance & *R*epair (M&R) is not taken into account here. According to operational experiences, automated vehicles of the transport systems being compared show an average equipment availability between 95 and 98%. Noting that, the availability of an automated SC is usually lower than that of an AGV since the distinct equipment technology leads to different M&R incidents (especially the lifting frame of the SC is susceptible to failure). The in here mentioned equipment prices are based on author's experience.

14.5 Conclusion

For the automation of container terminals on the quayside various possibilities do exist. In the foregoing sections just two automated operations systems were discussed more detailed, namely the AGV and the automated SC variant, both in combination with semi-automated quay cranes at quay wall and rail-mounted ASC within the yard area.

For a comparison of transport systems regarding their space requirements similar planning assumptions are taken into account, e.g., container handover is to be done in the backreach of quay cranes using four driving lanes to approach/leave handover positions. Usually, layout assumptions depend on a multitude of (local)

[4]Due to the considerably greater market success, electric AGV are considered for the investment comparison and not standard AGV (with diesel or diesel-electric engine).

parameters, inter alia the length of the quay wall, the number of quay cranes, the percentage of transshipment, etc. To support related design decisions or validate assumptions made for layout dimensioning, respectively, simulation of logistic terminal processes represents an effective instrument (see Stahlbock and Voß 2008). For instance, the definition and execution of appropriate simulation experiments help to determine the right number of main vehicle driveways allowed for layout requirements of the respective application case.

In addition to the comprehensive comparison of quayside layout aspects, the chapter also reviews the investment in both types of transport systems using the regular handling requirements of a single terminal berth. As shown in Table 14.1 the electric AGV variant ends up in slightly less equipment investment compared to the automated SC variant, although the average productivity of an AGV can be assumed lower than that of an automated SC which is able to lift, stack and lower a container autonomously. The economic evaluation does not change if you additionally consider the impact of M&R measures as the related costs are to be expected somewhat higher in case of the automated SC system.

The findings of the system comparison shall not be the statement on a better or worse variant. On the contrary, the investigations purpose is to present a general approach for layout planning of automated operations systems and to reveal basic layout requirements arising out of the use of AGVs or automated SCs on the terminal quayside.

Additionally, the mandatory decoupling of different logistic systems interacting with each other at container terminals is an issue of this chapter as well. On this matter, the particular role of horizontal transport equipment and the design of its traffic area are emphasized for smooth and time efficient container handling. In case of transport automation, very often one is losing sight of one issue, namely the necessity of parking areas for leaving automated transport units (e.g., AGV) enduringly. The non-operational equipment pieces have to be placed within related traffic areas to avoid constrictions of quayside container flow.

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Chapter 15
Raising Efficiency of Straddle Carrier Operations by Twin Container Handling

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Abstract Within the last 15 years the capacity of the largest deep-sea container vessels has more than doubled, bringing more containers to terminals within each single call. For the economies of scale to work, the throughput at container terminals also needs to increase. Among the strategies to increase quayside productivity are, e.g., pooling of carrying equipment as well as dual cycle and twin lift operations of quay cranes. The latter may be implemented with least impact on spatial and process change requirements and include the joint vertical movement of two 20 foot containers. But only if applied to operations of both lifting and carrying equipment container terminals will fully benefit from each twin move. Here, we see a gap regarding the assessment of the potential productivity gain by twin carry operations. In this chapter we want to fill this gap by the example of the implementation of twin carry operations for straddle carriers at the HHLA Container Terminal Tollerort.

15.1 Introduction

According to the Olympic motto "faster, higher, stronger" shipping companies developed larger vessels for the Europe-Asia shipping routes in the last decade, especially when the worldwide financial and economic crisis affected the container shipping industry. At the beginning of this millennium, vessels with a capacity

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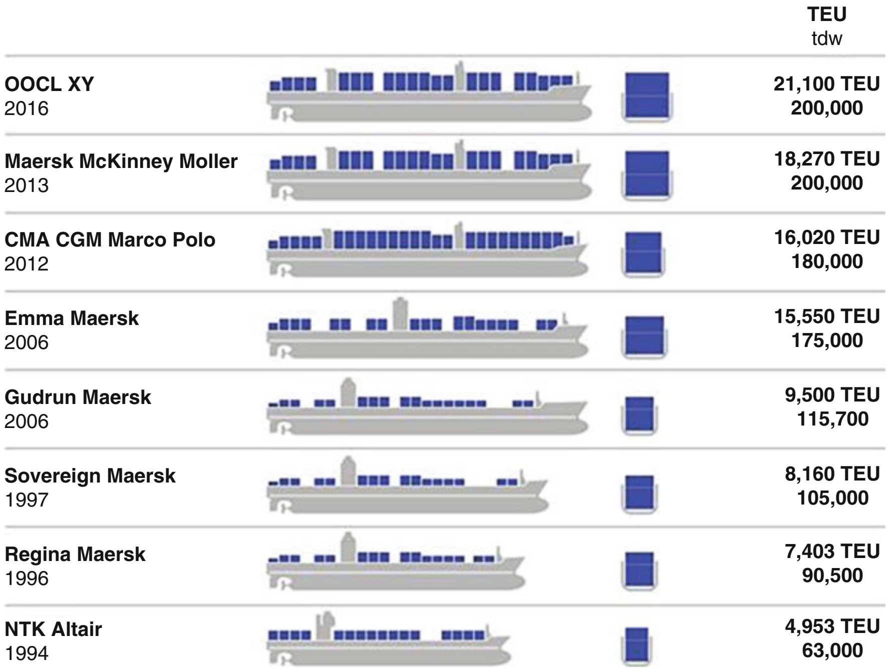

Fig. 15.1 Development of vessel capacity from 1994 to 2016 in TEU

of 8000 TEU[1] were the greatest in operation. Nowadays, however, vessels with a capacity of 20,000 TEU sail around the world (see Malchow 2015), and 22,000 TEU vessels are ordered or being delivered in 2019, respectively (see Ziyan 2018). This is due to the economies of scale as larger vessels are expected to reduce total unit cost. During the enduring crisis, shipping companies competed strongly with each other to gain and maintain the customer's demand. In a vicious circle of underbidding each other's freight rate, operational costs had to be reduced. Therefore, every year a new record-breaking vessel has been built, only to be outperformed by the next vessel. From 2005 until 2016 the capacity of *D*eep-*S*ea *V*essels (DSV) has more than doubled, see van Ham (2004), Malchow (2015) and Pinder (2016). Figure 15.1 shows this development.

Looking at the impact on the entire maritime transport chain, high investments had to be made in particular in seaports in order to prepare their supra- and infrastructure for vessels of this size (see Malchow 2015). For example, the HHLA *C*ontainer *T*erminal *T*ollerort (CTT) ordered five new quay cranes that can reach

[1]TEU is the abbreviation for *T*wenty-foot *E*quivalent *U*nit. The quantification of container volumes in TEU has the advantage that different volumes can be compared regarding their space requirements even though they consist of various types and shares of non-20 ft containers (see also Sect. 15.4).

up to 24 rows and 9 tiers above deck. These cranes can handle the latest type of container vessels[2] such as the OOCL Hong Kong and this investment was made only to keep up with the growing size of the DSV. However, it is not only the need for new handling equipment but also operational improvements of the terminals involved have to be considered. When processing larger vessels, larger numbers of containers have to be loaded and discharged, respectively, while berthing windows, however, mostly remain the same. This means that terminals have to accelerate vessel discharge and load operations. According to (Hacegaba 2014) as well as (Pinder 2016), larger vessels raise the importance of fast processing in ports; economies of scale only truly work if the round trip time of a vessel is preserved. Hence, the number of ports to call and/or the handling time (per container) needs to be lowered while volumes per call increase.

Considering this, CTT has found that not only container loading and discharging at quay but also carrying containers in twin mode is a key to success by considerably improving the overall productivity. Neither additional SCs have to be purchased nor is it necessary to employ more personnel. Therefore, we expected a productivity gain due to high efficient operations.

Figure 15.2 shows the typical amount of containers of a single *U*ltra-*L*arge *C*ontainer *V*essel (ULCV) call at the port of Hamburg, as well as the number of feeder, barges, trains, and trucks delivering and picking up containers corresponding with the call.

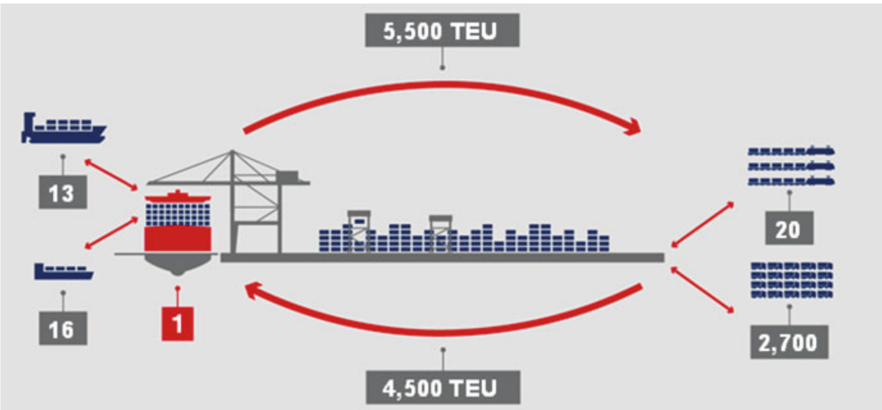

Fig. 15.2 Typical ULCV call and its influences on the pre- and on-carriage

[2]Vessel length: about 400 m, vessel width: about 59 m.

15.1.1 General Aspects

Twin lifting containers is a feature used by many terminals worldwide to boost quay crane productivity, and thus to increase their quayside service performance. Lifting two 20 ft (*f* oo*t*) containers at once greatly reduces the number of crane moves at a vessel bay and may increase handling rates far beyond the normal value, if "perfect" conditions for vessel processing are given. Today, most modern quay cranes are already equipped with automatic twin spreaders that allow picking up single 40 or 20 ft containers as well as two (twinned) 20 ft boxes.

With a TEU Factor of 1.64[3] (for the important Far East trade of the port of Hamburg) there is indeed a significant chance for making use of twin lift operations at the quay walls of Hamburg's container terminals (see Sect. 15.4). Cranes of the latest generation usually allow maximum rated loads that even cover the heaviest possible twin pairs; two 20 ft containers may weigh up to 65 metric tons. Modern twin spreaders allow to separate twin pairs to a distance that allows *S*traddle *C*arriers (SCs) to to either pick up a pair of boxes one by one or deliver a twin pair one by one. In this case, quay cranes can perform twin lift operations, while SCs pick up or deliver containers one by one. However, there are two SC carry moves required for one twin lift move of a quay crane. To streamline this process, twin capable SCs paired with twin capable planning and control software are necessary pre-requisites.

15.1.2 HHLA Container Terminal Tollerort

The CTT at the port of Hamburg is a conventional SC terminal with 4 berths – in parts capable of processing vessels of the 400 m class. The overall annual handling capacity is in the range of 1.4 million TEU. At the quayside, 14 *Q*uay *C*ranes (QC) are available; all of these are equipped with long twin spreaders.[4] On the terminal, container carrying, yard operations and truck service are performed by 4-high SCs. The fleet currently consists of 60 machines. Loading and unloading of railcars is performed at the terminal railhead by means of three manually operated rail mounted gantry cranes that pick up at or deliver boxes to a handover position parallel to the five rail tracks. There are three parallel rows of handover positions next to the rail with a gap every 14 boxes to avoid that SCs have to travel (in case of occupied handover positions) all the way along the 700 m of rail tracks. The rail cranes also perform twin lift operations to the extent possible. Figure 15.3 schematically shows the current layout of the CTT.

[3]According to HHLA Container Terminal Tollerort internal statistics of 2016.

[4]*Long twin* refers to a spreader being capable of separating two 20 ft containers from each other as well as picking up separated containers. The gap between separated containers may be up to as large as 5 ft, which makes it possible to operate in both 40 ft as 45 ft container positions.

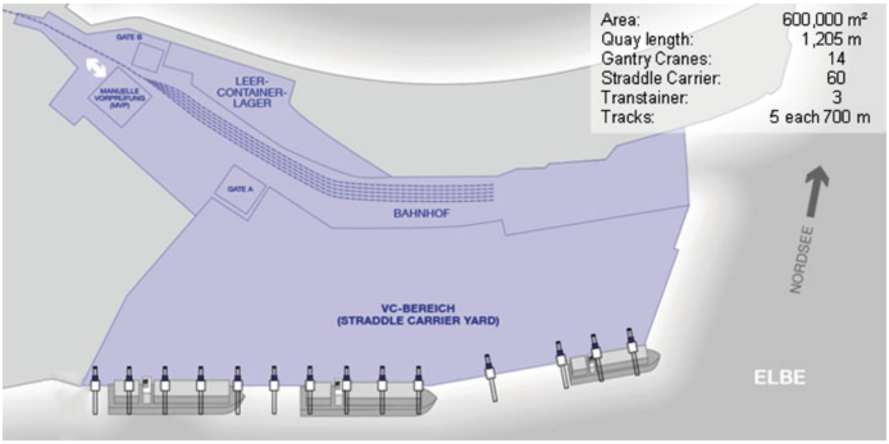

Fig. 15.3 Overview of the yard at CTT

In the following section, we present a literature overview of twin handling at SC container terminals. In Sect. 15.3, necessary pre-requisites to implement a full twin handling process[5] are being discussed and we briefly summarize CTT's experience with implementation of SC twin carry operations at the terminal quayside. In the main part, Sect. 15.4, we present an in-depth discussion on the actual twin carry potential at our terminal and an evaluation of twin carry operations by benefits in the fields of productivity, resource savings and environmental impact. In the last section, we recap our most important findings.

15.2 Literature Review

Several paper overviews on *O*perations *R*esearch (OR) literature at container terminals have been published in the past 15 years. The papers of Steenken et al. (2004) as well as of Stahlbock and Voß (2008) are pioneering and represent comprehensive works. Islam and Olsen (2013) presented the latest literature update on OR at container terminals. Carlo et al. (2014a) as well as Carlo et al. (2014b) presented two papers, namely one on transport and one on storage operations equipment both associated with literature classification schemes. All these papers also cover twin lift and twin carry operations in the context of SCs.

Furthermore, according to the authors, the need of sophisticated software solutions for planning, dispatching and control is important in order to use equipment

[5]In case of vessel discharging or loading, 20 ft containers are completely moved as twin pairs (if possible), i.e., they are twin lifted by QC at quay wall and twin carried by SC from and to the yard area.

more efficiently. Cañero et al. (2011) postulated that in general, twin working must be applied whenever possible to deploy the full effectiveness of container handling equipment.

Kim and Lee (2015) only briefly addressed SCs as being very flexible container handling equipment because of their capability to both carry and lift containers. Nevertheless, they also stated that to apply twin lift operations by quay cranes and yard cranes implies the use of twin carry capable equipment to be more efficient. Since the features of yard cranes and container carrying vehicles are combined within SCs, this conclusion also applies to SCs. Furthermore, Kim and Lee (2015) emphasize that the *T*erminal *O*peration *S*ystem (TOS) must have built-in functionalities to plan, execute and control both twin lift and twin carry operations. They even provide an overview of the features of different software systems within the domain of container terminals.

Hansen and Henesey's (2007) research contains actual figures about twin carry moves assumed as parameters for their simulation study. According to them, a twin lift share of 20% at quay and a twin carry share of 100% between quay cranes and yard result in 11% (full) twin handling cycles for 20 ft containers.

We want to conclude that various aspects of twin lift and twin carry operations at SC container terminals have already been discussed in literature and it has been clearly stated that operations will benefit from each twin move. Nevertheless, we see a gap regarding the assessment of the potential productivity gain by twin carry operations. In this chapter we want to fill this gap by the example of the implementation of twin carry operations at CTT.

15.3 Major Requirements for Full Twin Container Handling

For efficient twin handling, some preconditions within the scope of equipment, stowage, yard planning and TOS have to be considered. In this section, we will discuss general requirements for full twin container handling at a SC container terminal. We present our experience in implementing TOS-supported twin carry operations at CTT during the current decade.

15.3.1 Equipment Use

Basically, technical limitations of the equipment in use have to be taken into account when assigning SCs to their respective point of work such as the terminal quayside. Thus, within the twin capable part of the equipment fleet, weight restrictions of the equipment have to be considered. Given that twin carries of up to 65 metric tons are not uncommon, assigned SCs should be able to handle heavy twin pairs, avoiding to break them up during operation. This also has to be considered for spare and replacement equipment. The exchange of SCs just like the change of their work orders during operation negatively impacts productivity, and hence, should be avoided. Additionally, for QC operation, weight restrictions for the outer vessel rows and load limitations of the quay wall need to be taken into account. These restrictions may force QC operators to work in single mode for certain containers or a few rows in a vessel's bay. This of course affects QC productivity negatively, but still a twin carry by the SC remains possible.

As a rule of thumb, it is only recommended to work a vessel's bay in twin mode if the QC is able to perform twin operations continuously. Switching between 20 ft single and 20 ft twin modes makes it necessary to move the whole QC which is too time consuming.

15.3.2 Yard and Vessel Planning

Considering container stowage, at each port a *stowage instruction* is provided by the vessel's supercargo usually acting on behalf of the cargo owner. This instruction should be oriented to twin handling opportunities and avoid mixing full and empty cargo in paired bays due to weight reasons. Additionally, stowage planning has to consider twin container handling to the extent possible. Hence, the possibility of twin operations is a task for the whole container supply chain from the initial storing and loading of a container pair at the origin port until its discharge and drop down within the storage area at the destination port.

For twin discharge and loading, vessel design has to be taken into account. In some cases, the bottom tier on deck cannot be loaded or discharged in twin lift operation. In such cases, the *work program* of QCs should be able to deal with single moves and forego movements to single bays which could affect adjacent cranes.

Especially for twin productivity gains in case of vessel loading, it is important that the quay cranes' work program considers twin pairs opportunities and avoids frequent changes between handling of 40 ft containers and twin. When preparing the loading sequence, the operator has to consider that special containers (e.g. reefer) may not be loaded in twin mode due to terminal regulations (see Sect. 15.3.3). This could also affect the work program of surrounding QCs.

Furthermore, to push the SC twin carry rate at terminal quayside, the yard planning strategy needs to support stacking 20 ft boxes as feasible twin pairs in the yard. In other words, for the vessel discharging process, yard planning needs to make sure that a sufficient amount of twin capable stacks are available. For vessel loading, pre-stowing of 20 ft containers as twin pairs represents a proven procedure to reach high SC twin carry rates. This is not possible if the freight and transport data of containers entering the terminal is not already available. In addition, shortly before the vessel arrives, the amount of twin pairs may be increased by *housekeeping* moves. Of course, this is sometimes not being done due to scarce resources or for economic reasons resulting in higher twin shares for discharge than for loading containers at terminal quayside. In fact, the impact of housekeeping can be seen in the twin statistics of the terminal equipment (see Sect. 15.4.2). For a fair comparison and analysis of the processes, related extra housekeeping moves need to be taken into account for vessel loading (see Sect. 15.4.4). In conclusion, it can be stated that efficient twin operations are only possible, if the supercargo and the ship and yard planners at each terminal are planning accordingly.

15.3.3 TOS Use and Equipment Control

A major influence on twin productivity gains lies in adequate yard planning of load containers leaving the terminal at quayside (see Sect. 15.3.2). In this case, operations management can be effectively supported by a TOS. Due to flexibility reasons when stowing a vessel, containers of a whole (twin) yard stack should be of the same weight class. The range of the weight classes should be large enough enabling the TOS to build adequate stacks. At the same time, however, the range has to be small enough so that all containers of a stack can be planned in the same tier when stowing on the vessel. Otherwise, additional shift moves may occur.

Furthermore, a TOS has to consider several other factors for assigning load containers to yard slots if the twin handling share shall be influenced significantly. Beside the collecting vessel and the container weight class, typical examples in this regard are the port sequence of the vessel or potential problems in picking up twin containers. When physically placing a 20 ft container next to its designated twin partner in the adjacent stacks of a yard row, the equipment operator (or TOS) has to ensure that the twin pair can be picked up without difficulty. For example, the weight of each of the containers of a twin pair does not differ in a way that handling equipment will not be able to compensate.[6] Otherwise a twin carry will not be possible or failed balancing could cause serious damage to both the equipment and the container. In these cases, it could make sense to "correct" the position of a container and to carry it afterwards as a twin move. This means that the yard operator (or TOS) needs to assign (extra) equipment to prepare valid twin rows.

For load containers leaving the terminal at landside interfaces (railhead, truck holding area and main quay in case of barges), the potential twin productivity gain by adequate yard planning is significantly lower than for those to be loaded on vessels at quay wall. This results in less importance of the TOS for tapping the twin handling potential when storing these containers in the yard area. Usually, the hinterland carrier (incl. arrival time) is not confirmed at the time when its future load containers are stored in the yard. Therefore, shifters are unavoidable before the loading process of hinterland carriers starts if a larger volume of load containers shall be handled as twin pairs.

When creating the work program for the terminal handling equipment, the TOS should consider potential twin moves as well (see Sect. 15.3.2). If the system

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[6]Modern twin spreaders are able to balance mass differences between 20 ft containers up to 10 metric tons.

is able to integrate "twin data" in planning, the duration of work orders (i.e. container moves) and order sequences becomes more precise and leads to more effective container assignment or efficient resource use, respectively. Equally, 20 ft containers that cannot be moved in twin mode for some reason[7] may not be counted and considered by the TOS as a twin move in the work program.

15.3.4 Implementing Twin Carry Operations at CTT

By 2006, all SCs had been equipped with automatic long twin spreaders. This was a prerequisite for the introduction of twin carry operations by SCs. If only a part of the fleet had been equipped with long twin spreaders, overall deployment would have been difficult as part of the machines then could not be used for vessel or rail service. Twin carry moves for un-/loading trucks are usually not applicable because of missing information (see Sect. 15.3.3) and the low share of trucks carrying two 20 ft containers at CTT.

At CTT, twin carry operations by SCs have been possible and done by SC operators ever since the first twin spreaders were purchased for SCs in 2002, but it used to be a manual process due to the TOS not being capable to plan, dispatch or control twin carry moves for SCs until 2012. The TOS had to be adapted to the more complex requirements resulting from twin handling. This required a number of changes to be performed by the system supplier, and it took more time than originally expected to come to a working version of the TOS, noting that CTT obviously was the first terminal to use this system for completely TOS-controlled and optimized SC twin carry operations.

SC drivers also had to be trained in the application of twin handling. Our experience showed that drivers became used to the process in a very short time. Starting with two try-out vehicles on a Thursday afternoon, during the following weekend almost all SCs in use for box handling on a 10,000 TEU vessel successfully performed twin moves for discharge and load containers (see HHLA (2012)).

15.4 Statistical Analysis of CTT Handling Figures

In this section, we discuss the potential of twin carry handling by using statistics for 2016 taken from CTT's data warehouse. The database combines data of all SC jobs and data of container checks at quayside matched by each individual container visit. This includes among others the information on containers size, twin or single carry mode, container shifts connected to a container loading job as well as distances

[7] For example, special containers like dangerous goods, reefers, tanks and *O*ut-*O*f-*G*auge (OOG) boxes or containers with weight restrictions.

driven by SCs. We evaluate the positive impact of containers carried in twin mode on productivity, resource consumption and environmental pollution.

In order to verify the productivity gains due to twin carry operations several figures shall be analysed. For example, the amount of twin carried containers primarily depends on the size of handled containers: Since only 20 ft containers may be twin carried, an accurate figure to anticipate the potential of twin carried containers is the *T*EU *f*actor (Tf). Among others, this key figure shows the ratio between 20 and 40 ft containers where n_{20} is defined as the number of 20s, and n_{40} is defined as the number of 40s[8]:

$$Tf = \frac{(n_{20} + 2n_{40})}{(n_{20} + n_{40})} = 1 + \frac{(n_{40})}{(n_{20} + n_{40})} \tag{15.1}$$

When neglecting other box types, the decimal places of the *Tf* represent the share of 40 ft containers and 1 minus the decimal places results in the share of 20 ft containers. Accordingly, a *Tf* of 1 means that every container is a 20 ft box and a *Tf* of 2 that every container is a 40 ft box. As mentioned above, at CTT the *Tf* reached 1.64 in 2016. Depending on the vessel service, this figure generally oscillates between 1.58 and 1.72. In other words, up to 42% of all containers loaded or discharged are 20 ft containers. Consequently, at CTT, the maximum of productivity gain can be achieved is by saving 21% SC carries. As a rule of thumb, the lower the *Tf*, the higher the potential productivity gain.

15.4.1 Determinants of Twin Carry Ratio

This analysis focusses on 20 ft boxes and their *T*win *C*arry *r*atio (TCr). The twin carry ratio is defined as follows where $n_{20,twincarried}$ is the number of twin carried containers:

$$TCr = \frac{n_{20,\ twin\ carried}}{n_{20}} \tag{15.2}$$

Furthermore, the total number of SC moves results from the number of *single* and *twin carried moves* and is calculated as follows (when neglecting shifters!):

$$SCc = (n_{40} + n_{20} - n_{20,twincarried}) + \left(\frac{n_{20,twincarried}}{2}\right) \tag{15.3a}$$

$$= n_{40} + n_{20} - \frac{n_{20,twincarried}}{2} \tag{15.3b}$$

[8]The approach presupposes that 45 ft containers are being counted as 40s, whereas other box types (e.g. 10 or 30 ft containers) can be neglected due to their comparatively small number. At the CTT, such conditions are met.

15.4.1.1 Vessel Type's Influence

The potential of twin carry operations depends on the vessel type as well. Generally, there are three types to be distinguished:

- DSVs,
- *S*hort *S*ea *F*eeders (SSF) and
- barges.

In Hamburg, barges are considered as hinterland carrier. Nevertheless, they are handled at the terminal main quay wall along with DSVs and SSFs. Often there is no due notice about which import containers are to be collected by barge. Sometimes not even the time of arrival of barges is known in advance. This is because bay planning at pre-ports does not usually have any information on the hinterland carrier. Therefore, container stacking at the yard area to optimally twin carry containers for barges (and the other hinterland carriers) is hardly possible. As a result, at CTT for example, the average *TCr* of barges was only 9.8% in 2016.

Due to the handling volume and the requirements of container shipping companies, the primary operational goal of container terminals is to accelerate their DSV calls. Thus, when storing DSV import containers in the yard area, terminal operations planning usually puts more emphasis on easily stacking all discharged containers than on preparing twin moves for the subsequent loading process of the hinterland carrier (see Sect. 15.3.3). In a general view, barges only carry less than 2% of the containers handled at Hamburg's quay walls, therefore, terminal operators do not focus on increasing the *TCr* of barges.

SSFs, though, vary highly concerning their *Tf*. At CTT, for example, the average *Tf* was 1.62 and the *Tf* standard deviation was 0.21 in 2016. SSFs carried about 20% of all containers handled at CTT's quay wall in 2016. Their average *TCr* was approximately 29.0%. Even large SSFs at CTT, which carry up to 1500 TEU, generally do not achieve a *TCr* above 50% in total (i.e. discharging and loading).

About 80% of the quayside container volume handled at CTT during the last years is related to DSVs. Thus, CTT focused on increasing the *TCr* of DSVs. Against this backdrop, the present analysis shows a more detailed view on twin carry operations concerning DSV calls. Overall, the average *TCr* of DSVs was 74.2% at CTT in 2016. DSVs calling the terminal possessed an average *Tf* of 1.64 and the *Tf* standard deviation was 0.04. In conclusion, large vessels such as DSVs or large SSFs have usually higher twin carry ratios than smaller ones since more containers are handled per call and economies of scale can be achieved when the terminal management takes the "right" (preparatory) actions respecting twin carry operations (see Sect. 15.4.2).

15.4.1.2 Container Direction's Influence

As mentioned above, minimizing the DSVs' berthing time is one of the primary operational goals of a container terminal. Accordingly, QCs try to discharge as much as possible 20 ft DSV containers in twin mode. Additionally, the yard area of many container terminals is divided into certain areas for DSVs' discharge and DSVs' load containers. This makes twin carrying of 20 ft discharge containers quite easy, especially in case of import containers when little stacking requirements usually exist as the information about the hinterland carrier is missing (see Sect. 15.3.3).

Looking at the CTT figures in 2016, this impression manifests: DSV discharge *TCr* figures around 82% were common. Furthermore, less than a tenth of all DSVs calling at CTT possess a discharge *TCr* lower than 75% in 2016, and almost a third even show a discharge *TCr* between 85% and 95%. Here, it should be noted that the top 15 DSV discharge *TCr* figures are related to the same DSV class and owner. This seems to indicate that stowage planning on vessels can be a significant factor to increase the *TCr* if the creation of twin pairs is consequently considered for vessel discharging (and loading). Quite high discharge *TCr* figures could be achieved for SSFs as well. Actually, the average SSF *TCr* is comparatively low (see Sect. 15.4.1.1), however, only taking into account discharge containers, the average *TCr* of standard SSFs (600 to 800 TEU at CTT) was about 50%. Focusing on large SSFs, their ratio was even about 72% on average.

By comparison, only about 64% of the 20 ft DSV load containers were twin carried at CTT (2016). Examined in more detail, 15% of all DSV only achieved a *TCr* of less than 50%, and 11% a *TCr* of more than 75% for load 20 ft containers. In case of SSF loading about 10% of all 20 ft containers were twin carried. Here, a third of the vessels show *TCrs* higher than 20%, and only 8% a twin carry ratio in the range of 50%. Major reasons for the lower *TCr* of vessel loading processes are the following.

Generally, the containers do not arrive at the terminal in their later loading order. Compliance, however, with a specific order is necessary since containers have to be stacked on a vessel according to several specific criteria, e.g., above deck in the order of their gross mass, i.e., the heaviest first, the lightest on top. As yard space and/or container information are not always sufficiently available upon arrival, container storing in the yard area often does meet all existing order requirements of the loading process. Therefore, the anticipation of twin pairs is comparatively difficult when allocating yard positions to incoming load containers. Noting that, costly container shift moves by SCs become necessary if twin pairs shall be composed when the containers have already been stacked.

Another impediment for twin carry operations during the loading process are last-minute changes in the bay plan. The bay plan includes the future container positions on the vessel and has to be checked with the chief mate of the vessel each time when calling a terminal. Modifications are likely and originally planned twin pairs may no longer be feasible as the container positions in the yard do not fit to the updated bay plan or the resulting (new) loading order, respectively.

15.4.1.3 Influence of the Container Load: Full Versus Empty

In general, containers should be carrying cargo when transported. These containers are of main interest from the perspective of a container terminal. In case of CTT, more full import containers arrive and are to be discharged from vessels than full export containers leave after loading on vessels. As a consequence, shipping companies and sea freight forwarders order empty containers from CTT to fill this gap. In other words, a significant number of empty export containers has to be handled at the terminal as well. Most of these containers are collected by DSVs towards Asia.

Considering vessel discharging in detail, 99.2% of all 20 ft DSV import containers were full and only 0.8% were empty at CTT (2016). Accordingly, the quite high DSV discharge *TCr* figures (see Sect. 15.4.1.2) are based on full twin pairs and the influence of 20 ft empty containers on the discharge *TCr* is negligible.[9] As previously mentioned, export containers are more often empty at CTT. About 36% of all 20 ft load containers (that is 15% of all containers) did not carry cargo in 2016. The *TCr* of empty DSV load containers is relatively high and amounts to about 83%. A more detailed look at the loading process of empty containers reveals the reasons why the related *TCr* is clearly above 80%:

In case of DSVs, the number of empty containers is partly considerable – up to 49% of load containers are empties at CTT (2016). In comparison to full boxes, for empty containers there are only weak restrictions regarding the loading order to be followed. Additionally, one or more whole bay(s) on a DSV are generally dedicated to empty containers only. This offers operations planning the possibility to store them in one designated yard stack, which is reserved for the respective DSV. When containers are allocated to the yard slots possible twin pairs can be considered quite easily. Whilst loading empty containers from the same stack SCs can generally twin carry them pair by pair to the quay wall (allowing for scale effects). Explained in more detail, empty containers cause no "mass congestions" which may interfere twin carry moves. SCs are only allowed to twin carry two containers if their mass difference does not exceed 10 tons. Since all 20 ft empty containers weigh basically the same, no stacked pair has to be broken because of this. All in all, storage and carry requirements for empty load containers are comparatively low abetting twin carry operations during the loading process. By comparison, full load containers can have a mass between 2 and 32 metric tons. Accordingly, terminal yard planning is basically more challenged when storing 20 ft full containers as twin pairs since, in each case, two containers with similar mass values and for the same DSV are to be positioned next to each other considering limited yard capacity as well (typical SC yard occupation is between 75 and 85%.)

Additionally noted, full load containers reach the terminal by different carriers (truck, trains, barges and SSFs) within several days before the DSV and the terminal

[9]Considering full DSV discharge containers the *TCr* was 82.3%. By comparison, the *TCr* of all DSV discharge containers (i.e. including empty containers) was 82.2%.

Table 15.1 DSV twin carry ratios by full and empty containers in case of discharging and loading

	Discharge	Load	Total
Full	82.3%	54.6%	*72.9%*
Empty	55.7%	83.2%	*81.0%*
Total	*82.2%*	*64.1%*	*74.2%*

As neither discharge/load nor FCL/MT numbers are equal the italic values represent a weighted average. For analysis purposes it has been split up

usually has no complete information about all containers announced for a DSV call until the vessel arrives. This includes the freight information of each container as well as its transport information, namely the later stowage position on the vessel. Thus, container storing in the yard according to the ultimate loading order is only possible to a limited extend just as composing twin pairs by appropriate yard slot allocation.

All in all, the various impediments to more twin pair-related operations planning lead to a comparatively low *TCr* which amounts at CTT to about 54% in case of full load containers. Nevertheless, scaling effects can be seen here, too. The more full containers to be loaded on a vessel and the more of these containers arrive at a similar time, and by similar carriers, the higher *TCr* figures can be expected.

At CTT, the vessel service with the highest number of full containers to be loaded per call achieved a *TCr* of about 64% in 2016. A vessel's *TCr* on this level becomes possible for full load containers if customers of a service (such as huge automotive factories) deliver many boxes with similar mass which arrive at the terminal within a narrow time slot. Under these conditions, advanced operations planning will be in the position to store a higher share of full load TEU as twin pairs (than usual).

Table 15.1 serves as a summary and shows the exact CTT *TCr* values mentioned in this chapter. The figures are from 2016 and represent average values per call or absolute values per category, respectively.

15.4.1.4 Shipping Companies' Influence

The following table shows average DSV *TCr* values for discharge and load containers of different shipping companies in 2016. Looking at these figures, it is apparent that the overall figures of the shipping Companies B and D are significantly smaller than the overall *TCr* at CTT quayside (see Table 15.1). A valid explanation is that Company B's vessels possess midlocks[10] which prevent QCs to twin handle containers stored above deck. Consequently, those containers are regularly carried in single mode from or to the vessel, respectively.

[10]By the use of midlocks twin pairs can be stacked in 40 ft stacks on deck of these vessels. In some cases, the twin spreaders are not able to drop a twin pair on this special kind of twist locks simultaneously, but one after the other. This is due to technical limitations of the spreader.

Table 15.2 DSV twin carry ratios by different vessel owners

	Discharge	Load	Total
Shipping company A	82.7%	68.2%	*75.4%*
Shipping company B	77.4%	57.7%	*70.0%*
Shipping company C	89.5%	65.4%	*80.9%*
Shipping company D	81.8%	51.9%	*69.5%*

As neither discharge/load nor FCL/MT numbers are equal the italic values represent a weighted average. For analysis purposes it has been split up

Moreover, Company D orders a relatively small amount of empty containers which leads (according to Sect. 15.4.1.3) to a "low" *TCr*. In comparison, Company A orders the highest amount of empty containers, accordingly, it has a quite high *TCr*. Whereas for Company C not only one factor mainly drives the *TCr*, but different ones, in particular, the high number of empty and full 20s as well as the high number of containers in total (Table 15.2).

In conclusion, it is apparent that differences between shipping lines exist in terms of twin carry operations. This is due to the type and amount of containers transported by a service. Furthermore, it may depend on how many changes of the stow occur, the characteristics of vessels used within a service, and the effort spent on twin-related stowage planning by the shipping company and the terminals involved (see also Sect. 15.3.2).

15.4.2 Preparations to Increase Twin Carry Ratio

If 20 ft containers are not located "optimally" in the yard (i.e. twin carry moves are not possible), there is the possibility to do *housekeeping*. This is when SCs shift containers within the yard area in order to clear it up. Housekeeping usually aims at accelerating vessel processing and that is why necessary container shifts are completed before the actual arrival of the vessel. Typically, housekeeping is carried out when there is reduced workload at the terminal, e.g., at the landside during the night and on weekends or at the quayside after a DSV departure. Due to the volumes collected by DSV and the reasons discussed in Sects. 15.4.1.2 and 15.4.1.3 preparations to support twin carry operations are primarily made for *20 ft DSV load containers* at CTT. Therefore, the following figures and explanations only focus on them.

DSV load containers arrive at CTT by train, truck or barge (hinterland) as well as by SSF (seaway). They access the terminal in random order, and most likely not in the later container loading order. This is due to the fact that the final container destination and the related port of discharge as well as the container weight and other factors determine the loading order but not the arrival order of incoming export containers at landside terminal interfaces.

In case of SSF discharging, containers could be twin carried to their yard position in many cases. However, according to the given requirements of the loading order, SCs would frequently have to single-carry these containers to the QCs loading them on a DSV. As mentioned above, CTT aims at accelerating DSV calls and, hence, load containers shall be twin carried to the quay wall. Therefore, sometimes it is more useful to single-carry a discharged container from SSFs in order to optimize the yard for the DSV loading process.

Incoming trains deliver many times export containers for one particular DSV. These containers will most likely be stored close to each other in the yard area. Therefore, the subsequent DSV loading process can be carried out with lesser preparations.

Containers received at the terminal by truck, however, cannot be stored optimally at the first place because of their uncertain time of arrival which is associated with a random incoming order. Typically, at CTT, the modal split of outgoing DSVs containers is about 50% by truck, 30% by train, and 20% by SSFs. Hence, it is likely that a significant number of containers received by truck cannot be twin carried to the quay wall for loading purposes (unless appropriate preparations take place beforehand). In order to achieve a good *TCr*, it is therefore necessary to compose twin pairs of 20 ft containers received from trucks prior to the vessel call. This is an important objective of housekeeping at CTT.

On average, 23% of all DSV load containers have been shifted before loading.[11]

This figure results from shiftings of almost 33% of twin carried containers as part of housekeeping and 20% of the remaining DSV load containers (i.e. 20 ft not twin carried and 40 ft boxes) as part of other measures, e.g., restacking. According to this figure, housekeeping takes place and increases the number of twin carried load containers significantly by almost 50%.

[11] A simple example shall illustrate the correlations between the above-mentioned container shares: When considering *100 DSV load containers*, on average,

– *40 containers* are 20s (see introduction of Sect. 15.4)

  … of these containers, 64% are twin carried (approx. 25 boxes) and 36% are single carried (approx. 15 boxes), see Table 15.1

  … of the twin carried containers, 33% have been shifted as part of previous housekeeping (approx. 8 boxes)

  … of the single carried containers, 20% are shifted during the loading process as part of other measures (approx. 3 boxes)

– *60 containers* are 40s

  … 20% of these containers are shifted during the loading process as well (approx. 12 boxes)

In total, this leads to, on average, 23 load containers which have been shifted in the yard area before loading. Without housekeeping the number of twin carried load containers drops to 17 or, expressed differently, housekeeping increases the share of twin pair containers by 47% on average.

15.4.3 Productivity Gain Due to Twin Carry Operations

There are different key figures to evaluate and describe the resource productivity at container terminals, such as the number of container moves per resource hour. As several equipment types are in use, there are different ways of determining the reference basis for productivity calculation at terminals, e.g., berth occupation hours, quay crane operating hours or SC operating hours. In this regard, often reported key figures are the berth productivity (number of container moves per berth hour) or the quay crane productivity (number of container moves per crane hour). This chapter, though, is focused on the productivity of SCs.

A QC at CTT twin lifts 20 ft containers – if possible. This is joined with higher productivity of QCs especially when operating DSVs. Accordingly, either the number of SCs per QC or the individual SC productivity must be adapted to maintain the improved "operational speed" of QCs. Certainly, increasing the SC productivity is more economic. For example, in case of a strongly export-orientated DSV – where more loads than discharges are to be done – comparatively high twin carry requirements for SCs arise during the loading process when housekeeping measures have been executed before vessel processing. The *TCr* of importers solely depends on how 20 ft containers have been stowed on the vessel and, thus, this ratio is quite high anyway.

As mentioned above a simple way to calculate the *P*roductivity of *SC* (P_{SC}) is shown by Formula (15.4). Here, OH_{SC} is the number of SC operating hours and "$n_{40} + n_{20}$" the number of (productive) container movements carried out during this time. It should be noted that (unproductive) shift moves are neglected in Sect. 15.4.3 and only considered in Sect. 15.4.4:

$$P_{SC} = \frac{(n_{40} + n_{20})}{OH_{SC}} \tag{15.4}$$

Assuming that the average SC operating time per container move is constant (regardless of single- or twin carry moves), OH_{SC} can be replaced by the following term where x represents the average operating time per container move:

$$P_{SC} = \frac{(n_{40} + n_{20})}{x\,(n_{40} + n_{20})} \tag{15.5}$$

Formula (15.5) assumes that there is no twin carry at all. If there is twin carry, though, it has to be remodelled as follows:

$$P_{SC,\,twin} = \frac{n_{40} + n_{20}}{x\left(n_{40} + n_{20} - \frac{n_{20,\,twin\ carried}}{2}\right)} \tag{15.6}$$

The productivity gain factor $G_{P,\ SC} = \frac{P_{SC,\ twin}}{P_{SC}}$ can be approximately calculated only depending on the *Tf* and the *TCr*, which is shown in Formula (15.7)[12]:

$$G_{P,\ SC} = \frac{1}{1 - \frac{TCr \times (2 - Tf)}{2}} \tag{15.7}$$

In case of *Tf* = 2 (i.e. 100% 40 ft boxes), there is no productivity gain ($G_{P,\ SC} = 1$). In case of *Tf* = 1 (i.e. 100% 20 ft boxes), the productivity gain only depends on the *TCr*. A *TCr* of 0% evidently leads to no productivity gains ($G_{P,\ SC} = 1$), a *TCr* of 100% is associated with maximum productivity gain ($G_{P,\ SC} = 2$), i.e., the SC productivity doubles.

Considering the CTT figures of 2016 (*TCr* = 72.9% and *Tf* = 1.64) and neglecting all kinds of shifters, based on Formula (15.7), a SC productivity gain of about 15% can be calculated in case of an "average" DSV call. Other DSV calls with more discharging containers may gain about 17%. 'Usually, $G_{P,\ SC}$ is between 1.10 and 1.20 at CTT, only 2% of all DSV calls are below and 4% above these limits. To sum up, twin carry operations can allow for increasing the terminal's SC productivity significantly. It depends, however, highly on the realized *TCr* and the given *Tf*.

15.4.4 Savings in Resources and Carbon Dioxide Emissions

At a container terminal, SC twin carry operations increase productivity and, consequently, can save resources such as fuel (SCs at CTT are fired by diesel). The gain in productivity of 15% calculated for SC operations in Sect. 15.4.3 decreases the fuel consumption per DSV call by 13% on average.[13]

So far, housekeeping measures – as main enabler for a high twin carry ratio – have not been taken into account in the analysis. In the following, both shift moves due to housekeeping (before vessel loading) and shift moves due to container retrieval (during vessel loading) are included in the calculation. The results show that savings in terminal resources are even possible although there is a higher shift ratio through housekeeping (see Sect. 15.4.2). Firstly, this is because housekeeping previously conducted can reduce the number of necessary shifters during vessel loading. Secondly, the distance per (housekeeping) shift move is significantly smaller than the distance per loading move between the yard and QCs at quay wall.

[12]The Formulas (15.1) and (15.2) are necessary in order to achieve Formula (15.7) noting the following correlations: $(n_{40} + n_{20}) \times (2 - Tf) = n_{20}$ and $n_{20,\ twin\ carried} = n_{20} \times TCr$.

[13]A SC productivity gain of 15% reduces the operating time of vehicles by 13% and with that their fuel consumption by the same amount. Noting that this calculation supposes linear correlations, i.e., the increase in fuel consumption caused by higher transport weights (due to twin carries) is disregarded.

If SR is the *S*hift *R*atio and HR the *H*ousekeeping *R*atio,[14] the percentage of saved SC moves ($R_{SCmoves}$) can be calculated as follows[15]:

$$R_{SCmoves} = 1 - \frac{(n_{40} + n_{20} \times (1 - TCr)) \times (1 + SR) + (0.5 + HR) \times TCr \times n_{20}}{(n_{40} + n_{20}) \times (1 + SR)} \qquad (15.8)$$

[14]The *Shift Ratio* is the number of single carried containers being shifted during vessel loading divided by the number of single carried containers:

$$SR = \frac{n_{shifted,\, single\ carried}}{(n_{40} + n_{20} - n_{20,\, twin\ carried})}$$

with twin carry operations:

$$\Rightarrow n_{shifted,\, single\ carried} = SR \times (n_{40} + n_{20} \times (1 - TCr)) \;\; with \;\; n_{20,\, twin\ carried} = n_{20} \times TCr$$

without twin carry operation:

$$\Rightarrow n_{shifted,\, single\ carried} = SR \times (n_{40} + n_{20})$$

The *Housekeeping Ratio* is the number of twin carried containers being shifted before vessel loading divided by the number of twin carried containers:

$$HR = \frac{n_{20,\, house,\, twin\ carried}}{n_{20,\, twin\ carried}}$$

$$\Rightarrow n_{20,\, house,\, twin\ carried} = HR \times TCr \times n_{20} \;\; with \;\; n_{20,\, twin\ carried} = n_{20} \times TCr$$

15

$$R_{SCmoves}\ [in\%] = 1 - \frac{SC_{single\ \&\ twin\ moves}}{SC_{single\ moves}}$$

with

$SC_{single\ moves}$:	SC single moves with restacking shifters during vessel loading (no twin carry operations)
$SC_{single\ \&\ twin\ moves}$:	SC single & twin moves with housekeeping shifters before and restacking shifters during vessel loading

Considering the correlations of the previous footnote $SC_{single\ moves}$ and $SC_{single\ \&\ twin\ moves}$ can also be expressed as follows:

$$SC_{single\ moves} = n_{40} + n_{20} + n_{shifted,\, single\ carried} = (n_{40} + n_{20}) \times (1 + SR)$$

$$SC_{single\ \&\ twin\ moves} = n_{40} + n_{20} - \frac{n_{20,\, twin\ carried}}{2} + n_{shifted,\, single\ carried} + n_{20,\, house,\, twin\ carried}$$
$$= (1 + SR) \times (n_{40} + n_{20} \times (1 - TCr)) + (0,5 + HR) \times n_{20} \times TCr.$$

As measured at CTT in 2016, the SR is about 17% and the HR is about 33% in case of an "average" DSV call. Nevertheless, in comparison to vessel processing without twin carrying the move reduction can be calculated as about 8%.

With respect to resource consumption we integrate housekeeping and other shift moves into our analysis by an approximation. At CTT, the distance driven to shift a container (within the yard area) is on average approximately less than 50% of the distance driven for a load move (between the yard and quay wall). In order to calculate the energy savings, it is more accurate calculating the total distance reduction $R_{SCdistance}$. Therefore, we modify Formula (15.8). The above-mentioned driving distance for shifters now is replaced by the coefficient $c = 50\%$. Formula (15.9) shows how to calculate $R_{SCdistance}$:

$$R_{SCdistance} = 1 - \frac{(n_{40} + n_{20} \times (1 - TCr)) \times (1 + c \times SR) + (0.5 + c \times HR) \times TCr \times n_{20}}{(n_{40} + n_{20}) \times (1 + c \times SR)} \quad (15.9)$$

For our analysis of CTT figures, the reduction of the SC move distance calculates to 10% in 2016. Assuming that fuel consumption declines proportionally (see footnote 13), 10% of diesel can potentially be saved. Since carbon dioxide emissions are proportional to fuel consumption, CTT has been able to reduce its quayside-related carbon dioxide emissions from SC carries by approximately 10% by only using twin carry operations since 2013. Furthermore, energy costs for SC carries have also declined by 10%.

The productivity gain mentioned in Sect. 15.4.3 can also be expressed by other economic figures: A $G_{P,SC}$ of 15% can also be understood as a decrease of the OH_{SC} by 13%. Therefore, assuming that the number of containers per DSV is held constant, DSVs can depart 13% earlier reducing port fees. Assuming the necessary demand, additionally, the quayside throughput (containers per metre quay wall) can be significantly increased. This leads to a higher revenue.

15.5 Summary and Conclusions

In this chapter we showed the benefits of twin handling via SCs. Over the past 10 years, and especially during the maritime crisis, huge container vessels have been brought into the market. These vessels strongly influence container terminals and their operations. The expected cost reduction can only be applied if the berthing windows are of constant length as before and the amount of handled containers have increased. In order to do so, container terminals have to accelerate their operations. An adequate strategy for a conventional SC terminal is introducing twin lift by quay cranes, and hence, twin carry by SCs. We also discussed the pre-requisites for both container handling equipment and terminal operating systems.

Furthermore, we unveiled a lack of literature addressing SC twin carry, which we now find to have closed. After several years of practical experience, CTT has increased its productivity due to SC twin carry significantly. In order to calculate potential productivity gains, we provided formulas and key figures. Additionally, we showed the influence of the TEU factor as well as vessel class and a container's direction (import or export, respectively) on the twin carry ratio, and thus the potential productivity gain of the SC system. In the example of CTT, we clarified that on average up to 82.3% of all discharged 20 ft containers were twin carried by SCs afterwards. We also explained the significance of deep sea vessel operations at a container terminal, and hence elucidated why even a small twin carry ratio on short sea feeders or barges is negligible.

Preparations in order to increase the twin carry ratio should be executed as they can significantly increase the number of twin pairs, and additionally, process necessary shifts of containers on the fly. We showed that by taking those additional moves into account, the number of SC moves declined by 8%, and moreover, the distance driven by SCs declined by 10% due to the fact that shifts have a smaller distance than load moves. Not only does twin handling increase a container terminal's productivity but it also contributes to reducing its energy consumption. Executing twin carries by SCs reduces emissions of carbon dioxide and helps to protect and preserve the environment.

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Part IV
Planning Area: Terminal Yard

Chapter 16
Container Rehandling at Maritime Container Terminals: A Literature Update

Marco Caserta, Silvia Schwarze, and Stefan Voß

Abstract This chapter provides an updated survey on rehandling of containers at maritime container terminals. In particular, we review contributions with a particular focus on post-stacking situations, i.e., problems arising after the stacking area has already been arranged. Three types of post-stacking problems have been identified, namely (1) the re-marshalling problem, (2) the pre-marshalling problem, and (3) the relocation problem. This research area has received an increasing attention since the first version of this contribution appeared in 2011. Within this update, we discuss recent developments presented in literature. In particular, available solution approaches from the fields of exact and (meta-)heuristic methods are given and benchmark datasets are summarized. Moreover, an overview on extensions of post-stacking problems and according solution methods are discussed.

16.1 Introduction

Container terminals can be seen as buffers within larger logistic chains encompassing worldwide distribution systems. The major purpose of using container terminals is to serve as transshipment points. Container terminals are used as temporary storage points for containers, such that, e.g., unloading operations from a vessel and loading operations onto a train or a truck need not be synchronized.

Broadly speaking, a container terminal can be divided into three major areas: The quayside, i.e., the side in which vessels are berthed, the landside, i.e., the side in which other means of transportation operate (trucks, trains), and the container yard, i.e., the area in which containers are stored for future operations. The management of a container terminal yard is of paramount importance in determining

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the efficiency of a port. Due to the fierce competition in the global market, container terminal operators are forced to increase the efficiency of storage yard operations, in order to capture and retain customers.

As pointed out by a number of authors, e.g., Choe et al. (2011), Park et al. (2009), Stahlbock and Voß (2008), and Zhang et al. (2003), some performance indicators of container terminal efficiency are: (1) the vessel berthing time, and (2) the throughput of the quay cranes, i.e., the efficiency in unloading/loading containers from/to vessels. While such key performance indicators can be improved at the strategic level by adopting new technologies and structures, such as new equipment or the terminal layout design, at the operational level, a proven means to enhance the efficiency of container terminal operations is the optimization of the way in which such operations are carried out.

While such key performance indicators can be improved through the use of new technology, such as, e.g., new equipment, terminal layout re-design, etc., the efficiency of container terminal operations can also be enhanced by *optimizing* the way in which such operations are carried out. More specifically, a great deal of attention should be devoted to the definition of efficient container stacking policies.

As highlighted in Dekker et al. (2006), stacking can be seen as a three-level problem. *Strategic* stacking decisions must be made with respect to the layout of the container yard, the type of equipment, and the design of the container terminal itself. *Tactical* stacking decisions are concerned with decisions that affect capacity in the medium term, e.g., whether a pre-stacking area should be used, whether pre-arrangement policies should be implemented (re-marshalling, pre-marshalling, etc.). Finally, *operational* stacking decisions deal with the identification of slots to be assigned to containers, the rehandling of containers within the yard, the berth allocation problem, the assignment of equipment to tasks, the definition of a loading/unloading (stowage) plan, etc. In this chapter, we deal with operational stacking decisions, with a special focus on offering a comprehensive overview of published work dealing with operations that are carried out upon an existing stack or set of stacks of containers.

These types of problems, presented under the label "marshalling problems at container terminal yards," have received a great deal of attention in the last years. Two recent surveys, i.e., Lehnfeld and Knust (2014) and Carlo et al. (2014), have proposed classification schemes for the broad set of optimization problems arising at container terminal yards. More specifically, Carlo et al. (2014) classifies storage yard operations at container terminals along a number of dimensions, i.e., (i) yard design, (ii) storage space assignment, (iii) material handling equipment, (iv) container reshuffling optimization. In turn, this fourth dimension, i.e., optimization of container reshuffling, is subdivided into four main problem typologies:

(iv.1) selection of storage location;
(iv.2) retrieval and reshuffling, as in the *blocks relocation problem*;

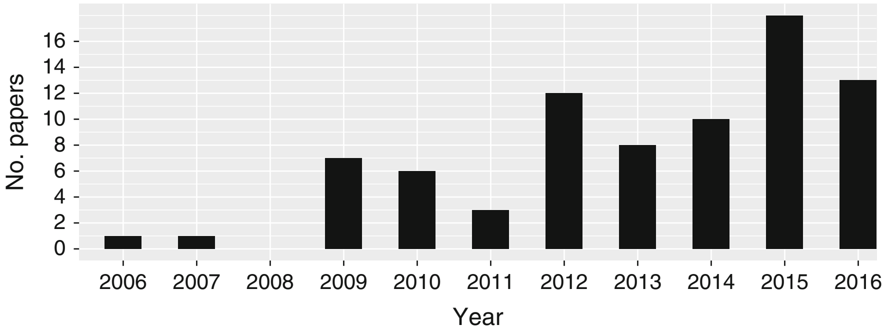

Fig. 16.1 No. of papers on post-stacking problems per year

(iv.3) *pre-marshalling* operations;
(iv.4) *re-marshalling* operations.

Borrowing from this classification, two more survey papers covering typologies (iv.2)–(iv.4) above, i.e., retrieval and marshalling operations, have appeared in recent years, i.e., Caserta et al. (2011a) and Dayama et al. (2016).
In this chapter, we build on the work presented in Caserta et al. (2011a) and provide an up-to-date overview of optimization approaches for marshalling and retrieval operations at container terminal yards. The motivation for this literature update springs from the increasing number of papers on marshalling and stacking problems appeared in recent years. To provide a glimpse of how active the research community in this field has been, Table 16.1 and Fig. 16.1 summarize the number of publications that appeared since 2006.[1] From Table 16.1, we can observe that 79 papers have been published in the last 11 years, of which 61 in the last 5 years alone. From the operational point of view, we focus on three problems:

- the *B*locks *R*elocation *P*roblem (BRP), also known as the *C*ontainer *R*elocation *P*roblem (CRP);
- the *C*ontainer *P*re-*M*arshalling *P*roblem (CPMP), i.e., intra-bay marshalling;
- and the *C*ontainer *R*e-*M*arshalling *P*roblem (CRMP), i.e., intra-block marshalling.

From the solution approach point of view, we hereby collect contributions on optimization methods for any of the three aforementioned problems. Broadly speaking, we identify the following solution approaches across the three problems:

- greedy heuristics, i.e., rules-of-thumb employed to select the next best move;
- metaheuristics, i.e., master mechanisms that coordinate the use of a pool of heuristic rules;

[1] In Table 16.1 and Fig. 16.1, a single paper being published in 2017 (see Wang et al. 2017) is assigned to 2016, the year of the online-first publication.

Table 16.1 Number of publications on post-stacking problems from 2006 to 2016

Year	Total no. papers	BRP	BRP extension	Re-marshalling	Pre-marshalling	Survey
2016	12	4	3		5	1
2015	18	6	4	3	5	
2014	10	5	1		3	1
2013	8	2	2	2	2	
2012	12	4	4		4	
2011	3	1		1		1
2010	6	3	2	1		
2009	7	3	1	1	2	
2008	0					
2007	1				1	
2006	1	1				
Total	79	29	17	8	22	3

Sources: Google Scholar, Scopus, ProQuesti, and EBSCOhost

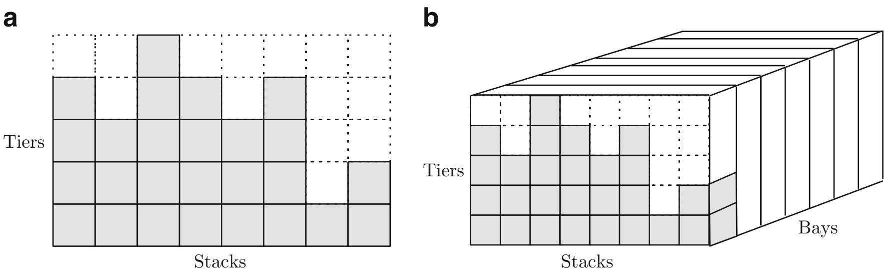

Fig. 16.2 Container bay and block

- exact approaches, i.e., approaches that guarantee the optimality of the provided solution; and, more recently,
- robust approaches, i.e., formulations and solution approaches that attempt to capture part of the uncertainty of the problem, thus providing a solution that should be of good quality even when some disruptive events occur.

In the sequel, we follow the typical terminology adopted in the context of container terminal operations. We indicate with the term *bay* a two-dimensional portion of the container yard, made up by a number of *stacks*, i.e., the width, and *tiers*, i.e., the height, as illustrated in Fig. 16.2a. A *block* is a set of consecutive bays, as presented in Fig. 16.2b. Finally, a *container yard* is made up by a set of blocks.
In addition, we assume that a *priority* (exact or estimated) is associated with each container in the stacking area. Priorities account for a number of different factors, such as (1) category: e.g., containers with the same priority might belong to the same category and could be piled up on top of each other; (2) departure time: e.g., containers with earlier departure time will have higher priority than containers

with later departure time; (3) size and weight: e.g., typically, containers with higher weight are not stored on top of containers with lower weight, in order to respect overall ship balancing constraints. It is worth mentioning that, since the precise departure date of a container might not be known when the container reaches the stacking area, it might be the case that *estimated* priority values are assigned to containers. A new line of research focuses on the definition of *robust optimization* methods to tackle this type of uncertainty.

The two terms *retrieving* and *rehandling* are used to describe movement of containers. More specifically, the term *retrieving* is used to indicate a movement of a container from the bay to the vessel. Conversely, we use the term *rehandling* to indicate a move of a container within the container yard, both in the case of intra-bay or intra-block movements. In all cases, we consider the layout of the stacking area as given, i.e., the position and priority, exact or estimated, of each container in the stacking area is known. Therefore, our interest is not centered on finding effective stacking policies. Rather, given a stacking area, we wish to determine how containers should be rehandled or retrieved in order to minimize the total number of unproductive movements.

The structure of the chapter is as follows: In Sect. 16.2, the complexity of post-stacking problems is discussed. Afterwards, Sect. 16.3 is devoted to the presentation of marshalling problems, aimed at reshuffling the storage area in order to eliminate, or reduce, the total number of future rehandling. Section 16.4 deals with a different type of problem, the blocks relocation problem. Section 16.5 constitutes a bridge between rehandling problems at maritime container terminals and similar problems arising in different realms. Some references to related work in other application domains are provided in this section. Finally, Sect. 16.6 concludes offering a brief overview of the current status in the container handling discipline along with a glimpse of future challenges and opportunities.

16.2 Complexity of Post-stacking Problems

Before surveying the available work in the field of post-stacking problems, we provide a brief overview on complexity issues:

First, the complexity of the BRP is stated as $\mathcal{NP}$-hard, see Caserta et al. (2012), by a reduction from the *M*utual *E*xclusion *S*cheduling (MES) problem on permutation graphs, proved to be $\mathcal{NP}$-hard in Jansen (2003). It is moreover shown that a particular case of the BRP, known as the *restricted* BRP (see, Sect. 16.4.1) is still $\mathcal{NP}$-hard. Moreover, regarding alternative objectives, the BRP minimizing the crane movement time, generalizes the BRP and, therefore, is $\mathcal{NP}$-hard, too; see, Schwarze and Voß (2015). Moreover, recent papers have addressed the issue of computational complexity of different variants of the marshalling problem. More precisely:

- The re-marshalling problem: Caserta et al. (2011a) proved that the problem is $\mathscr{NP}$-hard by reduction from the BRP.
- The pre-marshalling problem with fixed height: van Brink and van der Zwaan (2014) proved that both the *priority stacking* and the *configuration stacking*, i.e., a variant in which a pre-specified bay layout must be reached, are $\mathscr{NP}$-hard when the height is fixed $H \geq 6$. All reductions are from the MES problem on permutation graphs.
- The pre-marshalling problem with unlimited height: In van Brink and van der Zwaan (2014), a proof that the *priority stacking* with unlimited height is $\mathscr{NP}$-hard is presented. Again, all reductions are from the MES problem on permutation graphs. However, there is no formal proof for the complexity of the *configuration stacking* problem with unlimited height. To the best of the authors' knowledge, as of today, this seems to be an open question.

16.3 Container Marshalling Problems

In this section, we focus on the pre-marshalling and re-marshalling problems. In line with Carlo et al. (2014), we make the following assumptions:

A1-D. The container retrieval sequence, based on container priorities, is known in advance. This also implies that no further containers are expected to arrive; or

A1-S. The exact container retrieval sequence is not known, since the precise priority values of containers are not determined yet. This might be due, e.g., to uncertainty of the arrival time of collecting vessels. We thus assume that containers are assigned a time interval within which they are expected to leave.

A2. The reshuffling of containers is limited to the same bay (*pre-marshalling*) or the same block (*re-marshalling*);

Assumptions A1-D and A1-S are mutually exclusive and define the deterministic and stochastic versions of the corresponding marshalling problem, respectively. More rigorously, following the accepted terminology from the literature, we define the two marshalling problems as follows:

Pre-marshalling The pre-marshalling problem is concerned with finding an optimal, i.e., shortest, sequence of reshufflings that reorganizes the containers within a bay in such a way that, for a known retrieval sequence, no further reshuffling is required. This problem is also called *intra-bay re-marshalling*, since the containers are reshuffled within the same bay.

Intra-bay re-marshalling, or pre-marshalling, is motivated by the use of a specific technology. As pointed out by Lee and Chao (2009) and Lee and Hsu (2007), yards that use rail mounted gantry cranes as major container handling equipment typically solve the marshalling problem at bay level. For safety reasons, in some terminals where access of containers to and from the block is usually from the side, a gantry crane is not moved from one bay or block to another while carrying a container. Therefore, in those terminals, to move a container from one bay to another, it would be necessary to temporarily unload the container from the crane, put it on a truck, move the truck and, possibly, the empty crane to the target bay, pickup the container from the truck with the crane, and store the container within the target bay. This operation is time consuming and, therefore, it is avoided whenever possible. This consideration motivates the study, from a practical perspective, of the intra-bay pre-marshalling problem. The goal of the pre-marshalling problem is, therefore, to rehandle containers within the same bay in order to eliminate (or minimize) future rehandling while minimizing the total number of rehandlings during the pre-marshalling process itself. Two observations are in place here:

- The pre-marshalling problem does not require to reach a pre-specified bay configuration. In other words, as long as no further reshuffles will be needed during the subsequent loading/unloading phase, the bay configuration is considered optimal. Thus, a variant of the classical pre-marshalling problem can be envisioned, in which a pre-specified bay configuration must be reached, not only in terms of containers priority, as in the classical pre-marshalling, but also in terms of specific layout of the bay. The only authors that take into account this variant of the pre-marshalling are Lee and Hsu (2007) and van Brink and van der Zwaan (2014). Lee and Hsu (2007) defined a *M*ixed-*I*nteger *P*rogramming (MIP) model for the classical pre-marshalling problem that can be tailored to achieve a pre-specified bay configuration with the addition of a set of side constraints. Along the same line, in van Brink and van der Zwaan (2014) the difference between the *priority stacking* and the *configuration stacking* pre-marshalling problems is highlighted. They use the term priority stacking pre-marshalling problem to identify the "classical" version of the pre-marshalling, while the configuration stacking pre-marshalling identifies the variant in which a pre-specified bay layout must be reached.
- As long as the relocation of containers occurs within the same bay, only the number of crane movements is to be minimized. In other words, the distance covered by the crane is negligible and, therefore, is not taken into account in the optimization process. On the other hand, if containers need to be moved from one bay to another within the same block, or from one block to another, then some "transportation costs," typically proportional to the distance covered, should be taken into account.

Re-marshalling The re-marshalling problem is concerned with finding the minimum length sequence of container movements aimed at retrieving containers from a source bay and position them to a target bay (or bays) assigned to a specific vessel (or vessels) in such a way that no further reshuffling will be needed. This type of problem is also called *intra-block re-marshalling*, since movements of containers typically occur within the same block. These types of problems are not just a simple extension of the pre-marshalling problem, since cranes interference and transportation costs should now be taken into account.

As illustrated in Table 16.1 and Fig. 16.1, in the last years, a growing body of literature on optimization approaches for marshalling problems has been developing. More precisely, with respect to the pre-marshalling and the re-marshalling problems described above, we found 22 papers on the former problem and 8 papers on the latter problem, without including survey papers mentioning marshalling problems but not specifically dealing with the aforementioned problems.

From the solution approach point of view, these papers can be classified in the following four groups. In this regard, a comprehensive list of papers classified along the related dimensions is provided in Table 16.2:

- *Greedy, target-guided heuristic approaches*: These approaches typically define greedy scores to select a target container and a target stack among a pool of candidates. The targets are chosen according to the value of the greedy score and the moves needed to relocate the target container to the target stack are carried out. The types of moves defined can be *single moves*, i.e., at each step only one container is moved to a new position, or *compound moves*, in which cases all the relocations needed to achieve the target (moving the target containers to the target stack) are carried out. Examples of these approaches are Bortfeldt and Forster (2012), Expósito-Izquierdo et al. (2012), Jovanovic et al. (2017), among others.
- *Metaheuristic approaches*: These algorithms make use of the greedy rules and moves described above within the context of a metaheuristic, e.g., the corridor method (Caserta and Voß 2009b), simulated annealing (Choe et al. 2011), genetic algorithm (Gheith et al. 2016; Hottung and Tierney 2016), the pilot method (Tus et al. 2015), among others. In some instances, exact approaches, e.g., dynamic programming, are used in a metaheuristic fashion, in line with the definition of "matheuristics" (See, e.g., Caserta and Voß 2009b).
- *Exact approaches*: These are algorithms aimed at finding an optimal solution that exploit (1) Mathematical programming techniques, e.g., branch-and-bound (Zhang et al. 2015), dynamic programming (Prandtstetter 2013), branch-and-price (van Brink and van der Zwaan 2014), network optimization (Lee and Hsu 2007); (2) Constraint programming, e.g., Rendl and Prandtstetter (2013); (3) Search algorithms, e.g., A* and IDA* (Tierney et al. 2017).
- *Robust approaches*: This new line of research is currently represented by two papers, i.e., Tierney and Voß (2016) and Rendl and Prandtstetter (2013). Robust optimization attempts to capture the uncertainty of real-world marshalling problems due to potential delays of vessels arrivals. Since the arrival time of vessels at a berth is only an "expected" time, this uncertainty affects the priority value of containers which, consequently, should be dealt with as if it were a stochastic value. A common approach to deal with uncertainty is to treat container priority values as intervals, rather than deterministic parameters.

Table 16.2 List of papers on the CPMP, from 2007 to 2016

Paper	Approach	Method	Benchmark	Comment
Wang et al. (2017)	Heuristic	Target-guided/Greedy	CV, BF	Feasibility of a configuration is tested
Tierney and Voß (2016)	Robust/Exact	CP, IDA*	TV	Robust CPMP relaxed via CP and solved using IDA*
Hottung and Tierney (2016)	Metaheuristic	bRKGA	CV, BF	Learning mechanism, parameters fine tuning
Gheith et al. (2016)	Metaheuristic	GA	LH, LC, CV	Variable length of the chromosome
Tierney et al. (2017)	Exact	A*, IDA*	CV, BF, IG	Problem specific symmetry breaking rules for A* and IDA*
Wang et al. (2015)	Metaheuristic	BS	LC, CV, BF, WJL	Target-guided heuristic. Use of “giant” moves. Dummy stacks
Tus et al. (2015)	Metaheuristic	Pilot+AS	TRR	2D version, with lateral access to the bay
Tierney and Malitsky (2015)	Metaheuristic	Algorithm Selection	CV, BF, IG	Latent Features Analysis
Zhang et al. (2015)	Exact	B&B+Heuristic	CV, ZJY, LH1	Limited to Nr. Stacks $\times$ Max height ≤ 35
Ren and Zhang (2015)	Heuristic	Greedy Rules	LH, LC	Three-step iterative heuristic
van Brink and van der Zwaan (2014)	Exact	B&P	BZ	Two pre-marshalling variants: Priority *vs.* configuration stacking
Jovanovic et al. (2017)	Heuristic	Target Driven/Greedy	IG	Comparison of different heuristics within the framework of LPFH
Gheith et al. (2014)	Heuristic	Greedy Rules	LH	Three-step iterative algorithm
Rendl and Prandtstetter (2013)	Exact+Robust	CP	IG	Robust version defined using priority ranges
Prandtstetter (2013)	Exact	DP+BVB	EMM	Initialization via LPFH. Heuristic DP is also proposed
Bortfeldt and Forster (2012)	Heuristic	Tree Search	LH, LC, CV, BF	Computation of lower bound for number of moves
Expósito-Izquierdo et al. (2012)	Heuristic	Target Driven/Greedy	EMM	Instance generator IG. A* for small-size instances

(continued)

Table 16.2 (continued)

Paper	Approach	Method	Benchmark	Comment
Huang and Lin (2012)	Heuristics	Greedy Rules	LH	Labeling algorithms for two versions of the CPMP
Voß (2012)	Heuristic	Bound	LC	Computation of lower bound for number of moves
Lee and Chao (2009)	Heuristic	NS	LC-1, LC-2, LC-3	Neighborhood Search+IP Formulation
Caserta and Voß (2009b)	Metaheuristic	CM	LC, CV	Dynamic Programming + Corridor Method
Lee and Hsu (2007)	Exact	MCNF	LH	For both priority and configuration stacking. A heuristic is also proposed

A*	Algorithm for graph traversal
AS	Ant system
B&B	Branch-and-bound algorithm
B&P	Branch-and-price algorithm
bRKGA	Biased random key genetic algorithm
BS	Beam search algorithm
CM	Corridor method
CP	Constraint programming
DP	Dynamic programming
GA	Genetic algorithm
IDA*	Iterative deepening A* algorithm
LPFH	Lowest priority first heuristic
MCNF	Minimum cost network flow model
NS	Neighborhood search
Pilot	Pilot method

16.3.1 Container Pre-marshalling Problem

In this section, we present a brief overview of each paper dealing with the CPMP appeared in the years 2007–2016. A comprehensive list of publications, along with the solution approach, the benchmark instances used, and a short comment on each paper can be found in Table 16.2. In addition, we provide a list of publicly available benchmark instances for the CPMP in Table 16.3. These instances have been used by a number of authors to test the effectiveness of their algorithms and constitute a large library of instances, with different degrees of complexity, which could be used to test future work on the CPMP. We hereby present the contributions appeared in peer-reviewed outlets, starting with the most recent ones and going backward to the first work on the CPMP.

Wang et al. (2017) introduce a target-guided heuristic for the CPMP. A target-driven heuristic is a heuristic in which targets, i.e., containers, are moved to specific slots one at a time. Thus, at each step, the heuristic identifies the target, i.e., the container, to be moved and the destination stack. This relocation of the target container to the destination stack is called "valid task," and the way in which valid tasks are identified is based on a set of greedy rules. However, a difference that stands out between the approach presented in this paper and other target-driven rules in the literature is that, while in general target containers are selected in a predetermined order, e.g., according to the container priorities, in this approach the order is not fixed beforehand but, rather, dynamically determined during the search phase. In other words, the target container is selected depending on, among other things, the current layout of the bay. Finally, once a valid move is identified, the target container is fixed at the destination stack and will no longer be moved during the optimization process. The algorithm repeats the aforementioned steps until all the containers are fixed. To speed up the selection of moves, the authors propose a novel state feasibility test. Prior to moving a container to a slot, the feasibility of the resulting state, i.e., bay configuration, is tested and, if a move leads to an infeasible layout, that move is discarded. This feasibility check allows to explore large portions of the solution space in an efficient fashion. The authors tested their algorithm on two benchmark sets from the literature, CV and BF,[2] and the results obtained show the effectiveness of the proposed scheme.

Hottung and Tierney (2016) present a metaheuristic that employs the *b*iased *R*andom *K*ey *G*enetic *A*lgorithm (bRKGA) framework to guide a three-step iterative heuristic. The bRKGA is in charge of two major tasks: On the one hand, the metaheuristic learns and fine-tunes the decision as to which container to move and which stack to use in each step. That is, the rating mechanisms employed to judge the quality of candidate moves are guided by the bRKGA via the encoding and decoding of a part of the chromosome, thus allowing successive generations of the bRKGA to select better moves. Since the mechanism has some learning

[2]See Table 16.3 for the source of the benchmark and a description of the same.

Table 16.3 Benchmark instances for the CPMP

Name	Source	Nr. Instances	Description
LH	Lee and Hsu (2007)	2	The first one with $S = 6$ and $H = 4$, and the second with $S = 12$ and $H = 5$
CV	Caserta and Voß (2009b)	840	Twentyone groups of 40 instances each, with $H \in \{3, 4, 5, 6, 10\}$ and $S \in \{3, \ldots, 10\}$
LC	Lee and Chao (2009)	12	Three groups, of 1, 1, and 10 instances each, with $S \in \{10, 12\}$ and $H \in \{5, 6\}$
BF	Bortfeldt and Forster (2012)	640	Thirtytwo groups of 20 instances each, with $S \in \{16, 20\}$ and $H \in \{5, 8\}$
EMM	Expósito-Izquierdo et al. (2012)	3600	Three groups of 1200 instances each, with $S = 4$ and $H \in \{4, 7, 10\}$
IG	Expósito-Izquierdo et al. (2012)	–	Instance generator for the CPMP
BZ	van Brink and van der Zwaan (2014)	960	Fortyeight groups of 20 instances each, with $S \in \{3, 5, 7, 9\}$ and $H \in \{4, 6\}$
WJL	Wang et al. (2015)	1080	Thirtysix groups of 30 instances each, with $S \in \{6, 8, 10, \}$ and $H \in \{5, 8\}$. Designed with "dummy stack."
TRR	Tus et al. (2015)	600	Twevl groups of 50 instances each, with $S \in \{4, 6, 8, 10, 12, 14\}$ and $H = 4$. Instances obtained using IG
ZJY	Zhang et al. (2015)	100	Five groups of 20 instances each, with $S \in \{6, 7, 8, 9\}$ and $H \in \{4, 5\}$
TV	Tierney and Voß (2016)	900	Ninety groups of 10 instances each, with $S \in \{5, 8, 10\}$ and $H \in \{3, 4, 5, 6, 10\}$

features, it benefits from solving the same instance over and over, i.e., along multiple generations. On the other hand, the same chromosome devotes some of the genes to the encoding and decoding of values of some algorithmic parameters. Consequently, a second task accomplished by the bRKGA is that of fine-tuning the algorithmic parameters. The algorithm has been tested on the CV and BF instances and, at the time of writing, together with the Beam Search algorithm of Wang et al. (2015), the results reported in this paper are the best presented in the literature.

Gheith et al. (2016) discuss a solution approach that employs genetic algorithms. The encoding is such that each move in the bay is specified via two consecutive genes, one indicating the stack the container is removed from and the next specifying the receiving stack. A chromosome thus encodes the full set of moves of a solution to the pre-marshalling problem. The interesting variation introduced in the paper is that, since the exact number of moves required to reach the final configuration is not known, a variable length *G*enetic *A*lgorithm (GA) is used instead. The length of the chromosome is thus proportional to the number of moves required by a given solution. The fitness value associated to a chromosome is composed of two terms, i.e., the number of moves required (proportional to the chromosome length), and the number of mis-overlays of the final configuration, i.e., the bay configuration obtained after implementing all the movements encoded in the chromosome (ideally equal to zero for a proper pre-marshalling solution). The algorithm has been tested on instances LH, LC, and CV (see Table 16.3).

Tierney et al. (2017) present an exact algorithm based on a problem specific implementation of the A* and IDA* algorithms. The authors model the CPMP as a graph, in which the tree structure used to capture the problem is as follows: The root node is associated to the initial bay configuration; each branch of the tree leads to a node associated to a bay configuration that can be reached from the current state via a single move, i.e., relocating only one container. The leaves of the tree correspond to final solutions. At each node a cost is computed. Such cost is the sum of two terms, i.e., the cost of reaching the solution associated to that node, and the cost of completing such a solution, i.e., to reach the closest leave. Lower bounds for the latter term are obtained using the lower bound method proposed in Voß (2012) and Bortfeldt and Forster (2012). At each node, a branch for each possible container move is created. Problem specific symmetry breaking rules have been designed to speed up the search process and to prune dominated branches of the tree. The authors evaluated their approach on instances CV, BF, and a new set of randomly generated instances obtained using the instance generator of Expósito-Izquierdo et al. (2012). The proposed algorithm (IDA*) was able to solve over 500 previously unsolved instances to optimality.

Tierney and Voß (2016) discuss a robust variant of the CPMP, in which the priority of containers is not deterministically known. Rather, a time interval within which the container must be retrieved is provided. This problem is labeled *R*obust *C*ontainer *P*re-*M*arshalling *P*roblem (RCPMP). The authors first find a relaxation of the RCPMP solving a binary constraint satisfaction problem, which takes as input a “blocking matrix” and provides as output a deterministic CPMP, in which container priorities have been fixed respecting the blocking matrix structure. This deterministic CPMP is a relaxation of the original robust problem and is fed as input to the IDA* algorithm of Tierney et al. (2017), which, in turn, provides an optimal solution. Interestingly, the authors prove that a reasonable lower bound for the RCPMP can be found using a lower bound for the CPMP, i.e., the relaxed, deterministic version. The authors tested their algorithm on 900 new randomly generated instances, labeled TV in Tables 16.2 and 16.3, and compared their approach with the only available algorithm dealing with the RCPMP, that of Rendl and Prandtstetter (2013).

Wang et al. (2015) present a target-guided heuristic to tackle the standard CPMP and a variant of the same problem, called the *C*ontainer *P*re-*M*arshalling *P*roblem with *D*ummy *S*tack. The new variant of the CPMP arises from the observations that some block layouts at container terminals have a transfer line parallel to the block itself, as opposed to having transfer lines at both ends of the block. This lateral transfer line can be used by the gantry crane operating on a bay. Therefore, the pre-marshalling problem can be redefined as having an extra "dummy" stack, which can be used to temporarily store containers during the reshuffling operations of the pre-marshalling task. The only caution that must be taken is that the dummy stack must be emptied at the end of the pre-marshalling work. The authors label this variant of the pre-marshalling as CPMPDS. The key idea of the target heuristic is to fix containers to a certain position in a descending order of priorities. Containers are relocated using both compound moves, called *giant moves*, as well as single moves, called *baby moves*. The greedy heuristics presented in the paper are finally embedded into a metaheuristic scheme, the beam search, which allows to escape from suboptimal solutions. The proposed algorithm is tested on a large pool of instances, namely LC, CV, BF, and a newly generated set of random instances, called WJL (see Table 16.3), specifically designed for the CPMPDS. The results reported in this paper for the beam search algorithm are, at the time of writing, the best in the literature, along with those of Hottung and Tierney (2016).

Another variant of the CPMP is presented in Tus et al. (2015). These authors consider the case of small-medium size container terminals, in which, rather than gantry cranes, reach stackers are used. Reach stackers are forklifts that can only access the top containers of the leftmost and rightmost stacks of a container bay. They named this variant of the standard pre-marshalling problem the *2-D*imensional *C*ontainer *P*re-*M*arshalling *P*roblem (2D-CPMP). The authors adapt a lowest priority first heuristic, initially designed for the CPMP, to this variant of the pre-marshalling. Next, they embed this heuristic within two metaheuristics, the Pilot method and a Max-Min Ant System. To test the effectiveness of the proposed scheme, the authors generated a new set of instances using the instance generator of Expósito-Izquierdo et al. (2012). These instances are now available online and are labeled TRR (see Table 16.3). Their empirical analysis shows that the Min-Max Ant System is the best performing algorithm among those proposed in this paper, and that the difference with the other schemes is statistically significant.

An original approach to the CPMP is provided in Tierney and Malitsky (2015). They use algorithm selection to find the best performing algorithm for each instance. More specifically, four parameterizations of the A* and IDA* algorithms of Tierney et al. (2017) are used to form a pool of solvers. With respect to the instance pool, they use instances from CV, BG (see Table 16.3), and some newly randomly generated instances obtained using the instance generator of Expósito-Izquierdo et al. (2012). Each instance is characterized by a set of features, both observable and latent. These features are evaluated using *C*ost-*S*ensitive *H*ierarchical *C*lustering (CSHC). The performance of the portfolio obtained using CSHC is then compared with that of the best single solver, and the virtual best portfolio, i.e., a portfolio that always selects the best algorithm. The authors conclude discussing the importance of enriching the instance description with the use of latent features which, in turn, prove beneficial in the algorithm selection phase.

Zhang et al. (2015) present an exact approach for the CPMP. They design a heuristic-guided branch-and-bound approach, which effectively solves medium-size instances to optimality. The authors state that the algorithm requires an acceptable amount of running time as long as the product of the number of stacks with the maximum height ($S \times H$) is around 35. The problem is framed in the context of a branch-and-bound tree, in which the root node corresponds to the initial layout, each node of the tree is an intermediate layout, and each leave is a final solution. The role of the guiding heuristic is to generate a set of potential branches at each node. They also present an approach to compute a valid lower bound for the number of relocations required and they point out that such lower bound is looser than the one presented in Bortfeldt and Forster (2012), but easier to compute. The lower bound is of paramount importance in pruning the branches of the tree at each node, thus allowing for a more efficient exploration of the branch-and-bound tree. They tested their algorithm on a new randomly generated set of small-medium size instances, called ZJY (see Table 16.3), as well as on the small instances from CV and they were able to achieve an optimal solution for most of these instances in a reasonable amount of computational time.

Ren and Zhang (2015) design a three-step rule-based iterative algorithm. The first step, called local optimization, move ill-placed containers, i.e., containers creating mis-overlays in the current stack, to stacks with zero mis-overlays. The first step ends when moves of this type are no longer available. The second step aims at emptying one stack of the bay. Greedy rules are used to select the stack to be emptied and the destination stacks of containers removed from the emptying stack. Finally, the third stage takes care of refilling the empty stack. Again, heuristic rules are used to prevent deadlocks and to identify the relocated containers. The proposed algorithm has been tested on only three benchmark instances, two from LH and one from LC.

van Brink and van der Zwaan (2014) present an exact algorithm for two versions of the pre-marshalling problem, the priority stacking and the configuration stacking. The former describes the case in which no final specific bay layout is required, as long as no container with low priority is left on top of containers with higher priority. Conversely, the second problem describes the case in which a pre-defined bay layout should be reached, i.e., each container should be placed in a specific position in the bay. The exact method is based on branch-and-price and column generation. The problem is formulated as an integer linear program, and the task of generating new columns, i.e., a sequence of moves, with negative reduced cost is almost equivalent to finding a maximum weight independent set in a circle graph, which is polynomially solvable using dynamic programming. Thus, at each node of the tree, a series of linear programming relaxations with the addition of new columns is solved, until no further columns with negative reduced cost can be added. A lower bound is then used to either prune the branch of the tree or to create further branches. Another valuable result presented in this paper is related to the proof of complexity of the priority stacking and configuration stacking pre-marshalling problems with fixed height. The authors proved that both versions of the CPMP are $\mathscr{N}\mathscr{P}$-hard, as discussed in Sect. 16.2 of this paper.

Jovanovic et al. (2017) revisit the *L*owest *P*riority *F*irst *H*euristic (LPFH) presented in Expósito-Izquierdo et al. (2012) and modify each of the four basic components of such heuristic. The key idea is to identify the best heuristic to be used at each stage of the algorithm. The authors point out that, given a pool of competing heuristics for a given task, their performance is highly dependent on the features and properties of the instance at hand. However, since establishing a correlation between instance features and heuristic performance is often difficult, their approach is to test all the heuristics available for the task and select the best performing one. More precisely, at each stage of the LPFH, a pool of heuristics is used to come up with different solutions. A look-ahead mechanism and a backtracking procedure are employed to avoid reaching infeasible bay configurations. The authors tested the proposed method on instances obtained using the instance generator of Expósito-Izquierdo et al. (2012) and the results prove that the proposed algorithm outperforms the original LPFH. In the concluding remarks, the authors point out that (1) no heuristic outperforms the other on a complete set of instances, and, connected with this, (2) the performance of each heuristic is dependent on the features and characteristics of the instance at hand. These final remarks are in direct connection with the findings of Tierney and Malitsky (2015).

Gheith et al. (2014) proposed a rule-based heuristic, composed of three main steps: (1) sort container groups according to the frequency of mis-overlays; (2) find a destination stack employing a number of heuristic rules, (3) move the target container to the destination stack, again employing a number of heuristic rules. The three-step algorithm is iteratively applied until no further mis-overlays are present. The algorithm has been tested on instance LH, and on three randomly generated instances. Thus, a comparison of this heuristic with other approaches from the literature is difficult to carry out.

Rendl and Prandtstetter (2013) take a different approach to the CPMP, in which they formulate and solve the problem employing *C*onstraint *P*rogramming (CP). They iteratively try to solve the CP model in exactly k steps, i.e., number of relocations. The initial value of k is found computing a valid lower bound as in Bortfeldt and Forster (2012) and, at each iteration, k is increased by one if no solution could be found. Thus, the first solution returned is an optimal solution to the CPMP. Two sets of variables are employed in the CP model: The first set defines bay configurations, i.e., the layout of the bay after a certain number of steps; the second set is used to keep track of the moves performed at each point in time. Logical constraints ensure the feasibility of each intermediate configuration and drive the search toward a desired final layout. In addition, a specialized search heuristic, applied on the bay variables is employed to evaluate all the possible moves based on the current bay configuration. Another interesting contribution of this paper is related to the presentation of a robust variant of the CPMP. The authors point out that, in real-world settings, the arrival time of vessels is far from certain. Thus, in reality, only the *expected* arrival time of a vessel is known. The implication is that, since container priorities are based on the exact arrival time of a vessel, the final priority of a container is also uncertain. The goal is thus to produce a final bay layout that is *robust* with respect to vessel delays and container priority variations. More precisely, rather than dealing with a specific priority value, each container should be associated to a *priority range* $\{h, \ldots, l\}$, where h is the highest priority that could be associated to a container, i.e., the earliest possible time that a container will be collected, and l is the lowest possible priority of the same container. The authors modified and adapted the CP formulation to deal with the robust variant of the CPMP. Both models are tested on a set of instances produced using the instance generator of Expósito-Izquierdo et al. (2012).

Prandtstetter (2013) presents an exact approach for the CPMP. The key idea is related to the design of a *D*ynamic *P*rogramming (DP) scheme, which is then embedded into a branch-and-bound framework. To further shrink the DP tree, the author developed a method that allows to recognize the equivalence of DP states: Equivalent DP states should be evaluated only once and, therefore, when an equivalent state is reached, the corresponding branch of the tree can be pruned. In the branch-and-bound scheme, a lower bound is computed at each node using the method of Bortfeldt and Forster (2012) and, together with the upper bound value, allow to further prune the tree. In addition, to further reduce the size of the three, the author introduces a heuristic evaluation of equivalence of two states. Such evaluation of equivalence is "heuristic" in the sense that, while it further shrinks the state space explored by the DP scheme, it does not guarantee that (optimal) states will not be missed. The different variants of the proposed scheme have been tested on the benchmark instances EMM from Expósito-Izquierdo et al. (2012). The DP scheme embedded into the branch-and-bound scheme was able to solve to optimality a large number of instances from the EMM dataset within a maximum running time of 3600 s.

Bortfeldt and Forster (2012) present a tree search heuristic procedure, effectively coupled with the computation of a tight lower bound on the number of moves required to reach the final bay layout, given the current bay configuration. The use of such lower bound is paramount in pruning branches of the tree, thus making the tree search algorithm very effective, even when dealing with large instances. In the tree, the root node corresponds to the initial bay layout, while the leaves of the tree correspond to final configurations. Each node in the tree defines an intermediate state, reachable from its predecessor via a *compound move*, i.e., a sequence of relocations. The procedure was tested on a large set of benchmark instances, namely

LH, LC, and CV. In addition, the authors generated a new set of instances, labeled BF, composed of 640 instances of different size and complexity.[3]

Expósito-Izquierdo et al. (2012) propose a lowest priority first heuristic that iteratively places containers either at the bottom of a stack or above containers with lower priorities. Thus, the heuristic attempts to place containers in reverse order, starting with low priority containers first and eventually relocating containers with the highest priority. The proposed heuristic is stochastic in nature, since some of the decisions, e.g., the destination stacks of containers to be relocated, are randomly selected among a pool of candidate stacks. To assert the goodness of the proposed algorithm, the heuristic has been tested on instances CV and compared with the results from the literature as well as with an A* algorithm, implemented by the authors, which provided optimal values for the small-size instances. In addition, the authors also propose an *I*nstance *G*enerator, called IG in the sequel, which takes as input a set of parameters, e.g., the number of stacks and tiers of the bay, the set of container priorities, the bay occupancy rate, and a handful of parameters that affect the bay layout, and produces instances with varying difficulty levels. Finally, a computational study aimed at finding the correlation between instance difficulty and bay occupancy rate and container distribution was carried out.

Huang and Lin (2012) discuss two versions of the CPMP: Type A is the standard pre-marshalling, in which a final configuration with no mis-overlays must be reached; type B is a variant of the CPMP, in which a pre-specified bay configuration should be enforced. The authors propose two heuristics for the two variants of the problem. Both methods are labeling algorithms, in which stacks receive a label related to the condition of the stack itself (e.g., wrongly arranged, correctly arranged). The evaluation of the method has been conducted on two instances of the set LH for the type A version and on a randomly generated instance for the type B problem.

Caserta and Voß (2009b) present a metaheuristic algorithm for the pre-marshalling problem. The central idea of the approach relies on iteratively solving to optimality smaller portions of the original problem. The algorithm consists of four different phases, in which ideas from the corridor method, roulette-wheel selection, and local search techniques are intertwined to foster intensification around an incumbent solution. The algorithm is stochastic in nature and is based upon a set of greedy rules that bias the behavior of the scheme toward the selection of the most appealing moves.

Lee and Chao (2009) define a bi-objective problem: On the one hand, the authors attempt to create a reshuffled bay that requires the minimum amount of rehandlings during the loading phase; on the other hand, such desired configuration should be reached in the minimum amount of steps, i.e., the final configuration should be reached minimizing the total number of rehandling operations. The approach is hybrid in the sense that heuristic techniques, such as neighborhood search, and mathematical programming techniques, such as integer programming,

[3]See Table 16.3 for a description of this benchmark set.

are intertwined to deal with different subproblems. First, the neighborhood search heuristic is used to find a chain of movements to sort out the bay, in such a way that the number of further rehandling required during the loading phase is minimum. Next, a binary integer programming model is solved to reduce the number of movements required to reach that final configuration. A number of minor heuristic rules are used to foster the effectiveness of the proposed algorithm.

The first work on pre-marshalling was presented by Lee and Hsu (2007). They propose an integer programming model based upon a multi-commodity network flow formulation. The network accounts for two dimensions, time and space. Each level of the network describes a specific point in time and captures the state of the bay at that instant. Connections among different levels of the network account for moves of containers over time and space, i.e., edges within the network are used to model the movement of a container from one stack to another in a given time period. The basic mathematical model, along with some extensions, is presented in the paper. Finally, in order to reduce the number of variables and to make the model tractable, some simplifications are introduced. One drawback of the model concerns the need to pre-define a parameter T, i.e., the total number of time periods required to completely reshuffle the bay (which is unknown). The appropriate choice of the value of T has a strong bearing on the computational time required to solve the model. If T is chosen too large, then a very large number of variables is created and, therefore, the MIP solver might not be able to reach the optimal solution in a reasonable amount of computational time. On the other hand, if T is chosen too small, a feasible solution might not even exist. Some analysis about this trade off is presented by the authors.

16.3.2 Container Re-marshalling Problem

Typically, the CRMP refers to the problem of moving a set of containers to pre-specified bays within the same block. As indicated in Kang et al. (2006), the bays in which the target containers are located before re-marshalling are called *source* bays and the empty bays to which these containers should be moved are called *target* bays. Containers within a block are characterized by two types of information:

- a *group* or *category*, accounting for, e.g., the port of destination. In order to minimize the distance traveled by the cranes during the loading phase, containers belonging to the same group are placed in adjacent slots within the same block;
- a *priority*, accounting for, e.g., weight information, order of retrieval, etc. Within the same group, containers should be stacked by ensuring that no container with lower priority is found on top of a container with higher priority.

Therefore, the two-objective problem of intra-block re-marshalling is aimed at grouping together containers belonging to the same category and, for each set of containers of the same category, at piling up such containers taking into account priorities.

As pointed out in Caserta et al. (2011a), the CRMP should be seen as more than a simple extension of intra-bay pre-marshalling, since more than one crane could be used to handle the containers. Therefore, typically the re-marshalling problem also encompasses some considerations with respect to avoiding or minimizing interference among cranes within the same block. As mentioned in Sect. 16.2 of this paper, the authors proved that the CRMP is $\mathscr{N}\mathscr{P}$-hard.

In the sequel, we present a brief summary of the contributions from the literature dealing with the CRMP. Table 16.4 provides a list of the papers hereby presented, along with the type of approach used, and a short comment on the paper itself.

Shin and Kim (2015) deal with the study of steal plate storage systems, in which a multi-state re-marshalling problem is addressed. It is common practice to divide the storage yard into zones, each dedicated to the storage of plates with remaining duration of stay within a specified range. Then, plates are assigned to zones depending on their remaining duration of stay. When a period of time passes, the durations of stay of the plates are updated and, consequently, it might be required that some plates are relocated from their current zone to the next zone in the yard. Thus, the re-marshalling is done periodically between zones with consecutive remaining duration of stay ranges. Via a formulation and some enumerative procedures, the proposed approach finds the optimal number of stacks and the optimal frequency of re-marshalling operations, i.e., the set of parameters that minimizes the expected number of re-marshalling operations.

Choe et al. (2015) propose a novel approach to the re-marshalling problem. Most of the works presented in the literature assume that enough time is given to carry out a complete re-marshalling. More recent contributions have introduced the notion of "selective re-marshalling," e.g., Park et al. (2013) and Park et al. (2010). However, the constant feature of all the approaches presented in the literature is that the re-marshalling work is carried out in batches. In other words, a starting time for the re-marshalling is given and, considering the selective re-marshalling, an ending time is also provided. Within this time horizon, the goal is to find the best possible (partial) re-marshalling plan. This paper proposes to intertwine the scheduling of the two cranes typically assigned to a block, used to perform ordinary duties, with some re-marshalling operations, whenever such cranes are idle. Consequently, given a time horizon, the goal is to mix together the scheduling of ordinary tasks at the block with a partial re-marshalling. The scheduling of ordinary tasks is still the priority and, for this reason, one of the objectives is to minimize the delay of these tasks. However, a new objective is also introduced, i.e., the minimization of the makespan of *all* the jobs, both the ordinary and those due to re-marshalling. The re-marshalling jobs to be included in the time horizon are selected using heuristics inspired in the selective re-marshalling of Park et al. (2013) and Park et al. (2010). The authors use a GA for the iterative rescheduling and run extensive simulations to assert the effectiveness of the proposed approach.

A variant of the re-marshalling problem is presented in Ji et al. (2015), where an algorithm for the relocation of containers to vessels, along with the crane scheduling, is presented. Loading sequence and rehandling strategies are integrated within the same optimization model, which leads to the identification of the optimal

Table 16.4 List of contributions from the literature for the re-marshalling problem

Paper	Approach	Method	Comment
Shin and Kim (2015)	Exact	Enumeration	Applied to steel plate storage systems in port terminals
Choe et al. (2015)	Metaheuristic	GA	Re-Marshalling carried out during regular operations exploiting crane idle times
Ji et al. (2015)	Heuristic	Math Model	Optimal loading sequence with minimization of rehandles
Ayachi et al. (2013)	Heuristic	Greedy Rules	Different container types
Park et al. (2013)	Metaheuristic	CCEA	Only a selected subset of containers is rearranged
Choe et al. (2011)	Metaheuristic	SA	Two-stage, with depth-limited A*
Park et al. (2010)	Metaheuristic	GA	Dynamic replanning
Park et al. (2009)	Metaheuristic	CCEA	Two-stage greedy approach
Kang et al. (2006)	Metaheuristic	SA	Two-stage, partial-order graph, neighborhood search
Kim and Bae (1998)	Heuristic	DP	Loading sequence not available

CCEA Cooperative co-evolutionary algorithm
GA Genetic Algorithm
SA Simulated Annealing
DP Dynamic Programming

loading sequence and the minimization of required rehandling. Three strategies are considered, i.e., the lowest stack strategy, the nearest stack strategy, and the optimization strategy. The latter is the most effective strategy in terms of reducing the number of rehandles.

Ayachi et al. (2013) present a heuristic method for the re-marshalling of both inbound and outbound containers under uncertainty. The uncertainty arises from the imperfect information related to arrival and departure times. The authors show how to deal with different container types. Their method finds an optimal storage plan with respect to container departure time and minimizes the required re-marshalling operations at their departure time.

Park et al. (2013) consider the selective re-marshalling presented in Park et al. (2010), i.e., they consider the case in which the time allocated to re-marshalling is limited and, therefore, only a subset of containers can be reshuffled. The authors propose a three-step cooperative co-evolutionary algorithm: Container selection, target location identification, and re-marshalling schedule. In addition, a cooperative parallel search is carried out to find good solutions to each of the subproblems. In a fashion similar to what is done in Park et al. (2010), the method is iteratively repeated to deal with the uncertainty and the estimation errors introduced by the real-time operation of cranes.

Choe et al. (2011) study the intra-block re-marshalling problem where more than one crane is used to handle containers. Therefore, interference among cranes is taken into account. The authors propose a two-phase algorithm: During the first phase the target slots to which handled containers should be moved are identified, and in the second phase an optimal schedule of the cranes to actually perform the relocation of containers is found. The proposed algorithm, based upon simulated annealing, is aimed at finding a rehandling-free configuration of the block that can be achieved in the minimum amount of time. Based upon a partial order graph that captures all the feasible moves leading from the current block configuration to a target configuration, at each step of the search phase the algorithm evaluates the goodness of a candidate solution configuration by heuristically creating a crane schedule and estimating the time needed to complete re-marshalling to reach that particular configuration.

Park et al. (2010) introduce a new feature into the re-marshalling problem. The authors point out that it is quite possible that not enough time is given to carry out a complete re-marshalling of a block. Consequently, a "selective" re-marshalling must be carried out, in which only a subset of the containers is actually sorted out. The authors propose a two-step iterative algorithm: In the first step, an appropriate subset of containers is selected using heuristic measures; the second step is then focused on building the re-marshalling schedule for the selected containers. In addition, since the uncertainty associated to the crane scheduling at the block might introduce estimation errors, the two-step approach is iteratively applied within the context of a GA that exploits the solutions obtained in the previous iterations.

Park et al. (2009) analyze the re-marshalling problem with respect to export containers. Typical dimensions of the considered problem are 41 bays per block, where each bay is made up by 10 stacks and 6 tiers. A block is managed through the use of two cranes, one for export containers and another for import containers. Due to the large size of the considered blocks, the authors identify two sources of inefficiencies in the handling of containers. The first one is related to the horizontal movement of the cranes used to load containers to the vessel. Typically, export containers are unloaded from trucks and, therefore, are piled up near the landside of the block. Therefore, during the loading operations, the crane operating on the waterside is forced to travel long distances toward the landside of the block to pick-up export containers, hence affecting the overall time of the loading operation. A second source of inefficiency can be ascribed to the stacking of high priority containers below low priority containers, forcing a rehandling of the uppermost containers. The authors present a two-stage heuristic algorithm. The first stage uses heuristic rules to identify where, i.e., in which stacks, containers must be relocated. In the second stage of the algorithm, a cooperative co-evolutionary algorithm is used to identify the precise slot within which containers should be relocated (stack and tier), along with the order of movements of the containers to be reshuffled. Two populations are created to identify the slots and to define the order of movements. Information is exchanged in the following way: Initially, a solution for the target slots identification is found; such solution is then fed as input to the subproblem dealing with the movements sequence. In turn, the movements sequence defined by this last subproblem is used to find a better set of target slots, and the cooperative approach is repeated in cycles.

Similarly, Kang et al. (2006) deal with export containers, and the objective is to find a rearrangement that avoids future rehandling during the loading operation. As in Choe et al. (2011), multiple cranes are used within a block and, therefore, interference among cranes is also minimized. The proposed approach is similar to the one of Choe et al. (2011), since a two-phase algorithm is designed. First, a set of target locations is defined. Next, a partial order graph is created, with the goal of finding a set of feasible moves leading from the source configuration to the target configuration. The partial order graph captures all the possible moves leading from source to target configuration. Next, simulated annealing is used to find a solution that aims to minimize the overall time required to carry on the re-marshalling operations. Finally, a heuristic is employed to find a crane's feasible schedule. An interesting point brought out by the authors is related to the notion of neighbor solutions. Given a partial order graph, a neighbor of such graph is obtained by appropriately modifying the current one via the application of swapping among containers stored on different stacks of the same bay.

In a seminal work, Kim and Bae (1998) deal with the problem of how to efficiently move a set of containers from source bays to target bays. Containers in the target bays should be accommodated according to a pre-specified layout, called target layout. The intra-block re-marshalling problem is decomposed into two subproblems: (1) the bay matching and move planning problem, in which each source bay within the block is matched with the target bay in the target layout. Decisions with respect to how many containers should be moved between any two bays are made in this stage. This part of the problem is solved using dynamic programming (to define the bay matching needs) and the transportation algorithm (to plan the movement of containers among bays and assignment to cranes). Whenever crane interference arises due to container movements, the bay matching is called again under additional constraints that prohibit the conflicting bay matching; (2) the movement sequencing problem, in which the actual movements required to reach the target layout are scheduled. The authors adopt a "macroscopic" perspective of the problem, i.e., only the number of containers per group type and bay are considered, whereas the actual positions and rehandling within a bay are neglected.

16.4 Relocation and Retrieval

In this section, we provide an overview on publications related to relocation and retrieval at container ports. Such kind of problems, such as the BRP, are closely related to the previously discussed pre- and re-marshalling problems. However, a major difference arises: Pre- and re-marshalling problems only consider rehandling operations, but no retrieval activities. That is, moving a container from a bay to a destination vessel is not feasible. On the other hand, in the BRP, retrieval operations are included. That is, retrieving and rehandling operations are carried out in parallel. Consequently, the number of containers in the bay decreases for the BRP, whereas the number of containers in the bay (block) remains constant for pre-marshalling (re-marshalling) problems. The term CRP is an alternative name for the class of BRP. In the literature, it is an often used convention to apply the term BRP for two-dimensional scenarios, i.e., if a single bay is considered. The CRP, however, is introduced as a more general concept, for the treatment of two- or three-dimensional instances, i.e., described by bays or blocks. As the majority of papers is still addressing the two-dimensional case, in the remainder of this paper, we use mainly the term BRP, implicitly addressing also the CRP.

In recent years, the research activity in the area of the BRP has increased a lot. A total of 46 publications since 2006 can be identified.[4] In the sequel, after discussing the problem properties in Sect. 16.4.1, we focus on solution approaches in Sect. 16.4.2 and on problem extensions in Sect. 16.4.3.

16.4.1 Properties

Since the introduction of the BRP, several variations and extension of the BRP have emerged in the literature. However, there is a set of basic properties that hold for all BRP variants, which are presented next.

[4]See Table 16.1 from which 17 references address extensions of the BRP.

- Containers are piled up vertically in stacks, i.e., only the uppermost container of each stack is accessible for rehandling or retrieving; in addition, each container is either placed on the ground or on top of another container.
- The number of stacks describes the width of the bay.
- The height of stacks is bounded by the number of tiers.
- The number of bays defines the depth of the block (3D-case, only).
- The total initial number of containers in the bay is denoted by N.
- The initial configuration of the bay/block is given in advance.
- Each container in the bay is associated with a priority number, where more than one container can belong to the same priority group (indicated by the priority number).
- Containers have to be retrieved from the bay according to their priority number, i.e., a container with a certain priority can only be retrieved if all containers with higher priorities have already been removed.
- Containers to be removed next are called *target containers*. Rehandling operations become necessary, if no target container is accessible.
- A majority of models given in the literature add the following condition: (A1) Only containers located in the same stack as and above the current target container are allowed to be rehandled (see, e.g., Kim and Hong 2006). This stack is called *target stack*. Following the notation provided in the literature, see, e.g., Zhu et al. (2012), we call a BRP under A1 as *restricted* and a BRP neglecting A1 as *unrestricted*.

Moreover, there is a set of properties that are valid for the BRP. However, when some of these properties are relaxed or modified, extensions of the BRP are obtained. See Sect. 16.4.3 for an introduction to extended versions of the BRP.

- The objective of the BRP is to retrieve all the containers from the bay in the prescribed order while minimizing the number of rehandling operations.
- The retrieval sequence, indicated by the priority numbers of the containers, is given in advance.
- There are no containers entering the bay/block.

16.4.2 Solution Methods

In this section, we provide an overview on available solution approaches in the field of the BRP. As already detailed in Sect. 16.3 in relation to the container marshalling problems, solution methods for the BRP stem from the fields of exact approaches, metaheuristics, and greedy, target-guided heuristics. Tables 16.5 and 16.6 provide an overview on available references in this area sorted by the year of publication. For each publication, the chosen method and benchmark set as well as the BRP version are reported. An overview on benchmark instances for the BRP is given in Table 16.7. To survey the available literature in more detail, we first provide in this section an overview on exact methods and distinguish within this context work

Table 16.5 List of papers on the BRP and CRP, from 2006 to 2016

Paper	Approach	Method	Benchmark	BRP version
Galle et al. (2016)	Heuristic	Average case analysis	–	Restricted
Ku and Arthanari (2016b)	Exact	Abstraction/tree	LL	Restricted
Ku and Arthanari (2016a)	Exact/Heuristic	Stochastic opt./abstraction/tree	KA	Extension (CRPTW)
Tanaka and Takii (2016)	Exact	B&B[c]	ZQLZ	Restricted
Tricoire et al. (2016)	Exact/Metaheuristic	B&B[c]/rake search	CVS	Restricted/unrestricted
Zhang et al. (2016)	Heuristic	Tree	ZLK/CSV	Extension (BRP-BM)
Zehendner et al. (2017)	Heuristic	Target-guided/Online	CVS	Extension (OCRP)
Borjian et al. (2015)	Heuristic	Average case analysis	–	Restricted
Eskandari and Azari (2015)	Exact	MILP[a]	CVS	Restricted
Expósito-Izquierdo et al. (2015b)	Exact	B&B[c]	CVS	Restricted
Expósito-Izquierdo et al. (2015a)	Heuristic	Target-guided	ELAMM	Extension (SP)
Jin et al. (2015)	Metaheuristic	Look-ahead/tree	CVS/BF/ZQLZ	Restricted
Lin et al. (2015)	Heuristic	Target-guided	LL	Extension (crane time)
Schwarze and Voß (2015)	Exact	MILP[a]	CVS	Extension (crane time)
Tanaka and Mizuno (2015)	Exact	B&B[c]	ZQLZ	Unrestricted
Tang et al. (2015)	Exact/Heuristic	Target-guided/simulation	TJLD	Restricted/extension (DCRP)
Zehendner et al. (2015)	Exact	MILP[a]	CVS	Restricted
Akyüz and Lee (2014)	Heuristic	MILP[a]/target-guided/B S[b]	AL	Extension (DCRP)
Expósito-Izquierdo et al. (2014)	Exact/Heuristic	A*/knowledge-based	CVS	Restricted/unrestricted
Jovanovic and Voß (2014)	Metaheuristic	Chain heuristic	WT	Restricted
Olsen and Gross (2014)	Heuristic	Average case analysis	–	Restricted
Tanaka and Takii (2014)	Exact	B&B[c]	ZQLZ	Restricted
Zehendner and Feillet (2014)	Exact	BVB[c]	CVS	Restricted
Lehnfeld and Knust (2014)	Survey	–	–	–

[a]Mixed-integer linear programming
[b]Beam search
[c]Branch-and-bound

Table 16.6 List of papers on the BRP and CRP, from 2006 to 2016, cont.

Paper	Approach	Method	Benchmark	BRP version
Borjian et al. (2013)	Heuristic	Stochastic opt.	BMBJ	Extension (DCRP)
Hussein and Petering (2013)	Heuristic	Target-guided/GA[a]	HP13	Extension (BRP-W)
Jin et al. (2011)	Metaheuristic	Look-ahead/tree	CVS/BF	Restricted
Petering and Hussein (2013)	Exact/Metaheuristic	MILP[b]/Look-ahead	CSV/LL	Unrestricted
Caserta et al. (2012)	Exact/Heuristic	MILP[b]/priority	CSV	Restricted
Forster and Bortfeldt (2012b)	Heuristic	Tree	CVS/BF	Restricted
Forster and Bortfeldt (2012a)	Heuristic	Tree	LL	Extension (crane time)
Hussein and Petering (2012)	Heuristic	Target-guided/GA[a]	HP12	Extension (BRP-W)
Rei and Pedroso (2012b)	Heuristic	Tree/multiple-simul.	RP	Extension (SP)
Rei and Pedroso (2012a)	Heuristic	MILP[b]	RP2	Extension (SP)
Ünlüyurt and Aydin (2012)	Exact	B&B[e]/target-guided	ÜA	Extension (crane time)
Zhu et al. (2012)	Exact	A*/IDA*[d]	ZQLZ/CVS/LL	Restricted/unrestricted
Caserta et al. (2011b)	Exact	Dynamic progr.	CVS	Restricted
Caserta et al. (2011a)	Survey	–	–	–
Lee and Lee (2010)	Heuristic	MILP[b]	LL	Extension (crane time)
Wu and Ting (2010)	Metaheuristic	BS[c]	WT	Restricted
Wu et al. (2010)	Metaheuristic	Tabu search	WHT	Restricted
Zhang et al. (2010)	Metaheuristic	IDA*[d]	ZGZLC	Restricted
Zhu et al. (2010)	Heuristic	Filtered BS[c]	ZF	Extension (crane time)
Caserta et al. (2009)	Metaheuristic	Look-ahead	CVS	Restricted
Caserta and Voß (2009a)	Metaheuristic	Corridor method	CVS	Restricted
Caserta and Voß (2009c)	Metaheuristic	Corridor method	CVS	Restricted
Wan et al. (2009)	Exact	MILP[b]/target-guided	WLT	Restricted/extension (DCRP)
Kim and Hong (2006)	Exact/Heuristic	B&B[e]/target-guided	KH	Restricted

[a]Genetic algorithm
[b]Mixed-integer linear programming
[c]Beam search
[d]Iterative deepening A*
[e]Branch-and-bound

Table 16.7 Benchmark instances for the BRP

Name	Source	Inst	groups	Inst/group	*B*	*W*	*H*
KH	Kim and Hong (2006)	13	13	1	–	3, ..., 8	3, ..., 5
WLT	Wan et al. (2009)	600	12	50	–	6	2,3,4,5
LL[a]	Lee and Lee (2010)	70	10	5	1,2,4,6,8	16	6,8
WT	Wu and Ting (2010)	1920	48	40	–	3, ..., 10	3, ..., 8
ZGZLC	Zhang et al. (2010)	12500	125	100	–	6, ..., 10	3, ..., 7
WHT	Wu et al. (2010)	600	60	10	–	3, ..., 12	3, ..., 8
ZF	Zhu et al. (2010)	10	10	1	–	3, ..., 10	3, ..., 10
CSV[b]	Caserta et al. (2012)	840	21	40	–	3, ..., 10	3,4,5,6,10
BF	Bortfeldt and Forster (2012)	640	32	20	–	16,20	5,8
ZQLZ	Zhu et al. (2012)	12500	125	100	–	–	3, ..., 7
ÜA	Ünlüyurt and Aydin (2012)	8000	200	40	–	3, ..., 7	4, ..., 7
HP12	Hussein and Petering (2012)	1200	12	100	–	3,6,10,14	3,5,7
RP	Rei and Pedroso (2012b)	24	6	4	–	2,3,4,10,20,40	–
RP2	Rei and Pedroso (2012a)	12	6	2	–	2,3,4,10,20,40	–
HP13	Hussein and Petering (2013)	1200	12	100	–	3,6,10,14	3,5,7
BMBJ	Borjian et al. (2013)	150	2	120,30	–	3,4	3,4
AL	Akyüz and Lee (2014)	2400	4	600	–	6	2, ..., 6
TJLD	Tang et al. (2015)	400	8	50	–	6	2, ..., 5
ELAMM	Expósito-Izquierdo et al. (2015a)	420	42	10	–	4,5,6,7,8,9,10	5,6,7,8,9,10
ZLK	Zhang et al. (2016)	15	15	5	–	5, ..., 10	4, ..., 10
KA[c]	Ku and Arthanari (2016a)	720	24	30	–	5, ..., 10	3, ..., 6

[a] https://sites.google.com/site/smallcontainerworld/
[b] https://www.bwl.uni-hamburg.de/iwi/forschung/projekte/dataprojekte/brp-instances-caserta-etal-2012.zip
[c] http://crp-timewindow.blogspot.com

regarding the restricted and the unrestricted BRP. Later, we investigate heuristic methods and separate this area accordingly into material on the restricted and on the unrestricted BRP. Afterwards, in Sect. 16.4.3, extensions of the BRP are discussed together with a description of the corresponding solution approaches.

Several exact methods for the BRP are available in the areas of mathematical modeling: Branch-and-bound, tree search, A*-algorithms, and dynamic programming. A subset of articles focus only on exact methods, whereas other references introduce exact methods but add heuristics for addressing medium and larger instance sizes, see column "Approach" in Tables 16.5 and 16.6. In the sequel, the respective work is clustered and discussed according to the chosen approaches and BRP version. First, exact approaches are given for the restricted and afterward for the unrestricted BRP.

For the unrestricted BRP (without assumption A1), Caserta et al. (2012) provide a first mathematical formulation (BRP-I). Later, Petering and Hussein (2013) introduce BRP-III, an alternative mathematical model for the unrestricted BRP that requires a reduced number of decision variables. The improvement of running times when using the BRP-III is illustrated in experiments. Moreover, Expósito-Izquierdo et al. (2014) provide an A* algorithm that can be adapted to both, the restricted as well as the unrestricted BRP. Similarly, the Iterative Deepening A* algorithm presented by Zhu et al. (2012) can be applied to both versions of the BRP. Moreover, Tricoire et al. (2016) introduce a branch-and-bound approach and compare it against the A* algorithm of Expósito-Izquierdo et al. (2014). Their results indicate that their branch-and-bound approach with depth-first policy outperforms the A* algorithm concerning the number of solved instances in a given time frame. Finally, Tanaka and Mizuno (2015) develop dominance criteria for excluding a subset of feasible solutions from the search space. They apply this approach within a branch-and-bound method.

A first mathematical model for the restricted BRP is proposed by Wan et al. (2009) and used in the extended context of locating ingoing containers, see Sect. 16.4.3. Furthermore, the mathematical model BRP-I serves as basis for the BRP-II, a mixed-integer linear program modeling the restricted BRP (Caserta et al. 2012). A corrected and improved version of the BRP-II is provided by Zehendner et al. (2015) together with a pre-processing procedure and a new upper bound that is implemented as cut in the model. An alternative correction of the BRP-II is proposed by Eskandari and Azari (2015). Experiments illustrate that the improved BRP-II-A performs better than the corrected BRP formulation regarding computational time and number of solved instances. Moreover, branch-and-bound approaches are suggested by Kim and Hong (2006), Ünlüyurt and Aydin (2012), Expósito-Izquierdo et al. (2015b), and Tanaka and Takii (2016) (see Tanaka and Takii 2014 for an earlier version of this article). As stated above, Expósito-Izquierdo et al. (2014) and Zhu et al. (2012) provide A* and Iterative Deepening A* algorithms for the restricted BRP. Finally, a dynamic programming method is introduced by Caserta et al. (2011b) and a branch-and-price method is presented by Zehendner and Feillet (2014). Recently, Ku and Arthanari (2016b) proposed an abstraction method for the restricted BRP which allows to reduce the search space and that is applied within a tree search.

The $\mathcal{NP}$-hardness of the (restricted and unrestricted) BRP justifies the usage of heuristic approaches that in particular become relevant when addressing realistic problem instances of larger sizes. For the unrestricted case, Petering and Hussein (2013) present a look-ahead algorithm which extends a similar approach given by Caserta et al. (2009) for the restricted case. In this approach, Petering and Hussein (2013) include voluntary moves into the set of activities. That is, the rearrangement of a block that is not located in the target stack is feasible. Tricoire et al. (2016) joins voluntary as well as forced relocation options under a modified approach, introducing a set of policies for choosing moves. These policies are embedded within *rake search*, a metaheuristic framework based on tree search. Furthermore, Expósito-Izquierdo et al. (2014) present a domain-specific knowledge-based heuristic which consists of a set of basic rules and a heuristic evaluation for guiding the search strategy.

For the restricted BRP, Kim and Hong (2006) propose a first heuristic method that chooses the next move based on the *E*xpected *N*umber of *A*dditional *R*elocations (ENAR) in the resulting bay layout. The heuristic is experimentally compared with the exact branch-and-bound approach proposed in the same paper, indicating an average increase of moves by up to 7.3%. Furthermore, a simple heuristic priority rule is proposed by Caserta et al. (2012) and measured against the exact solution and the heuristic solution of Kim and Hong (2006). Olsen and Gross (2014) investigate a priority heuristic similar to that one provided by Caserta et al. (2012) and add a discussion of its performance. More detailed, an average case analysis based on assumptions on initial stack height and stack capacity is given. Along the same line, Galle et al. (2016) study the performance of the heuristic given by Caserta et al. (2012) for the case of asymptotically growing number of stacks. For this case the convergence of the expected number of relocations to a lower bound is proved. Moreover, Borjian et al. (2015) carry out similar considerations for the A* algorithm. A metaheuristic approach for the restricted BRP is presented by Caserta and Voß (2009b). In this work, the corridor method is adapted to the BRP, where the corridor limits the number of potential stacks for relocation. The presented approach embeds a dynamic programming scheme and applies it by iteratively solving to optimality "constrained" versions of the original BRP. Metaheuristic approaches adapted and applied to the restricted BRP are presented by Caserta and Voß (2009c) and Caserta and Voß (2009a). In these approaches, parameterization and tuning methods for the corridor method are proposed, where the corridor limits the number of potential stacks for relocation.

Caserta et al. (2009) describe an alternative encoding of the bay using a binary matrix, which enables fast access to layout information and fast bay transformation. This encoding is applied for the implementation of a random-guided look-ahead procedure that explores the quality of potential moves by evaluating their potential future performance. Look-ahead policies are later also considered by Jin et al. (2011) and Jin et al. (2015). In these approaches, a tree search is performed including inspection by look-ahead procedures combined with a locally applied probing heuristic. A particular version of look-ahead is performed within the chain heuristic, proposed by Jovanovic and Voß (2014), where information about the container to be moved next is included in a current decision. The evaluation of simple move strategies within a tree search based evaluation is found in further approaches. For instance, Wu and Ting (2010) design a beam search algorithm that inspects only a subset of the search tree. Moreover, Forster and Bortfeldt (2012b) develop a tree search approach including lower bounds on the number of relocations. Related to tree search approaches is the class of A* approaches which can be performed as heuristics by reducing the search space. Zhang et al. (2010) and Zhu et al. (2012) propose an *I*terative *D*eepening *A** (IDA*) algorithm that includes lower bounds and a heuristic probing approach to evaluate and prune nodes during the search. Finally, a tabu search approach is implemented by Wu et al. (2010) and compared based on a simple branch-and-bound presented in the same paper.

16.4.3 Problem Extensions

Since the introduction of the BRP, several extensions have emerged in the literature. By relaxing particular properties of the original BRP, e.g., the property that no ingoing containers are allowed, or, by adding additional parameters, like the weight of containers, new versions of the BRP arise. In the sequel, we present an overview on recent models and solution approaches.

Already mentioned above is the extension from a two-dimensional to a three-dimensional stacking area. This extension in dimension directly elevates the relevance of crane activities for modeling approaches as the time consumption for a crane movement across a bay is usually different from the time required for crane movements within a bay such that a more detailed consideration of crane working times might be of interest for a realistic model. The consideration of crane working times naturally leads to the definition of alternative objective functions. The standard objective function for the BRP, as introduced by Kim and Hong (2006) is to minimize the number of relocations. As an alternative approach, objectives can be designed based on the crane working time including time consumption for picking-up/placing-down containers, for moving trolleys across the stacks and for moving gantries across bays. A basic model for the crane time supposes that the time for picking-up/placing-down is constant, i.e., independent of the number of tiers that are crossed. A more detailed approach includes tier-dependent pick-up/place-down effort in an extended crane time model. Lee and Lee (2010) develop a three-phase heuristic to minimize the sum of relocations and basic crane time in a three-dimensional setting. Also with respect to a three-dimensional yard, Forster and Bortfeldt (2012a) introduce a tree search heuristic to minimize the basic crane time. For a two-dimensional bay, i.e., neglecting gantry operations, Ünlüyurt and Aydin (2012) propose a branch-and-bound approach as well as a heuristic. Finally, Zhu et al. (2010) include a consideration of spreader and trolley movements and thus address extended crane times. A filtered-beam search approach is suggested. Moreover, Lin et al. (2015) considers extended crane times including a tier-dependent effort for picking-up/placing-down and includes those measures into a heuristic that is, however, focusing on minimization of the number of relocations. Finally, Schwarze and Voß (2015) investigates the relation between different objectives by analyzing to which extent optimal solutions are changed when the objective function is replaced.

The consideration of fuel consumption is included into the *BRP* with *W*eights (BRP-W), see, Hussein and Petering (2012). In that setting, the weight of each container is known and impacts the energy consumption for container movement. Consequently, the BRP-W aims at minimizing the total energy required for removing all containers from the stacking area. Hussein and Petering (2012) propose a *G*lobal *R*etrieval *H*euristic (GRH) that relies on a set of parameters describing preferences for container movement. Using these parameters, a penalty score is computed for each stack. The GRH is embedded in a genetic algorithm that searches for a good configuration of the parameters. The results are extended by Hussein and Petering (2013) by modifying the penalty function.

One assumption of the BRP is that there are only retrieval or relocation activities; however, storing new items into the bay is not feasible. Nevertheless, such operations are often required in practice, such that it is a natural extension to allow incoming items. The DCRP is a *dynamical* variant of the BRP that joins relocation, retrieving and stacking of incoming items. For this problem class, Wan et al. (2009) propose heuristic approaches including basic priority rules for choosing stacks as new location for incoming or relocated containers. In a second approach the expected number of additional relocations is considered, inspired by the heuristic of Kim and Hong (2006). Moreover, a further heuristic is proposed that includes the solution of a series of CRP formulations. Later, Tang et al. (2015) propose rule-based heuristics for the DCRP and evaluates them through a simulation approach. Furthermore, Borjian et al. (2013) add uncertainty to the DCRP by assuming incomplete information and solving the resulting problem using a two-stage stochastic optimization model. A mathematical formulation for the (deterministic) DCRP is provided by Akyüz and Lee (2014). Furthermore, in this work, three heuristics are developed for the DCRP. First, index-based heuristics add weights to the columns in order to position incoming and relocated containers. A second heuristic applies the mathematical model for the DCRP on small portions of the planning horizon. Finally, a beam search heuristic is proposed including upper and lower bound approaches allowing to reduce the size of the search tree. Similar to the DCRP is the *S*tacking *P*roblem (SP), which was formulated for an application in the steel industry by Rei and Pedroso (2012b) and Rei and Pedroso (2012a). A simulation approach is proposed that combines simulation with a construction heuristic. Furthermore, a probabilistic tree search method is developed. A two-phase heuristic for the SP is proposed by Expósito-Izquierdo et al. (2015a). Their approach joins two basic steps, namely the selection of target stacks for relocated or ingoing containers and, second, the exploitation of idle crane time to resolve conflicts and improve the crane productivity.

A further extension of the BRP that includes time windows is described by Ku and Arthanari (2016a). In their approach, the case of import containers is considered. Import containers are stored at the yard until their pick-up for the hinterland transport. In such scenarios, *T*ruck *A*ppointment *S*ystems (TAS) handle the visit of trucks from the hinterland and monitor announced time slots of arrival. Within this pre-defined time slot, the actual arrival time of the truck is unknown. The *CRP* with *T*ime *W*indows (CRPTW) includes this uncertainty by allowing stochastic retrieval sequences within time windows under the objective of finding a minimum expected number of rehandles. To that end, a stochastic dynamic programming model is developed and an exact tree search method with depth-first search is proposed together with an abstraction heuristic that allows to reduce the search space. Furthermore, an index-based heuristic is proposed that evaluates the expected number of containers in a column that depart earlier than a container that is potentially relocated to this column.

An alternative approach that considers incomplete information regarding the retrieval sequence is proposed by Zehendner et al. (2017). In line with the above described CRPTW, the *O*nline *CRP* (OCRP) relaxes the assumption of known priority numbers. However, while the CRPTW includes stochastic retrieval sequences for time windows, the OCRP assumes the retrieval sequence to be revealed in an online fashion over time. Consequently, online optimization techniques are applied to evaluate the success of the proposed target-guided leveling heuristic. More specifically, the competitiveness ratio of the leveling heuristic is determined and average and worst-case analysis are carried out. Finally, a recent extension of the BRP addresses new crane technology that enables lifting of more than one item and that could become an option, e.g., in steel plants. The *BRP* with *B*atch *M*oves (BRP-BM) is introduced by Zhang et al. (2016). This problem formulation addresses new features of crane technology that allow to lift more than one item at the same time. Such moves are called batch moves. Zhang et al. (2016) propose a greedy heuristic for the BRP-BM. Furthermore, lower bounds on the number of relocations are proposed and applied within tree search methods.

16.5 Related Research Fields

In this section, we give a brief outlook on work in related research fields and the relationship to the above discussed post-stacking problems in order to refer the interested reader to related notions and concepts. However, we do not aim at giving a comprehensive overview over work in those fields beyond maritime shipping.

In the previous sections, we have studied pre-, re-marshalling, and retrieval in container yards. As pointed out by Steenken et al. (2004), the selection of storage locations for incoming containers is an additional main task in container reshuffling and thus related to the aforementioned problems. This relation is already addressed in the DCRP, see Sect. 16.4.3, by proposing a joint handling of incoming items and reshuffling operations. Moreover, see Bruns et al. (2016) for a recent study on complexity issues for storage loading problems. In a broader context, the task of locating incoming containers includes moreover the assignment of storage space to containers or container groups, see, e.g., Chen and Lu (2012); Woo and Kim (2011) as well as the selection of storage allocations, i.e., the question of how containers should be piled up in the stacking area, see, e.g., Borgman et al. (2010); Dekker et al. (2006); Jang et al. (2013). Moreover, see Carlo et al. (2014) for more detailed classification and literature on storage space assignment.

In the event of available crane time, pre- and re-marshalling, see Sect. 16.3, can be carried out to resolve conflicts within a bay or block before the retrieval process starts and in order to speed up the subsequent stowing operations. This idea of saving berthing time by carrying out operations in advance, before the arrival of the vessel, is transferred to the complete yard area through the approach of transporting containers to positions closer to the scheduled berth. This process is known as *housekeeping*, see, e.g., Legato et al. (2013), Ehleiter and Jaehn (2016), and Cordeau et al. (2015) for more details in this field.

Moreover, stacking, sorting, and rehandling problems are discussed not only in the context of containers and ports, but also in different areas like warehousing, production planning, and artificial intelligence. Some warehouses are organized following the stacking principle, by storing uniform items piled up on top of each other, where access is only granted for the uppermost item. Stacking operations in those warehouses follow similar rules as in container yards. However, a major difference between container yards and warehouses is given by the item flow, as warehouses have to offer retrieving and receiving operations in parallel (see, e.g., Nishi and Konishi (2010)), whereas in container yards, the receiving operations are usually completed before the retrieval operations take place. Moreover, in general, warehouses handle a much larger number of items than container yards. In addition, the physical properties of the items in a warehouse might differ from that of a box-shaped container. For instance, in the steel industry, coils are stored by stacking them on top of each other. The resulting storage setting is not forming “stand-alone” stacks, as each coil is placed on top of two consecutive coils from the row below (see, e.g., Zäpfel and Wasner 2006). See Tang and Ren (2010) and Tang et al. (2012) for approaches that include crane times into problems from stacking in the steel industry.

Also the handling of trains involves stacking operations; see, e.g., Felsner and Pergel (2008). A train can be seen as a sequence of wagons. It might happen that the wagon sequence of a single train needs to be changed or that the wagons of several trains have to be *reshuffled* to new collections of trains. These operations are physically carried out on dead end sidings, where trains or parts of trains can be stored intermediately and taken away later on. Thus, on dead end sidings, trains can be “stacked” together and moreover, rehandling of wagons is possible. Each of those dead end sidings relates to a stack in the container yard, where only the uppermost container/wagon is accessible.

A well-known concept in artificial intelligence is that of blocks-world. (See, e.g., Romero and Alquézar 2004, Gupta and Nau 1992.) The blocks-world is carried out on a “table” where blocks are stacked on top of each other. A typical blocks-world instance consists of a given initial table state and a desired goal state. The task is to transform the initial state to the goal state with a minimum number of moves. Variants of blocks-world incorporate limitations on the table size and different levels of given conditions for the goal state. Gupta and Nau (1992) prove the $\mathcal{NP}$-hardness of blocks-world and Caserta et al. (2012) show that the BRP is a particular case of blocks-world.

16.6 Conclusion and Future Challenges

Ever since the first containers were introduced in the early 1960s, container handling techniques and strategies have always been key factors in measuring the efficiency of major ports. However, due to the growth of container vessels in recent years, whenever one of such ships berths at a port, a number of containers that would have been unthinkable some time ago must be handled in just a few hours. This poses a serious challenge for container terminal operators, since the volume of traffic has grown substantially while the available surface for managing such traffic has remained virtually unchanged. Therefore, optimization techniques for handling and rehandling containers acquire a prominent role in fostering efficiency of container terminal operations.

Moreover, in the stages of design, construction, and operation of a container terminal, simulation tools have turned out to play a crucial role, examples are given in, e.g., Gambardella et al. (1998) and Yun and Choi (1999). Questions of interest are, among others, the layout of the terminal itself, including location and size of facilities (container yards, mooring, maintenance areas, etc.), design and operation of transport systems (AGVs, cranes, etc.), and modeling of container flows. Optimization methods, like those addressing rehandling and stacking operations at ports, are suited to extend and enhance classical simulation approaches. For instance, integrated simulation-optimization establishes a simulation tool on a superior level which has the permission to call optimization methods on a sublevel. In such a setting, the optimization algorithm can, e.g., take over a tactical position and be used to define and control general system parameters on an aggregate level (Saccone and Siri (2009)). In an alternative setting, optimization tools could be used to take decisions on a detailed, operational level. For instance, while analyzing transport systems at a container terminal using simulation, it is helpful to call optimization tools that solve particular rehandling and stacking problems to obtain information on capacity utilization of cranes and vehicles. Along the same line, while designing a terminal layout through simulation, analysis of detailed stacking operations at container yards is relevant to determine required storage and handling capacities. The availability of fast optimization techniques is a crucial issue of integrated simulation-optimization tools as typically, optimization methods will be called quite often. Thus, the development of efficient optimization techniques is an important matter of terminal planning.

In this chapter, we have presented an updated survey on techniques for post-stacking situations, based on an earlier version (Caserta et al. 2011a). We have focused on three classes of post-stacking problems, namely the re-marshalling, the pre-marshalling, and the relocation problem and provided a comprehensive overview on exact and (meta-)heuristic methods in this areas. This includes a summary of available benchmark instances and a description of problem extensions. Moreover, work in related fields has been discussed.

In Caserta et al. (2011a), we mentioned the design of efficient algorithms for online optimization, the use of recent findings in the metaheuristic field, and the development of broader, integrated approaches for container terminal logistics as open challenges for the aforementioned problems. It can be observed that since then, a number of publications have addressed problems from the mentioned areas. Examples of this research stream can be found, e.g., in the field of BRP extensions. Integrated approaches for related operational tasks, like handling of incoming items and the subsequent restacking, are proposed and combinations with online optimization policies are suggested there. Moreover, Tables 16.5 and 16.6 illustrate that the variety of existing metaheuristic approaches for post-stacking problems is rich. Although this activity illustrates that the interest in this area is high and that quite a bit of work has been done to answer research questions, still the mentioned challenges remain as open working areas and offer opportunities for new research. For instance, in the broader context of housekeeping in container yards, it will be worthwhile to transfer available methods and knowledge from the field of post-stacking to related problem areas and focus on integrated solution approaches.

A further avenue for advancing the work in this field is identified in Caserta et al. (2011a) as the exploitation of recent methods in computer technology, like parallel computing and grid computing. The increase in computational power obtained by using such techniques will not only allow to address larger problem sizes but could also enable to handle problem types of a higher integration level, that are harder tractable from a computational perspective.

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Chapter 17
State-of-the-Art Yard Crane Scheduling and Stacking

Nils Kemme

Abstract As the interface between waterside and landside transport chains, the container yard plays a vital role for the performance and competitiveness of container terminals as a whole. Most terminals of relevant size nowadays deploy gantry cranes for container stacking operations, which are therefore key elements of modern terminal planning. The creation of an efficient terminal design therefore requires a profound understanding of the capabilities and performance of gantry cranes, which is in turn largely determined by the rules and strategies defining the way these machines are deployed in operation. Against this background, the present work firstly reviews academic works on container stacking and yard crane scheduling, then critically discusses their practical relevance, and finally explains the strategical implications of these strategies for terminal planning.

17.1 Introduction

Over the last decades, the volume of seagoing container traffic has increased tremendously, often with double-digit growth rates. It has become one of the greatest drivers and profiteers of the globalization process. In parallel, also vessel sizes increased notably, and in spite of the downturn in container traffic growth in recent years, an end of this trend cannot be foreseen yet. Moreover, as result of increased price competition among international steamship companies, economies of scale have become even more important, and thus vessel sizes tend to increase even faster.

As a consequence, container terminals, which have also expanded significantly over the last decades, are faced with constantly increasing requirements. Along with increasing vessel sizes, the draft of access channels, turning basins, and berths has to grow accordingly, quay cranes need to become higher and have more outreach, and storage and handling capacity have to be prepared for higher peak volumes. In

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fact, shipping lines tend to make fewer but bigger calls with their larger vessels, i.e. the number of containers discharged and loaded in each port (moves per call) is increasing, while asking for similar short service times in port. Hence, ever increasing container volumes have to be loaded and discharged as well as handled and stored in the yard in short periods of time, thus inducing increasing peak requirements in storage and handling capacity.

Therefore, the efficient use of available storage space and processing time to turnaround a vessel are nowadays major challenges for seaport container terminals. Researchers and operators have traditionally focused on ship operations, when optimizing the turnaround time of vessels, although being largely dependent on an undisturbed container flow between vessel and storage yard. In fact, long and unpredictable times for storing containers in or retrieving containers from the storage area directly lead to interruptions for the quay cranes' discharging and especially loading processes. Therefore, the storage yard also plays a vital role for the turnaround times of vessels. In total, the container yard is not just the storage area for containers; it is the interface between waterside and landside transport chains. Most of the terminal operations either originate from or cease at the container yard.

The most prevalent stacking technology is the use of gantry cranes. Two systems have to be distinguished, namely the *R*ubber-*T*yred *G*antry (RTG) crane system and the *R*ail-*M*ounted *G*antry (RMG) crane system. Several authors evaluate the performance of these systems by comparison (see, e.g., Saanen et al. 2003; Chu and Huang 2005; Vis 2006). Compared to *S*traddle *C*arrier (SC) stacking, the crane systems offer significantly denser stacking along with still acceptable storage and retrieval times. One of the major advantages of RMG systems – especially for high-labor-cost countries – is their proven potential for automation, while automated RTGs are available, but have not yet gained acceptance. Hence, the so-called *A*utomated *S*tacking *C*ranes (ASC) usually refer to the automated versions of RMGs.

The efficiency of RTG and ASC storage yards mainly depends on the way available storage and crane resources are deployed, which is determined by the underlying container stacking and crane scheduling strategies applied by a terminal. Container stacking strategies define the rules where to stack incoming containers, while crane dispatching and sequencing of storage and retrieval requests is defined by the crane scheduling strategies.

Within the scope of this work, a critical overview on container stacking and crane scheduling for RTG and ASC terminals is given. Both scientific algorithms and practically applied strategies are reviewed and discussed with regard to performance aspects and operational restrictions. Laying the foundation for this review, firstly differences in RTG and ASC storage yard operations are explained in Sect. 17.2. Thereafter, container stacking and yard crane scheduling for RTG and ASC terminals are addressed in Sects. 17.3 and 17.4, respectively. In Sect. 17.5, the importance of stacking and scheduling strategies for strategical terminal planning is discussed. Finally, summary and conclusions are given in Sect. 17.6.

17.2 Container Yard Operations

The container storage yard can be operated by different types of equipment, including gantry cranes, straddle carriers, reach stackers, and forklifts, which lead to different layouts and operations for the storage yard. While the reach stackers and forklifts are mostly applied for rather small container terminals that require very flexible machines, straddle carriers and gantry cranes are the most common types of storage equipment for medium to large-sized terminals (Brinkmann 2011). In fact, according to a survey on container terminal characteristics by Wiese et al. (2009), which essentially is still valid today, as no new storage equipment type has been introduced and widely adapted in practice during the present decade, straddle carriers and gantry cranes are used as storage equipment by 110 of 114 terminals of relevant size all around the world. The present work focuses on gantry crane systems. Subsequently, differences in yard layout and storage operations for the two most common types of gantry crane systems – RTGs and ASCs – are briefly explained.

17.2.1 RTG Yard Operations

An RTG is a gantry crane type that is used at container terminals all around the world for container stacking operations. It is usually combined with manned *T*ractor *T*railer *U*nits (TTU) for the horizontal transport between quay and storage yard. While most operational RTGs are still diesel driven, RTGs with electric engines are becoming increasingly popular. The stacking height of RTG-operated storage yards varies greatly. Most common are RTGs that facilitate stacking heights of 1-over-4 and 1-over-5 (see Chu and Huang 2005), but even 1-over-7 cranes are available, which can lead to the highest stacking density among established yard systems. Therefore, RTG-operated storage yards are typically found at large and very large terminals that require dense stacking operations (see Brinkmann 2011). Examples of the RTG system are in operation in the ports of Hong Kong (China) and Charleston (South Carolina, USA).

An RTG-operated storage yard is usually subdivided into several yard blocks and driving lanes. The yard blocks, which are laid out parallel to the quay wall, consist of several rows, in which the containers are stacked end to end, as well as an additional handover lane, which is reserved for terminal tractor units and *E*xternal *T*rucks (XT) that interact with the RTGs. In contrast to straddle carrier blocks, additional wheel spaces are not needed between the rows. Thus, from experience in terminal operations, only 30–40 cm space is required in order to ensure safe crane operations. All yard blocks are arranged in an alignment form a yard zone. In Fig. 17.1, the general layout of an RTG-operated container terminal with eight yard blocks and four yard zones is schematically illustrated from a bird's eye view. Blocks 1 and 5 are in zone (I), bocks 2 and 6 are in zone (II), and so on. Length,

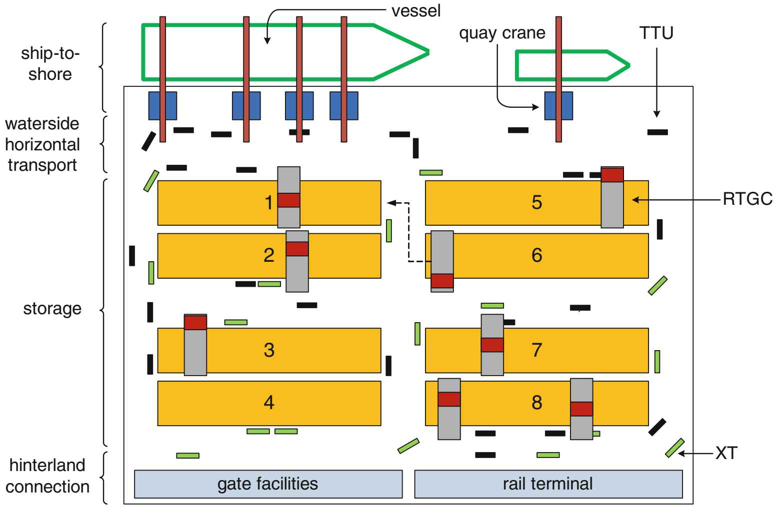

Fig. 17.1 Exemplary RTG terminal layout

width, and quantity of the yard blocks vary notably between international container terminals and depend on several factors, such as space availability, required storage capacity, and prevailing vessel length. Most common are block lengths in the range from 30 to 60 bays for RTG systems, depending on the vessel sizes being typically handled at the respective terminal in order to ensure short TTU travel distances for vessels served in parallel to the yard blocks, as illustrated for the left vessel in Fig. 17.1. Typically, containers are stacked 6 rows wide in RTG-operated yard blocks, which means, the blocks are $6 + 1$ rows wide due to the additional handover lane. Yard blocks up to $8 + 1$ rows wide are reported by Chu and Huang (2005).

The RTGs are dimensioned such that the whole yard blocks, including the handover lanes, are spanned by their portals. RTGs easily traverse bay-wise along an entire yard block and from block to block within the same yard zone – such movements are called linear-gantrying. In addition, as the cranes are able to turn the wheels by 90°, they can also move to blocks of adjacent yard zones by using the driving lanes perpendicular to the quay wall. In practice, such a crane movement is a rather time consuming maneuvre (up to 15 min) that is called cross-gantrying. In Fig. 17.1, this maneuvre is illustrated by the dotted line, indicating a cross-gantrying movement of a crane from block 6 to 1. As a consequence, multiple cranes can simultaneously work in one yard block and RTG systems can flexibly react to workload imbalances between different yard blocks.

RTGs usually do not traverse bay-wise when laden with containers. They only move containers within the rows of the same bay by trolley movements. Therefore, TTUs and XTs have to drive to the bay where the relevant containers have to be stored or retrieved by an RTG. Likewise, containers are also only be shuffled within the same bay. After finishing work within one bay, the RTG can move empty to the next bay and/or block.

XT and TTU operations are usually intermingled at RTG-operated container yards, sharing the same handover and driving lanes in the storage yard. As automated equipment shall usually be clearly separated from manual operations, it is consequently hardly possible to automate the horizontal transport between quay and storage yard for RTG systems. Furtherly considering the heavy interaction between XTs and TTUs with RTGs, resulting from handovers, linear-gantrying, and cross-gantrying, the automation of the RTGs itself is also very complex, and associated with major safety problems. Consequently, almost all RTGs in operation are still manned, although automated RTG solutions are meanwhile available.

17.2.2 ASC Yard Operations

Superficially, ASCs are quite similar to RTGs – both are gantry crane types that are used at seaport container terminals for storage purposes only. From a technical perspective, the most obvious difference is that an ASC moves on rail tracks while an RTG is rubber tyred. Consequently, ASCs cannot cross gantry to other yard blocks to react to workload imbalances.

Container terminals that make use of ASCs for stacking operations are usually organized in form of several parallel yard blocks which can be arranged parallely or perpendicularly to the quay wall. This paper focuses on the most common ASC yard being laid out perpendicularly to the quay wall with handover positions only at the waterside and landside ends of the blocks. XTs are usually only served at the landside block ends, while horizontal transport machines between quay and yard blocks are only handled at the waterside block ends. Due to the clear separation of internal and external traffic the layout offers high potential for automation of the yard cranes themselves as well as the horizontal container transport between quay and yard cranes. The latter is usually done by *A*utomated *G*uided *V*ehicles (AGV) or (automated) straddle carriers. The layout of an exemplary ASC container terminal, to which we refer here, is shown in Fig. 17.2.

Apart from their arrangements, the yard blocks are very similar to RTG-operated yard blocks, as containers are stacked end to end in several rows that are separated by only 30–40 cm clearance. Since the handover takes place at the front ends of the block, no handover lane is required inside the crane portal. The dimensions of yard blocks differ between terminals, but typically the order of magnitude for perpendicular ASC yard blocks is 28–48 bays long and 6–10 rows wide. The transfer between the handover areas and the storage positions in the block is performed by the ASCs by means of bay and row-wise portal and trolley movements, respectively. Thus, different to RTGs, long laden crane movements alongside the yard block are an inherent part of front-end-loading ASC systems.

Nowadays, four variants of ASC systems are known for the perpendicular block layout, which are all illustrated in Fig. 17.2. They are quite similar in terms of

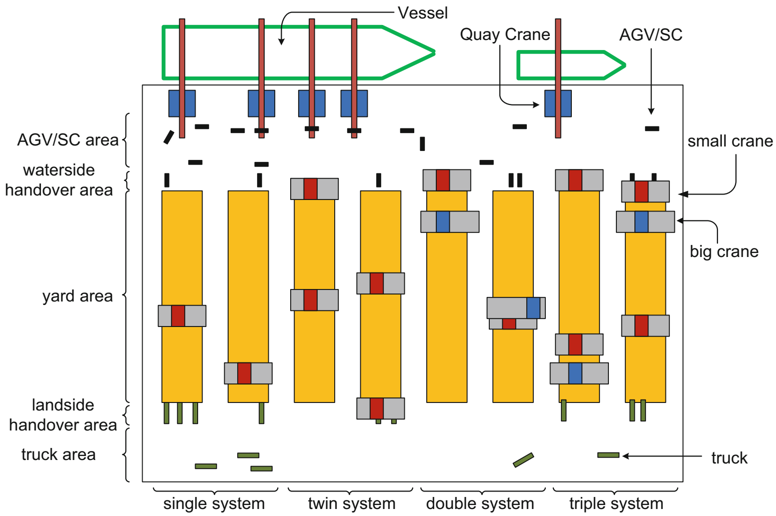

Fig. 17.2 Exemplary RMG terminal layout

container flow and at first glance mainly differ in the number of cranes used per block. The single crane system is the oldest ASC crane system and was introduced at the ECT Delta Terminal in Rotterdam, Netherlands in the 1990s. Each block is operated by a single ASC crane, which serves landside and waterside handover positions. The major advantage of the single system is its comparably simple behavior, which simplifies the crane scheduling problem. But the handling capacity of just one crane is rather small, therefore, the system can result in long waiting times for external trucks and disturbed supply chains for the quay cranes.

A consequent derivative is the usage of two identical yard cranes per block. As the cranes have the same size and share the same rail track, passing of cranes within the same block is impossible. Consequently, one crane serves the waterside handover positions and the other one the landside handover positions. Subsequently, this system is referred to as twin. On the one hand, it is beneficial that the system offers an increased handling capacity compared to the single one, but on the other hand, it is more complex to operate, since crane interferences have to be regarded. In addition, the system is more vulnerable to machine breakdowns, since crossing of the cranes is not possible and thus a defective crane may jam the whole yard block in the worst case. A twin system is, for example, in operation at the container terminal Virginia International Gateway in Portsmouth, Virginia (USA).

A comparable handling capacity along with a higher degree of flexibility can be reached by the double crane system which also uses two cranes per block but allows for crossing. Hence, each handover position can be served by both cranes. This can be facilitated by using two cranes of different sizes which do not share the same track but have their own pair of rails each. However, crossing is only possible if the trolley of the bigger crane is moved to a special crossing position which is located at the side of the big crane, beyond the profile of the small crane. Such a system is in operation at the HHLA *C*ontainer *T*erminal *A*ltenwerder (CTA) in Hamburg (Germany). The benefits of the crossing possibility are reduced (but nevertheless existing) crane interferences and reduced consequences of machine breakdowns. The downside is a higher area requirement per block as well as higher rail and crane investments. This is due to the second track and the crossing lane and not least because of the different sizes of cranes. Thus, fewer blocks can be installed on a given yard area, for example.

The latest development of automated ASC systems is the triple crane system, which is in operation at the HHLA Container Terminal Burchardkai in Hamburg. Three cranes will be used per block: Two identical cranes sharing the same tracks and one bigger crane with its own rails. While – comparable to a twin system – the two small cranes cannot pass each other, the bigger one can pass both small ones, which is comparable to a double system. On the one hand, deploying three cranes per block increases the handling capacity, on the other hand, besides higher block investment, more crane interferences have to be regarded which makes scheduling even more complicated than for the twin and double systems.

17.3 Container Stacking

The container stacking problem deals with the question where to place incoming containers in the yard area. Even today, this operational planning problem is not that easily solved, since several conflicting objectives and constraints have to be considered. A trend towards increasing stacking height, more flexible short-notice container deliveries, and increasing demand for on-time retrieval processes lead to more elaborated problems. Within this section, first the objectives and constraints of container stacking are explained. Thereafter, a literature overview on related solution strategies and methods for both RTG and ASC systems is given. Finally, operational considerations on the discussed strategies are shared and practical relevant constraints and solution approaches are identified.

17.3.1 Problem Description

Depending on the location of container terminals, the area available for container stacking often is a scarce resource. Especially for terminals located in grown industrial port structures, the amount of area available is not unlimited when it comes to terminal expansion plans. Therefore, terminal operators are usually seeking for efficient usage of the available storage area, i.e. a high storage capacity should be realized per yard space. Hence, terminal operators tend to increase the stacking height, if yard space is a scarce resource. In addition, the storage yard indirectly affects the quay crane performance, which is often regarded as the most important performance indicator. The quay cranes and the storage yard are connected by the waterside horizontal transport vehicles. An efficient use of this equipment, as well as a timely accurate container flow to and from the quay cranes is facilitated by fast and punctual storage and retrieval processes of the container yard. Besides the efficient use of yard crane resources, which is controlled by the used crane scheduling method, smooth yard operations depend on the number of required shuffle moves. By avoiding stacking of containers on top of containers that have to be retrieved before the others, an appropriate stacking strategy can minimize the number of unproductive shuffle moves. Hence, two major stacking objectives – maximizing the number of containers stored per yard space and minimizing the number of shuffle moves – are identified. But since high and dense stacking generally leads to more shuffle moves (see, e.g., de Castilho and Daganzo 1993 as well as Kim et al. 2008), these are conflicting objectives. However, this trade-off can be mitigated by stacking approaches which take advantage of the available information for each container.

Accurate data on container departure times is the most crucial information that is needed in order to avoid shuffle moves. Usually this information is not directly given, but can only be anticipated from the other characteristics of the containers. However, availability and accuracy of container data are greatly dependent on the corresponding flow direction. Import containers arrive in large container vessels and continue towards their destination through hinterland transport. While the arrival of import containers is to some extent predictable, the departure can be regarded as unpredictable, since the arrival time of external trucks is generally not announced in advance, unless a truck appointment system is in place, and additionally depends on external events like traffic jams. For export containers, the situation is reversed. While the arrival via hinterland transport is somewhat random, their departure is usually more predictable, as it is connected with a vessel. Subsuming, waterside processes are more predictable than hinterland processes. Since the outflow is more important for container stacking, waterside outgoing containers, i.e. export as well as the so-called transshipment boxes, are therefore more suitable for the application of elaborated stacking approaches. Besides the flow direction, information on the type, size, weight, departing mode, and destination of the container may be available and usable for deciding on efficient storage positions for containers.

17.3.2 RTG Literature

Due to its importance for the performance of seaport container terminals, the container stacking problem is widely addressed in the academic literature. Most works, however, deal with stacking for RTG systems, while only few papers address stacking for ASC systems. In fact, an analysis by Kemme (2013) reveals that only five of 28 found stacking references deal with ASC systems, while the remainder refers to RTG systems. Another analysis by Abbas (2016) shows that 60% of stacking-related literature aims at minimizing the number of shuffle moves.

Subsequently, selected references on RTG systems are described, which mainly differ in the research approach applied. According to Dekker et al. (2006), most references on container stacking are based on analytical calculations or detailed simulation studies.

Taleb-Ibrahimi et al. (1993) and de Castilho and Daganzo (1993) are among the first to investigate the relation between the stacking height and the resulting number of shuffle moves. While Taleb-Ibrahimi et al. (1993) discuss this relation for export containers only, the discussion is continued by de Castilho and Daganzo (1993) for stacking import containers.

The problem of estimating the number of required shuffle moves both to retrieve a single import container from a stack and to retrieve all containers of a bay in a given sequence is addressed by Kim (1997). He proposes several tables and equations to estimate these numbers as a function of the block width, stacking height, and initial filling rate of the bay.

Kim and Bae (1998) address the problem of remarshalling export containers from an unsorted stack configuration to a stowage-plan-compliant configuration with the objective of minimizing the number of relocated containers and the resulting driving distances. The problem is decomposed into three sub-problems that are solved in a two-stage process. In the first stage, the bay-matching problem and the move-planning problem are solved simultaneously, while the task-sequencing problem is solved on the second stage. Both the bay matching-problem and the task-sequencing problem are solved by dynamic programming, while the move-planning problem is formulated and solved as a transportation problem.

Kim and Kim (1999a) aim for stacking arriving import containers in a shuffle-move-minimizing way with respect to given space constraints for a container terminal using a retrieval time stacking strategy, which does not allow to stack newly arrived containers on top of containers that are planned to depart earlier. The problem is mathematically formulated for constant, cyclic, and dynamic arrival rates of import containers. A Lagrangian-relaxation-based solution method is suggested to solve these problems to optimality.

The problem how to stack export containers with an unknown arrival sequence and unknown departure times in such a way that the number of shuffle moves is minimized during the future vessel-loading processes is addressed by Kim et al. (2000), Kang et al. (2006a), and Kang et al. (2006b). Kim et al. (2000) try to exploit the fact that heavy containers are usually stored below lighter ones on the vessel. Therefore, it is expected that heavy containers have to be retrieved from the stack before lighter ones. Based on this analysis, decision rules to use weight groups for stacking export containers are derived by Kim et al. (2000). These rules are evaluated by comparing the resulting decisions with optimal decisions from a dynamic programming method. Zhang et al. (2010) show that this dynamic programming method is incorrect with respect to its key model transformation. They analyze the errors in the original derivation of the model transformation and present the correct form. In contrast to Kim et al. (2000), it is argued by Kang et al. (2006a) and Kang et al. (2006b) that the weight information available at the time of container arrival is only an estimate, which may lead to disadvantageous stacking decisions depending on the estimation quality. They propose as an alternative a simulated annealing algorithm in order to find shuffle-move-minimizing stacking positions for arriving export containers with uncertain weight information.

In another paper of a similar group of authors, Kang et al. (2006c) study the problem of remarshalling export containers in a yard block with multiple RTGs. In order to minimize the required time for all remarshalling operations in a yard block, it is aimed for finding a remarshalling plan that minimizes the number of relocated containers and the crane interferences during remarshalling. They propose a simulated annealing algorithm to solve this problem and show that this algorithm is able to produce an efficient remarshalling plan in reasonable time.

The remarshalling problem is also addressed by Hirashima et al. (2006), Hirashima (2008), and Hirashima (2009) as well as Lee and Hsu (2007). In order to reduce the vessel turnaround times, they all strive to find a remarshalling plan that minimizes the number of relocated containers during the remarshalling operations. For solving this remarshalling problem, Hirashima et al. (2006), Hirashima (2008), and Hirashima (2009) consider the use of a Q-Learning algorithm that belongs to the class of reinforcement learning techniques, while Lee and Hsu (2007) develop an *I*nteger *P*rogramming (IP) formulation and a heuristic for this purpose. The model formulation is based on a multi-commodity network flow model and a set of additional constraints, representing physical restrictions of the containers.

Saanen and Dekker (2006a) and Saanen and Dekker (2006b) are the first to investigate different stacking strategies by means of a fully integrated simulation model of a complete transshipment terminal using RTGs and TTUs in the yard. The stacking performance is evaluated with respect to several performance figures like the quay crane productivity, the TTU service times as well as RTG and TTU productivities. The simulation results show, among others, a negative correlation between the average yard-filling rate and the quay crane productivity, the number of shuffle moves and the quay crane productivity, the RTG travel time per job and the quay crane productivity as well as a positive correlation between the average yard-filling rate and the RTG travel time per job. It is found that the performance differences between more sophisticated stacking strategies, that make use of several stacking criteria, and a simple random stacking strategy are rather small.

Tang et al. (2015) address the problem of minimizing the number of shuffle moves for a given bay configuration with both no new container arrivals and continuously arriving new containers during retrieval, which is referred to as the static and dynamic shuffling problem, respectively. Based on the first model formulation for the static problem from Wan et al. (2009), which is proven to be NP-hard by Caserta et al. (2011), they present an improved MIP model, develop effective heuristics, and analyze the performance of these algorithms. The results show that the improved model can be solved more quickly than previous formulations and that the proposed heuristics are superior to existing ones for both static and dynamic problems.

17.3.3 ASC Literature

Although several terminals with ASC systems have been built in recent years, academic literature on container stacking for ASC systems is still not as widespread as for RTG systems, perhaps because the problem does not easily lend itself to analytical solutions (see Dekker et al. 2006). In fact, contrary to RTG systems, all subsequently presented stacking references on front-end-loading systems are based on simulation studies. While Duinkerken et al. (2001), Park et al. (2006), Dekker et al. (2006), Borgman et al. (2010), and Gharehgozli et al. (2014a) consider stacking for single crane ASC systems, Park et al. (2011), Yu and Qi (2013) as well as Gharehgozli et al. (2017) investigate container stacking strategies for multi-crane systems.

Duinkerken et al. (2001) compare different stacking strategies like simple random stacking, category stacking, positional stacking, retrieval time stacking, and levelling stacking by means of a detailed simulation model of the Delta Sealand Terminal in Rotterdam, Netherlands. The strategies are evaluated with respect to several performance figures like the number of shuffle moves, the quay crane productivity as well as the average execution times for storage and retrieval jobs. They find the random stacking strategy to perform worst among the tested strategies, while category stacking leads to the best results for all considered performance figures, even for situations of only imperfect knowledge about the container characteristics.

Various combinations of container stacking strategies and dispatching rules for the horizontal transport equipment are compared by Park et al. (2006) with respect to the makespan of the loading operations for certain amounts of containers. Comparable to Duinkerken et al. (2001), the stacking strategies of random stacking, positional stacking, and category stacking are tested for a container terminal with single ASCs and AGVs. The findings of Duinkerken et al. (2001) are confirmed by the results of Park et al. (2006) for their simulation of a small-sized terminal with only one berth and four yard blocks. Likewise, category stacking is found to perform best in most cases, while random stacking mostly leads to the worst performance.

A simulation study on stacking strategies for an automated single ASC system with 27 blocks, each 40 TEUs long, 6 wide, and 3 high is carried out by Dekker et al. (2006). The horizontal transport at the waterside is done by AGVs. In order to simplify, the crane capacities are not realistically mapped and the average filling rate of the container storage yard has been set to only 50% of the physical capacity. Several enhancements and modifications of category stacking are examined and compared with a base case in which containers are stacked randomly. The proposed enhancements of category stacking are mainly inspired by other stacking strategies like levelling stacking, positional stacking, and retrieval time stacking. Once again, category stacking is found to clearly outperform random stacking in terms of the number of shuffle moves, while the retrieval time feature appears to be the most promising enhancement for the category stacking strategy.

Borgman et al. (2010) use the same simulation model as Dekker et al. (2006) to investigate the trade-off between minimizing the retrieval time of containers by stacking close to the outgoing handover area and minimizing the number of shuffle moves by stacking containers only on top of containers that are expected to depart later. Variants and combinations of the positional and retrieval time stacking strategies are compared to the benchmark strategies of random and levelling stacking. The performance is evaluated with respect to the number of shuffle moves and the average time needed to retrieve a container from the stack. It is found that avoiding shuffle moves is more important than stacking close to the outgoing handover area. Even in case of only imperfect knowledge about the container departure times, retrieval time stacking is shown to be superior to positional stacking.

Gharehgozli et al. (2014a) propose a decision-tree heuristic for finding shuffle-move-minimizing stacking positions in single crane ASC yard blocks. The heuristic is based on a stochastic dynamic programming model which can be solved to optimality in reasonable time for small-scale problems. For solving large scale problems with realistic yard block sizes a generalized decision-tree is generated using the optimal results of the exact programming model for small-scale problems. Simulation experiments confirm that the proposed heuristic outperforms commonly used stacking strategies for ASC systems. Further simulation experiments show the advantageousness of a shared-stacking strategy, which allows containers of different vessels to be stacked on top of each other, as compared to a dedicated stacking strategy.

Container stacking in the field of ASC multi-crane systems is first addressed by Park et al. (2011). An online search algorithm is proposed which dynamically adjusts and optimizes a stacking strategy by continuously generating and evaluating different variants of stacking strategies while they are actually applied to determine the stacking positions. Simulation results for a twin ASC system show that the operational performance of the container storage yard in terms of the vehicle waiting times in the handover areas can be substantially improved by the proposed algorithm.

Yu and Qi (2013) study the problem of stacking import containers in a twin crane ASC yard block in a way that minimizes the waiting time for external trucks upon container collection. For that purpose, alternative block space allocation and housekeeping strategies are developed and tested. For block space allocation, three alternative optimization models are proposed, differing in the way containers of different periods are mixed in bays, and optimal solution methods are developed for each model. Complementing the block space allocation, housekeeping aims at reorganizing container positions overnight after retrieval of some containers. It is found that the housekeeping problem is NP-hard, and therefore, a heuristic housekeeping algorithm is developed. The proposed strategies are tested and analyzed by simulation, showing the advantage of multiple period segregation over single-period segregation and non-segregation as well as the benefits of housekeeping.

The interrelation between container stacking and crane scheduling for a twin crane ASC yard block is studied by Gharehgozli et al. (2017). They suggest the use of a handshake area, which is a temporary storage location inside a yard block where a container can be placed by one crane and picked by the other crane to complete the corresponding stack-in or stack-out job, to minimize interferences between the cranes and thus to minimize the makespan to finish all stacking requests. By means of a simulation model different scenarios with and without such a handshake area are tested, analyzing the performance effects of (1) the used crane scheduling strategy, (2) the storage location of the containers in the handshake area, (3) the location of the handshake in the block, (4) the size of the handshake area, and (5) the number of handshake areas. It is found that of all tested parameters the system performance is mostly determined by the applied crane scheduling strategy for both scenarios with and without handshake area. However, simulation results also show that virtually all settings with the suggested handshake areas are outperformed by settings without such areas.

17.3.4 Operational Considerations

In principle, the previously presented works and algorithms comprise promising stacking approaches for container terminals, helping to improve the stacking quality and performance of the storage yard. In practice, however, most of them are not applied as such for different reasons:

17.3.4.1 Data Quality

As accurate data on container departure times, which are most important to avoid shuffle moves, are usually not directly given, academic stacking approaches often rely on other container characteristics, such as weight information and announced departure carrier, to anticipate the future retrieval sequence from stack (see Sect. 17.3.1). In practice, container terminals are faced with incomplete, wrong, and changing information on container characteristics. In fact, the departure vessel or train for a container is sometimes unknown upon arrival at the terminal, and even if known, shipping lines may decide to change the departure carrier of containers after having already stacked in the terminal, thus spoiling the planned retrieval sequence. Also container weight information is often missing or highly inaccurate, which complicates stacking decisions. In the future, weight information are expected to improve due to newly imposed SOLAS (*S*afety *O*f *L*ife *A*t *S*ea) regulations, requiring each container to be weighed before loaded onto a vessel.

17.3.4.2 Computation Times

A container stacking decision usually has to be made upon arrival within very few seconds, which is referred to as real-time in this context, in order not to delay the container handling process. Sophisticated stacking algorithms may take much longer to compute the (near) optimal stacking position for a container, thus being virtually inapplicable for container terminals.

17.3.4.3 Understandability

Although stacking decisions are usually made or at least supported by the *T*erminal *O*perating *S*ystem (TOS), terminal employees, often the so-called yard planner, control and/or supervise IT-based stacking decisions to different degrees. Considering the operational background of most yard planners, they usually prefer plain and easily understandable stacking strategies to effectively control and supervise the TOS. Most academic algorithms might be too complex and difficult to understand for non-operations-research experts, thus having limited acceptance among terminal staff.

17.3.4.4 TOS

Modern container terminals usually rely on the stacking strategies built in to their TOS, thus making it a determining factor for the stacking approach applied by a terminal. While a proprietary TOS can theoretically be designed and developed to include the terminal's desired stacking strategy, much more common commercial TOS can only be customized and extended to feature special stacking strategies at great efforts. Traditionally, commercial TOS tend to include conservative stacking approaches rather than innovative ones as presented above, thus preventing the widespread implementation of highly sophisticated stacking algorithms.

Although not using the latest academic stacking strategies in practice for these reasons, some elaborated stacking approaches have been developed and established, in particular for ASC systems. In fact, due to the higher degree of automation for ASC systems, also stacking decisions tend to be more automated and purely IT-based as compared to RTG systems, thus facilitating the use of more advanced algorithms.

State-of-the-art stacking strategies for RTG terminals firstly separate containers according to the flow direction, stacking import boxes in landside blocks, while stacking export containers in blocks closer to the waterside. In export blocks, bays are reserved for each calling vessel and only containers of the same category (i.e., having the same departure vessel, size, port of destination, and weight class) are stacked on top of each other. Modern TOS feature dynamic reservation of export bays as required upon container arrival, while outdated systems still reserve all bays for a future vessel call several days or even weeks in advance, thus virtually blocking notable storage capacities. In import blocks, containers are just stacked somewhat randomly, trying to level the stacking height. The use of remarshalling strategies is becoming less common, but is mostly just used in certain situations to support high quay crane productivities when particularly fast vessel handling times are required.

In ASC terminals, import and export containers are not separated by blocks, but stacked scattered over all yard blocks. In addition, no advance reservation of bays or slots for vessels or container categories is required. Moreover, modern TOS calculate a stacking position in real-time upon arrival of the container at the terminal. Considering progress in computer technology, nowadays the TOS can search for a well-suited storage position in all yard blocks, evaluating thousands of alternative stacking positions by (simple) heuristic approaches pre-implemented in the TOS software. The evaluation is based on a variety of criteria that can be individually weighted by the terminal (i.e., customization), including travel distance for horizontal transport device, filling rate of yard block, occupancy of handover lanes, and resulting likelihood for shuffle moves.

17.4 Yard Crane Scheduling

After a storage position has been chosen for a container, a crane has to be selected for performing that stack-in operation (i.e., crane dispatching) and a sequence for all stacking operations assigned to that crane has to be defined (i.e., job sequencing). These operational decisions are referred to as yard crane scheduling, which is addressed in this section. Firstly, the objectives and constraints of the crane scheduling problem are explained for different crane systems. Afterwards, a literature overview on crane scheduling approaches for RTG and ASC systems is given, and finally, practical considerations on crane scheduling and the presented methods are provided.

17.4.1 Problem Description

All types of stacking jobs have an origin and a destination, which are positions where the corresponding container is picked up and where it is placed by the used yard crane, respectively. Mainly three types of jobs have to be scheduled: stack-in jobs, stack-out jobs, and repositioning jobs. While the origin of a stack-in job is usually a designated handover area, where containers are forwarded from horizontal transport equipment to the cranes, its destination is a position in the yard block. Vice versa, the origin of a stack-out job is located in a yard block and its destination is located in a handover area. For repositioning jobs, both origin and destination are located in a yard block.

From the vantage point of a gantry crane, each stacking job contains the same time components. These components are listed in chronological order in Fig. 17.3. The distance between the end location of the previous job and the pickup location of the current job requires the crane to do an empty move, which requires some *E*mpty *D*riving *T*ime (EDT). Only in case of identical end and start locations of two successive jobs, no EDT is necessary. Early arrival at the pickup location of

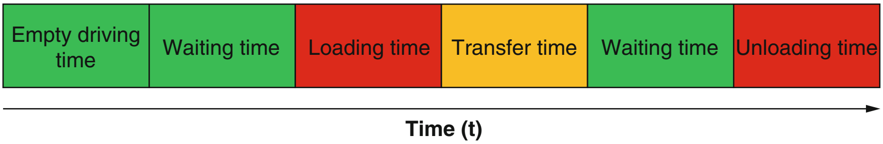

Fig. 17.3 Time components of transport jobs of gantry cranes

the current job may lead to waiting time for the crane, if the container to be picked up is not yet available. This is the case if the container has not yet been supplied by external trucks or internal vehicles or if another container has to be shuffled (by another crane) before the current container can be picked up. On the other hand, late arrivals lead to undesired waiting times for horizontal transport machines. After picking up the container, the crane travels from the start to the end location of the job, where the container is unloaded. Once again, depending on the end location, early arrival may cause waiting time for the cranes and late arrival may have a negative impact on the adjacent transport systems. In case of multiple cranes per yard block, dynamic crane interferences may cause prolonged EDT and transfer times.

The controllability of the time components by scheduling decisions is indicated by the background color in Fig. 17.3. While the loading and unloading times are not controllable, which is indicated by a red background, EDT and waiting times greatly depend on the scheduling decisions, which is indicated by the green background color. The transfer distance is fixed by the start and end location, but as the transfer time may depend on the amount of crane interferences, the transfer time is at least to some extent influenced by scheduling decisions.

In general, yard crane scheduling aims at supporting the overall terminal objective of profit maximization by deploying the available yard crane resources in the most efficient way and providing high service quality for waterside and landside customers. In fact vessels shall be handled with high waterside productivities, which requires the yard cranes to serve horizontal transport machines such that the quay cranes will not have to wait for them. Similarly, external trucks shall be served as fast as possible by the yard cranes in order to minimize the truck turn time on the terminal. However, terminal operators often pay a lot of attention to the yard crane productivity, which is generally measured by the number of productive jobs (excluding repositioning jobs) performed per operating hour. But the yard crane productivity is not the sole performance indicator, since it is not necessarily aligned with the minimization of turnaround times of vessels and external trucks. Short turnaround times require an undisturbed flow of containers to and from the quay crane. Thus, the horizontal transport system is of great importance and waiting times for horizontal transport machines at the yard blocks have to be avoided, because this directly leads to delays in quay crane supply. But since the maximization of yard crane productivity is achieved by minimizing the transport times per job of the cranes, which do not consider the due dates of certain jobs, waiting times of horizontal transport machines are not necessarily minimized by this objective. In fact, some jobs may be handled late compared to their urgency, directly leading to waiting times for horizontal transport machines and quay cranes. Therefore, synchronization with the horizontal transport (i.e., minimizing late arrivals of the yard cranes) is at least as important an objective as maximizing the yard crane productivity.

In addition, the maximization of the yard crane productivity cannot be directly operationalized. The main precondition to ensure high productivity is an efficient use of crane resources. Therefore, empty driving and crane waiting times due to early arrivals have to be minimized. Furthermore, minimizing EDT reduces the energy consumption of yard cranes, which satisfies overall financial and ecological objectives.

Assuming that each job j can be assigned a due date d_j, which defines when the assigned gantry crane has to arrive at the pickup location of the corresponding container in order to avoid (too much) waiting time for horizontal transport machines, resulting earliness E_{jc} and lateness L_{jc} of assigning crane c to job j are defined as

$$L_{jc} = a_{jc} - d_j; a_{jc} > d_j$$

$$E_{jc} = d_j - a_{jc}; a_{jc} < d_j$$

where a_{jc} is the estimated arrival time of crane c at the pickup location of job j.

Overall, taking into account both general yard crane scheduling objectives, maximization of yard crane productivity and minimization of waiting time for horizontal transport machines, the following three operational objectives for the yard crane scheduling problem can be defined:

- Min L_{jc}: Minimization of late arrival of crane c at the pickup location of job j
- Min E_{jc}: Minimization of early arrival of crane c at the pickup location of job j
- Min EDT_{jc}: Minimization of EDT from the destination position of crane c to the pickup location of job j

Although the scheduling objectives are in principle identical for RTG and ASC systems, they are addressed in different ways, considering different planning restrictions and framework conditions induced by the system's technical capabilities and logistical processes. In fact, ASCs cannot move between yard blocks, thus limiting the number of candidate cranes for a stacking job to those working on the relevant block, whereas RTGs can work on multiple blocks in the same lane and can even move to blocks in other lanes, thus having more flexibility and more candidate cranes for performing a stacking job. At the same time, minimization of gantry travel times is implicitly facilitated by the parallel handover and the ways containers are stacked in the RTG system which often leads to several stack-in and stack-out jobs in the same bay, without requiring any gantry movements, while long gantry movements are an inherent feature of ASC systems as a result of the handover at the block ends. On the other hand, ASCs move much faster than RTGs, even allowing for fast laden gantrying, and are therefore more flexible in moving long distances between bays. Taking into account these system characteristics, different scheduling approaches are suggested for RTG and ASC systems in the relevant literature, which are briefly reviewed in the following two sections.

17.4.2 RTG Literature

Similar to the container stacking problem, the scheduling problem of storage machines at seaport container terminals has been addressed by a great number of papers so far. Again, the majority of works address the crane scheduling problem for RTG systems, for which empty crane movements, crane interferences, and cooperation among the cranes are less important issues than for ASC systems. In fact, the literature overview of Kemme (2013) presents 21 scheduling works for RTG systems, while only eight for ASCs are reported. However, in parallel to the increasing use of ASC systems globally, also the ASC scheduling problem is more frequently addressed by the OR community in recent years. Subsequently, selected references on RTG systems are briefly described, which can be distinguished with respect to the considered number of yard cranes per yard block and the applied research method.

Kim and Kim (1997, 1999b) address the problem of routing a single gantry crane in a yard block during loading operations of export containers out of the stack onto waiting vehicles. Their objective is the minimization of the total container handling time of the crane with respect to the setup times at the bay and the travelling times between consecutive bays. In both papers, a mixed-integer programming formulation as well as an optimal solution algorithm is presented, that is based on dynamic programming and solves the problem in real-time. The solution provides the optimal sequence of bay visits and the number of container retrievals in each bay, but the handling sequence of individual containers within a specific bay is not determined.

Comparable to Kim and Kim (1997) and Kim and Kim (1999b), Narasimhan and Palekar (2002) address the problem of finding an optimal sequence of bay visits and container pickups for a single gantry crane with the objective of minimizing the total container handling time of the crane for executing a given load plan with a given bay plan of export containers. Firstly, an IP formulation is provided and the problem is proven to be NP-hard. Thereafter, an optimal branch-and-bound algorithm and a heuristic method are developed. Finally, computational tests on randomly generated problems are conducted, which show the heuristic to be more applicable to real-world problems.

The problem of scheduling multiple RTGs to perform a given set of jobs with different due dates in a yard block is studied by Ng (2005). He formulates the scheduling problem, which is noted to be NP-complete, as an integer discrete time program with the objective of minimizing the sum of total crane delays in comparison to the due dates of the jobs. In order to allow exact modelling of interferences among the cranes, the time is discretized with respect to the required crane movement time for a single bay. Sequence relations among jobs that result from the need for shuffle moves are not taken into account. A dynamic programming-based heuristic to solve the problem and an algorithm to find lower bounds for benchmarking the schedules found by the heuristic are developed by Ng (2005). Finally, computational experiments are carried out to evaluate the performance of the heuristic.

Jung and Kim (2006) and Lee et al. (2006) address a very similar scheduling problem as Kim and Kim (1997) and Kim and Kim (1999b) and Narasimhan and Palekar (2002) do. But instead of routing a single gantry crane per yard block, Jung and Kim (2006) and Lee et al. (2006) analyze the problem of routing multiple cranes per yard block. They aim to find a near optimal routing schedule for each crane of a yard block during retrieval operations of export containers in reasonable time. While the sequence of bay visits as well as the number of container retrievals at each bay is determined by a routing schedule, the retrieval sequence of individual containers within a specific bay is outside their focus. The optimization problem is formulated as an IP model with the objective of minimizing the makespan of all crane operations for executing a given vessel load plan. The objective function includes the crane movement times between different bays, the container handling times at each visited bay, and the crane waiting times caused by crane interferences. A genetic algorithm and a simulated annealing algorithm are designed by Jung and Kim (2006) for the solution of the problem. By means of numerical tests, the simulated annealing algorithm is shown to perform better in terms of computation time and objective value. In contrast, Lee et al. (2006) develop a problem specific priority rule and a simulated annealing algorithm, whereof the priority rule is shown to perform better.

A problem setting that is very similar to that of Ng (2005) is investigated by Li et al. (2009). They address the problem of scheduling multiple sideway-loading gantry cranes in a single yard block to perform a given set of storage and retrieval jobs with certain due dates. Likewise, the problem is formulated as an IP model with the objective of minimizing the sum of total crane delays in comparison to the due dates of the jobs. But in contrast to Ng (2005), the time axis is discretized into rather long intervals of 3.5 min, and minimum safety distances between the cranes are additionally included. In order to reduce the computation time for the problem solution, two heuristic program modifications are developed: Firstly, restrictive time windows around the due dates are implemented to narrow the search space of the program. Secondly, the IP model is embedded into a rolling horizon algorithm that repeatedly solves the program for smaller instances.

A simulation-based investigation of several yard crane dispatching rules is provided by Petering et al. (2009). They discuss the use of look-ahead times and IP approaches for yard crane scheduling and come to the conclusion that they are mostly inappropriate for yard crane scheduling, as the planning horizon has to be kept short in order to avoid deadlocks. Therefore, twelve different yard crane dispatching rules are proposed that differ with respect to the considered priority rule principle (e.g., nearest neighbor, FIFO) and the prioritization of certain types of jobs. A simulation model of a pure transshipment terminal with dozens of yard blocks and multiple sideway-loading gantry cranes per yard block is then used to evaluate the suggested crane dispatching rules with respect to the resulting gross quay crane productivity over a 3-week period. The numerical results show a strong negative correlation between the quay crane productivity and the average vehicle waiting times alongside the yard blocks.

Guo and Huang (2012) propose a new hierarchical approach for the problem of minimizing vehicle waiting times in a storage yard with multiple RTGs per block. In contrast to Ng (2005) and other works on this topic, their approach (1) uses average vehicle waiting time instead of the number of stacking jobs to balance the workload among RTGs, (2) creates by means of a space partitioning algorithm flexible RTG working zones that are not based on units of yard blocks, and (3) decides RTG deployment not in fixed, but in dynamic intervals determined by a time partitioning algorithm. The proposed approach, which combines simulation and optimization algorithms, first assigns cranes to different rows of yard blocks, then creates working zones for cranes in a row using space and time partitioning algorithms, and finally dispatches stacking jobs to RTGs. Simulation results show that their binary partitioning algorithm leads to substantially shorter vehicle waiting times than the approach of Ng (2005) for all tested scenarios.

Li et al. (2015) present a comprehensive work on scheduling of multiple RTGs in a yard with the objective of minimizing waiting times for vehicles. After a detailed introduction to container terminal yard operations, the development of a discrete time model and associated algorithms for rapid yard crane scheduling is started, based on realistic operational constraints such as inter-crane interference, fixed separation distances, and simultaneous storage/retrievals in the yard. Thereafter, a continuous time model with additional practical constraints is studied, focusing specifically on the effects of last minute job insertions. Heuristics and a rolling horizon algorithm are presented to solve real-world instances of that model quickly and robustly in polynomial time. Finally, due to complexity of the yard crane scheduling problem, which is proven to be NP-hard (see Bish et al. 2001), the importance of heuristics in yard crane scheduling is highlighted, and different heuristic algorithms are discussed and compared.

While previous works on yard cranes scheduling mostly aim at optimizing the operation efficiency, He et al. (2015) are the first to also consider ecological aspects, analyzing the trade-off between service efficiency and energy-savings. For that purpose, they convert the yard crane scheduling problem for multiple RTGs working in a storage yard with multiple rows of yard blocks into a vehicle routing problem with soft time windows, which is formulated as a mixed-integer programming model with the two objectives of minimizing the total completion delay of stacking jobs and the total energy consumption of all yard cranes. For solving that problem, an integrated simulation optimization method is presented, which uses an optimization algorithm for exploring the solution space and simulation for evaluating solutions. The optimization algorithm combines a genetic algorithm for global search and particle swarm optimization for local search. The efficiency of the suggested method is demonstrated through a series of numerical experiments, which show a clear trade-off between minimizing energy consumption and time delays, where energy-savings are only possible at the cost of longer completion delays.

17.4.3 ASC Literature

The references on ASC scheduling can mainly be distinguished with respect to the variants of ASC systems studied. While the single crane system is only analyzed by Zyngiridis (2005) and Gharehgozli et al. (2014b), scheduling of twin systems is addressed by Zyngiridis (2005), Choe et al. (2007), Carlo and Vis (2008), Park et al. (2010) as well as Gharehgozli et al. (2014c). Carlo and Vis (2008), Stahlbock and Voß (2010), Vis and Carlo (2010) as well as Speer et al. (2011) deal with crane scheduling for double crane systems. Scheduling of triple crane systems is addressed by Dorndorf and Schneider (2010) and the works of Kemme (2013), Heitmann (2015) and Speer (2017) are applicable to all types of ASC systems.

An IP-based three-step solution procedure for scheduling of both single and twin systems is developed by Zyngiridis (2005). He considers a single yard block that is served by SCs in the waterside and landside handover areas. In contrast to other studies, the crane scheduling problem is not solved as an isolated problem. Moreover, an integrated solution of the container stacking and crane scheduling problems is aimed for by Zyngiridis (2005). This integrated planning problem is solved by two similar three-step solution procedures for single and twin systems that are based on solving consecutive IP models. In the first step, stacking positions for inbound containers and the crane movements for storage and retrieval jobs are scheduled. In the second step, stacking of shuffle containers and the related crane movements are scheduled. In step three, housekeeping jobs are scheduled and potential crane interferences are identified and repaired. Although the avoidance of any delays in the handover areas is formulated as primary objective, the objective functions of the solution procedures aim at minimizing the penalties for the stacking positions of incoming containers, while delays in the handover areas above a certain limiting value are prohibited by model restrictions. Finally, several computational experiments and sensitivity analyses are conducted by Zyngiridis (2005).

Choe et al. (2007) address the crane scheduling problem for a twin yard block that is served by AGVs and XTs in the waterside and landside handover areas, respectively. Whenever a new job is requested by an idle crane it has to be decided which job out of a given set of jobs with different due dates should be assigned next in order to minimize the AGV and XT-waiting times in the handover areas. In a more detailed paper of the same group of authors, Park et al. (2010) provide an IP formulation for this scheduling problem. The program does not contain any restrictions on the avoidance of crane interferences. Due to not being real-time compliant, both Choe et al. (2007) and Park et al. (2010) propose heuristic solution approaches for this scheduling problem. Different degrees of cooperation among the cranes and different scheduling methods are developed by them. The degree of crane cooperation is defined by the yard-block zone in which a crane is allowed to perform shuffle jobs required by main jobs of the other crane – the greater the zone, the more crane cooperation. Besides myopic priority rules, a simulated annealing algorithm and a hill-climbing algorithm are proposed as scheduling methods. Finally, several simulation experiments are conducted to evaluate different combinations of crane cooperation and scheduling methods. The results reveal performance advantages for a higher degree of cooperation and for the application of metaheuristics.

The crane scheduling problem of both single and double crane systems is addressed by Carlo and Vis (2008). They look at the scheduling of two gantry cranes performing a given set of storage and retrieval jobs – but no shuffle jobs – in a single yard block with the objective of minimizing the makespan. The scheduling problems for both types of ASC systems and its system-specific restrictions are verbally described in detail, but no optimization programs for these problems are formulated. Different heuristic solution methods are developed for both types of ASC systems, which are based on a transformation of the two-crane scheduling problem into a standard travelling salesman problem. The transformed problem can then be solved with a methodology from Vis and Roodbergen (2009), which yields the optimal solution with respect to the total movement time of the cranes, but not necessarily with respect to the makespan. The heuristic for twin systems is completed by a repair procedure which has to ensure that the final crane routes do not cross at any point in time. However, some variants of crane interferences are not realistically modelled, in particular the fact that crossing maneuvers are not possible in the double system while hoisting operations of the outer large crane is completely neglected by Carlo and Vis (2008).

In a more recent paper on a similar problem setting, Vis and Carlo (2010) only address the crane scheduling problem for double crane systems with the objective of minimizing the makespan of the crane operations. In contrast to Carlo and Vis (2008), a mixed-integer programming formulation is provided for the double scheduling problem, but the crane interferences are likewise not modelled correctly. Due to the complexity of the modelled problem, a simulated annealing algorithm is proposed for its solution which can be evaluated on the basis of a derived lower bound for the makespan. Numerical experiments demonstrate that the proposed simulated annealing algorithm is capable of solving large problem instances with up to 50 jobs very close to optimality within seconds.

The crane scheduling problem for double ASCs is also addressed by Stahlbock and Voß (2010). They investigate the problem of scheduling two cranes in a single yard block performing a given set of jobs with certain due dates in such a way that the waiting times for the AGVs in the waterside handover area are minimized. An optimization program for that problem is not formulated by Stahlbock and Voß (2010). Instead, quite detailed formulae for the computation of movement times and crane interferences are presented which can be used to calculate the resulting vehicle waiting times of certain schedules. A simulated annealing algorithm, which is based on these formulae, is proposed to replan the crane scheduling problem each time a crane becomes idle. Several extensive simulation experiments are conducted to compare this simulated annealing algorithm with other priority rule-based scheduling methods. It is shown that these myopic rule-based methods are outperformed by the simulated annealing algorithm – in particular for situations with high workloads.

A similar setting of the crane scheduling problem for the double system is addressed by Speer et al. (2011). But in contrast to Stahlbock and Voß (2010), they aim at minimizing the weighted sum of the vehicle waiting times in the handover areas, the crane cycle times, and the makespan of the crane operations. An optimization program for that problem is not formulated either, but several practical insights into scheduling issues and approaches at the fully automated CTA in Hamburg are given. In contrast to the greedy priority rule used at the CTA, Speer et al. (2011) propose a branch-and-bound algorithm, that is based on accurate estimations of crane movement times, to schedule a user defined number of urgent jobs to optimality with respect to the weighted objective function each time relevant scheduling information becomes known. By means of simulation experiments, the branch-and-bound algorithm is tested against different priority rules for a real-world problem instance from the CTA. It is found that the operational performance of the container storage yard can greatly be improved with the branch-and-bound algorithm – in particular during peak workloads and even when considering only a small number of most urgent jobs.

The crane scheduling problem for triple crane systems is studied by Dorndorf and Schneider (2010). They analyze the problem of scheduling and routing three gantry cranes in a single yard block to perform a given set of jobs with the objective of maximizing the crane productivities. In contrast to the other studies on ASC systems, Dorndorf and Schneider (2010) do not only address the crane assignment and sequencing. In addition, quite detailed crane routing decisions on the right of way in interfering situations and the execution of crane crossing maneuvers are connected with the crane assignment and sequencing problem. But no optimization program for the joint crane scheduling and routing problem is formulated. Instead, the problem to route cranes for a given, fixed sequence of assigned jobs so that the cranes do not interfere, is modelled as a separate discrete time program which can be linearized. For the solution of the whole scheduling and routing problem, a heuristic is developed by Dorndorf and Schneider (2010) that is based on a combination of beam search for finding promising schedules and branch and bound for optimal crane routing of promising schedules. The performance of this heuristic solution procedure is tested and evaluated in extensive simulation experiments. It is shown that commonly used rule-based scheduling and routing methods are clearly outperformed by the proposed heuristic.

An IP-based formulation of the crane scheduling for all four types of ASC systems is introduced by Kemme (2013). His model formulation, which is partly inspired by Ng (2005), aims at minimizing the waiting times for vehicles at the waterside and landside block ends. Firstly, a basic program formulation is introduced by Kemme (2013), including problem objectives as well as crane movement and scheduling restrictions applicable to all types of ASC systems. Thereafter, additional system-specific restrictions are provided, which are needed to consider the risk for crane collision and interferences among cranes correctly for twin, double, and triple crane systems. Finally, some numerical experiments are presented, which reveal that real-world problem instances cannot be solved to optimality by modern solver technology within reasonable time.

Gharehgozli et al. (2014c) address the crane scheduling problem of minimizing the makespan for a given set of storage and retrieval requests in a single yard block that is operated by twin ASCs. The problem is modelled as multiple asymmetric generalized travelling salesman problem with precedence constraints. An adaptive large neighborhood search heuristic to quickly compute near optimal solutions is developed and tested in extensive computational experiments. It is found that the heuristic obtains near optimal solutions for small problem instances, while outperforming other heuristics from practice for large instances, yielding even better solutions than CPLEX truncated after 4 h.

In another work of a similar group of authors, Gharehgozli et al. (2014b) present a method for minimizing the total travel of a single ASC to perform a given set of container storage and retrieval requests in a yard block. The problem is formulated as continuous time IP model and proven to be NP-hard. For quickly obtaining optimal solutions, a two-phase solution method is proposed. In the first phase, a merging algorithm is used to patch sub-tours of an optimal solution of an assignment problem relaxation of the full problem in a way that a complete crane tour is created without adding travel time to the optimal objective value of the relaxed problem. If no optimal solution is found, the solution of the first phase is used as a starting point for a branch-and-bound algorithm to solve the problem to optimality in the second phase. Numerical results confirm that the presented method is able to quickly solve real-world instances of the problem, outperforming nearest neighbor heuristics.

To handle real-world ASC scheduling and routing instances of the problem formulation presented by Kemme (2013), an alternative solution method is developed by Heitmann (2015) which is based on a problem decomposition. The whole problem is divided into the scheduling and routing problem, which are solved consecutively such that the result of the scheduling problem – the job assignment and sequencing – are used for the calculation of the routing problem. By means of numerical analyses the decomposition approach is found to outperform the solution of the whole mixed-integer model with commercial solvers, requiring significantly shorter computation times.

Speer (2017) introduces three alternative approaches for scheduling of all four types of ASC systems. The first approach aims at optimizing crane scheduling of a single yard block, using a branch-and-bound algorithm that incorporates several real-world aspects like crane interferences. The second approach goes further, aiming for an integrated optimization of the entire terminal system by taking the interrelations of the yard cranes with horizontal transport and quay cranes into account. The third approach is a combination of the branch-and-bound-based approach and the integrated scheduling approach. By means of extensive simulation experiments it is shown that all three scheduling approaches outperform a standard FIFO priority rule. Detailed descriptions of these scheduling approaches as well as additional simulation results are provided in the related works of Speer and Fischer (2016) and Speer (2017).

17.4.4 Operational Considerations

Similar to container stacking, the previously presented academic works and yard crane scheduling strategies may theoretically improve crane productivity and performance of the storage yard as a whole, but are in practice hardly used as such due to different reasons. Again, lacking data quality, long computation times, poor understandability, and conservative TOS systems (see Sect. 17.3.4) are main reasons for not using the above introduced scheduling algorithms. Additionally, several works are based on simplifying assumptions, such as discretization of time (see, e.g., Ng 2005 as well as Heitmann 2015) and neglect of crane interferences (see, e.g., Carlo and Vis 2008), which limits credibility of claimed performance improvements and thus reduces operational acceptance.

Several works do also not consider the online-optimization character (see, e.g., Fiat and Woeginger 1998) of the crane scheduling problem, addressing it like a classical offline optimization problem, assuming that all input data is known before applying an algorithm and will not change thereafter. In practice, the arrival times and sequences of external trucks and internal transport vehicles at the handover positions of the yard blocks are, however, highly uncertain or even unknown, thus leading to frequent updates of the input data for the algorithms. Consequently, a previously computed optimal crane schedule may turn out to be sub-optimal after new information becomes available. Hence, the additional complexity and computation time of optimal algorithms and sophisticated heuristics, as presented before, does in reality not necessarily pay-off in terms of higher crane performance. Moreover, simple heuristics and greedy priority rules are reported to provide similarly good or even better results (see Kemme 2013).

Considering the fact that RTGs are usually still operated by a driver, crane scheduling at most RTG terminals is nowadays not based on any computer algorithms, but manually decided. In fact, although performance improvements may be realized by applying intelligent algorithms, crane scheduling at most RTG terminals is controlled in cooperation with yard planner and crane operator. The yard planner assigns RTGs to certain working zones, which are often yard blocks, within which the assigned RTG shall handle all stacking requests. The assignment of working zones is usually based on the expected workload for the different yard blocks in the next shift as resulting from the vessels at berth and the stacking pattern that was previously decided by the yard planner. If required by the workload, the assignment of working zones may change throughout the course of a shift and RTGs may move to other yard blocks upon direction of the yard planner. Sequencing of stacking requests within a working zone is at the sole discretion of the crane operator, minimizing gantry travel distances while limiting waiting times for trucks.

In contrast, crane scheduling in ASC terminals is usually fully computer controlled. Depending on the IT architecture, crane assignment and sequencing of stacking requests are either decided by the TOS or the crane control system, which is in charge of all ASC movements. However, unlike most previously presented works for ASC systems, in practice less sophisticated algorithms are applied, but fast and easily understandable cost-function-based priority rules are mostly used in operation. Depending on the terminal and the underlying IT system, the cost function may consider various criteria with different weighting, including empty travel distances for the cranes, urgency of the stacking request, resulting waiting time for the horizontal transport machines, and potential interferences with other cranes.

17.5 Terminal Planning Implications of Stacking and Scheduling Strategies

Terminal planning usually refers to the design of container terminals, requiring decisions on layout as well as type, combination, and quantity of terminal handling equipment that shall be used. Despite this strategical character of terminal planning decisions, they are to some extent also affected by operational decisions on container stacking and crane scheduling as this has notable effects for the performance and efficiency of relevant resources.

In principle, terminal planning is based on static and dynamic planning tools. While static spreadsheet-based terminal planning models already provide good insights into terminal planning details such as equipment requirements, they can by nature not fully consider the complex character of a container terminal with numerous entities, several stochastic effects, and dynamic interdependencies. In contrast, dynamic simulation tools, as, for example, the terminal simulation tool HPCsim (see Fig. 17.4), can take into account all individual equipment movements and container flows with all relevant interdependencies and stochastic influences, thus accurately predicting behavior and performance of a terminal system. Consequently, simulation has become one of the most accepted and widely used tools for planning container terminals.

Fig. 17.4 Example visualization of HPCsim (see Kemme 2017)

State-of-the-art terminal simulation tools explicitly model all equipment movements on the terminal and the underlying operating strategies and algorithms. Flexible simulation tools even allow to adapt the applied container stacking and crane scheduling strategies to terminal specific framework conditions and TOS capabilities, thus being able to accurately consider the effects of alternative operating strategies on equipment productivities and to reliably predict resulting resource requirements (see Kemme 2017). In fact, as discussed in Sects. 17.3 and 17.4, elaborated container stacking and crane scheduling strategies can easily improve the performance of yard cranes by 10–20%, and thus reduce equipment requirements accordingly. In contrast, static terminal planning models and several commercial simulation tools cannot realistically consider the effects container stacking and crane scheduling strategies, but can only anticipate performance effects by means of changing productivity assumptions based on guesstimates and experience. Considering the fact that terminals usually differ significantly, such assumptions will most likely lead to sub-optimal and even wrong terminal planning decisions. Therefore, advanced terminal simulation tools are a mandatory element of modern terminal planning.

Since the storage yard is the center of the terminal where most processes originate or terminate, more than just the superstructure decisions on the storage yard are influenced by stacking and crane scheduling strategies. Obviously, the number of yard cranes needed is directly influenced by the applied strategies and the resulting crane performance. Consequently, the number of yard blocks and the layout is also influenced by the operational decisions. Moreover, the number of required transport vehicles between quay cranes and storage yard is also affected by the decisions on stacking and scheduling. Even the number of quay cranes and the dimensions of the hinterland gate facilities are to some degree implicitly influenced by these decisions. Subsequently, these connections are illustrated with some small numerical instances.

Assuming ten quay cranes are simultaneously working at 30 moves per hour each in peak situations, and thus a total ASC performance of 300 moves/h is required at the waterside block ends, then an increase in the yard crane productivity, e.g. by improved scheduling, from 15.00 to 16.67 moves/h may reduce the number of required ASCs by 10%. Alternatively, one can assume that such an improvement in the ASC productivity enables an increase in the average stacking height from 3.75 tiers to 4.00 tiers without any performance losses involved. Consequently, in a storage yard with a required capacity of 30,000 TEU, the number of ground slots can be reduced by 500 slots. Consequently, the block layouts can be modified, allowing for savings in required storage area. Furthermore, by improving the yard crane punctuality at the waterside by 30 s per job on average, 120 min of AGV operation time can be saved per hour, if 16 yard blocks are in operation with an average of 15 waterside jobs per hour each, which would allow to reduce the AGV fleet size by two units. But since a container terminal is a very complex system, these numerical examples are overly simplified insofar as not all effects and interdependencies of operational improvements and system changes are considered.

However, in summary, it has been shown that operational strategies for container stacking and crane scheduling, as studied here, indeed have remarkable effects on terminal planning decisions. By reducing shuffle moves, empty driving times and crane interferences, the crane productivity and punctuality can be improved, leading to reduced area and equipment requirements, not just for the storage yard, but also for the related subsystems.

17.6 Summary and Conclusions

The operational planning problems of container stacking and yard crane scheduling for state-of-the-art RTG and ASC systems at seaport container terminals are addressed in this work. Following the initial discussion of differences in storage yard operations, for both problems objectives and relevant restrictions are identified, literature overviews on existing planning strategies and methods are given, and these approaches are critically discussed regarding their practical relevance.

For the stacking problem, the minimization of shuffle moves is identified as principal objective, while yard crane scheduling mainly aims at maximizing the yard crane productivity and minimizing the waiting times for horizontal transport vehicles. For both operational planning problems and yard crane systems a whole lot of academic works is identified and reviewed, presenting sophisticated strategies and algorithms to improve storage yard performance. Based on the author's industry experience from many years of terminal planning and optimization all around the world, it is, however, noted that hardly any of these academic approaches is in practice applied as such. Several reasons for this gap between research and practical application are listed, which can be subsumed as a lack of practicability on the research side and only moderate willingness for innovation on the terminal side, and commonly applied stacking and crane scheduling approaches for RTG and ASC systems are briefly outlined.

Finally, the effects of container stacking and crane scheduling decisions on strategical terminal planning are explained. It is concluded that decisions on both operational planning problems have significant effects on several strategical terminal planning decisions. Not just layout and equipment decisions for the storage yard are affected, also equipment decisions for the related subsystems are notably influenced by these operational storage yard problems.

Considering the huge optimization potential in container stacking and crane scheduling, which may lead to notable savings in terminal investments and operating costs, more efforts for closing the gap between research and industry application seem to be required. In particular, in view of terminal overcapacities and increasing competition between container terminals in several regions of the world, the use of more advanced container stacking and crane scheduling strategies offer an efficient way to improve terminal performance and to meet today's challenging market requirements (e.g., increasing vessel sizes) at comparable low costs. Therefore, researchers should, on the one hand, more accurately consider practical requirements, which would at the same time increase the acceptance by terminal operators. On the other hand, the port industry should be more willing to think out of the box and to also accept innovative and sophisticated algorithms that are not easily understandable.

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Chapter 18
Comparison and Optimization of Automated Yard Crane Systems at Container Terminals

Ulf Speer and Kathrin Fischer

Abstract In this chapter, four different automated *R*ail-*M*ounted *G*antry (RMG) yard crane systems – Single RMG, Twin RMG, *D*ouble RMG (DRMG) and *T*riple RMG (TRMG) – are compared with respect to their characteristics and performance. Furthermore, different approaches for their scheduling are presented: On the one hand, a branch-and-bound procedure for single yard block optimization which incorporates important aspects like crane interference, and on the other hand, an integrated scheduling approach which optimizes the equipment at terminal yard and waterside simultaneously, taking the interrelations with horizontal transport and quay cranes into account. Moreover, a combination of the two approaches is studied. Using a specifically designed simulation model, both the crane systems and the different scheduling approaches are extensively examined with respect to their performance and practical use, e.g. in case of disturbances. Standard priority rules (e.g. First-IN-First-OUT) serve as a benchmark here. It turns out that both approaches are advantageous compared to simple priority rules, and that the crane systems with overtaking possibility are well-adaptable, optimizable, flexible and productive. Moreover, it can be concluded that optimization aspects should already be taken into account in the terminal planning phase, in order to reach optimal productivity levels later on.

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18.1 Introduction

In the last decade, the planning and development of new container terminals have shown a strong trend to automation. Particularly in countries with high wage level, terminal equipment for container transport and handling is more and more operated without direct human involvement. This does not only hold true for the horizontal transport which is frequently carried out by *A*utomated *G*uided *V*ehicles (AGV), but also for yard crane systems. In contrast to manually operated *R*ubber-*T*yred *G*antry (RTG) cranes where yard blocks are usually arranged parallel to the quay, automated yard cranes are rail mounted and operate on blocks perpendicular to the quay until today (see Fig. 18.4). In this case, the transfer of containers between RMG cranes and other vehicles takes place at the head of the yard block and allows for a fully automated operation inside the yard block and (in case of automated horizontal transport) also on its waterside. Furthermore, automated yard cranes allow for a higher stacking of containers in the yard than, e.g. straddle carriers or reachstackers, which is important particularly when terminal space is limited.

For RMG-based yard crane systems with perpendicular block orientation, the integration of the storage area in all the main processes of the container terminal may lead to problems. Hence, when technical improvements of other terminal devices take place, e.g. when multiple-load (see Stahlbock and Voß 2008) or dual cycle options (Goodchild and Daganzo 2006; Song 2007) or additional devices for horizontal transport are added, the handling requirements increase for the yard system. In this case, the number of stacking cranes within the yard area may become the bottleneck of the terminal, since additional cranes cannot be put into operation without bigger efforts (i.e. not without building new RMG blocks). Therefore, concerning automated RMGs for yard operations, the choice of an adequate variant of this crane system type is an important issue for terminal planning, and the scheduling of yard cranes and the synchronization with the devices of the surrounding terminal (sub-)systems are important criteria for the choice and customization of the *T*erminal *O*perating *S*ystem (TOS).

Currently, four variants of the automated RMG yard system are in use on container terminals. This chapter focuses on the comparison of these four system variants and quantifies their potential with respect to two different scheduling approaches, a block-wise optimization approach and an integrated optimization approach. In particular, it is investigated which impact the different approaches have on quay crane productivity and how disruptions may influence the different crane systems' performance.

The rest of the chapter is organized as follows: Sect. 18.2 describes the four RMG system variants with their operational characteristics. Furthermore, a definition of the scheduling problem considered in this work is given. In the literature review in Sect. 18.3, different approaches for yard crane and integrated scheduling are discussed and in Sect. 18.4, details of the approaches evaluated in this work are presented. Section 18.5 provides details of the simulation model used, and in Sect. 18.6, simulation results for the different crane systems and their scheduling are discussed and compared. Section 18.7 provides a conclusion and suggestions for further research.

18.2 Yard Crane Systems and Their Scheduling

In recent years, four variants of the automated RMG system with transfer positions at both heads of the block have been established. In the planning phase of an automated container terminal, the terminal operator has to choose one of these variants, if automated RMGs are selected for yard operations. In this section, the four crane systems are compared with respect to their number of cranes and rails, resulting space requirements and maintenance aspects. Moreover, the size of the yard block, cost aspects and the complexity of the necessary control system may be important decision criteria. A comparison with respect to performance and effectiveness will be given in Sect. 18.6.

18.2.1 Automated RMG Variants for Yard Operations

18.2.1.1 Single RMG

The Single RMG (see Fig. 18.1, left) is the simplest and cheapest possible automated yard crane system, which is currently used at the ECT Delta Terminal in Rotterdam, Netherlands (see Saanen 2004). Only one crane serves the entire block including quay and landside operations. Hence, crane interference is not an issue (see Speer et al. 2011) and therefore the crane can work efficiently and without a sophisticated control system. A small size of the yard block should be chosen with respect to the limited block handling capacity that can be achieved by one crane in comparison to system variants with more RMGs per block. Therefore and due to the single pair of rails, this system has only moderate space requirements. However, when the crane fails, the containers of the respective block are no longer accessible.

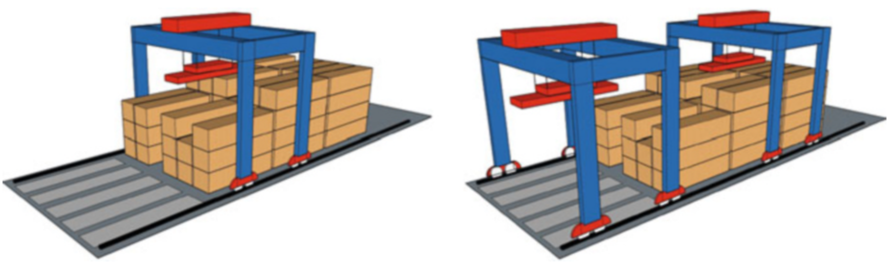

Fig. 18.1 Single RMG (left) and Twin RMG (right), see Speer (2017)

18.2.1.2 Twin RMG

In the Twin RMG system (see Fig. 18.1, right), two identical cranes operate in each yard block. One is responsible for the quayside and the other for the hinterland, which allows adequate service levels on both ends of the block (Gharehgozli et al. 2013). However, in peak situations on one side of the block, which for transshipment terminals occur particularly on the quayside, productivity is more limited than in the case of those system variants where cranes can overtake each other on a second rail (see below). Nevertheless, the Twin RMG system provides significantly higher block productivity than the Single RMG, but does not need additional space, except for a maintenance position on each side of the block which is required due to the missing ability of cranes to pass each other. This allows the continuous service of the block in the case of a failure of one of the cranes. Twin RMGs are in use at Virginia International Gateway (VIG), Virginia/USA (see Kemme 2012), at the DP World Antwerp Gateway, Belgium and at Euromax Terminal, Rotterdam/Netherlands (see Johnson 2007).

18.2.1.3 DRMG

In the DRMG system, one crane has a higher and wider portal than the other crane and operates on a separate pair of rails (see Fig. 18.2, left). This design enables the cranes to pass each other, after the trolley of the large crane has been moved to a sidewise transfer position. Depending on the exact design, this may only be necessary when the large crane carries a container. The overtaking possibility allows both cranes to operate on both sides of the block and provides higher productivities in peak situations at one side of the yard block. Furthermore, based on authors' experience, reliability of the yard block and the terminal performance are improved, since if one crane fails, the other crane can access most parts of the yard block and continue the service without moving the broken crane to a maintenance position

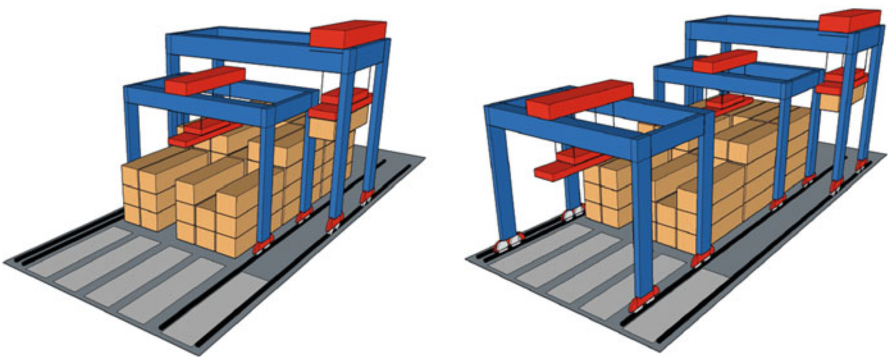

Fig. 18.2 DRMG (left) and TRMG (right), see Speer (2017)

(however, when the large crane fails, its gantry has to be moved to the transfer lane.) Only one maintenance position is needed in this variant, but the additional pair of rails and the sidewise transfer lane require additional space. Furthermore, the second, larger crane and the rails incur additional costs. Finally, due to the overtaking possibility, a complex control system is required, which may also result in higher costs.

Currently, DRMGs are in use at the HHLA *C*ontainer *T*erminal *A*ltenwerder (CTA), Hamburg/Germany (see Stahlbock and Voß 2010 as well as Speer et al. 2011). The technical parameters for this crane system are provided by Koch (2004) as well as Speer and Fischer (2016). These settings are similar to those used for the comparison in Sect. 18.6.

18.2.1.4 TRMG

The TRMG system is a combination of the Twin and DRMG system (see Fig. 18.2, right). Three cranes operate on a yard block, two small cranes on the same rail (similar to the Twin RMG) and a third, large crane drives on a separate pair of rails (similar to the large crane of the DRMG). This allows for high productivities in peak situations, also when they occur simultaneously on both sides of the block. Also in case of crane failures, the block can achieve a high service level. This allows for a larger yard block layout, especially for longer blocks, which enable unhindered work of the three cranes. On the other hand, there are considerable initial costs for the three cranes, the requirement of a highly sophisticated control system (see Kemme 2011) and the additional space requirement for a second maintenance position. TRMGs are used at the HHLA *C*ontainer *T*erminal *B*urchardkai (CTB), Hamburg/Germany (see Dorndorf and Schneider 2010 as well as Kemme 2011).

Table 18.1 summarizes the characteristics of the different crane systems, as far as discussed above. Productivity is not listed in Table 18.1 as this aspect is part of the study presented below.

Table 18.1 Comparison of automated yard crane systems

Criteria	Single RMG	Twin RMG	DRMG	TRMG
Space requirements and block size	Small	Medium	Medium	Large
Reliability	Low	Medium	Medium/high	High
Flexibility	Low	Medium	High	Very high
Control complexity	Low	Medium	High	Very high
Costs	Low	Medium	High	Very high
Example	ECT Delta Terminal, Rotterdam	VIG, Virginia; DP World Antwerp Gateway, Antwerp; Euromax Terminal, Rotterdam	CTA, Hamburg	CTB, Hamburg

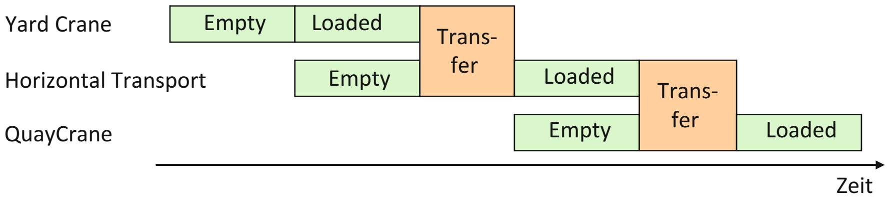

Fig. 18.3 Requirements of synchronization of transfers in a multi-stage transportation process (here: transport moves of a container from yard to quay crane)

18.2.2 Approaches for Yard Crane Scheduling

As described in the previous sections, yard cranes are an important part of the transport chain on a container terminal and are likely to form a bottleneck of the terminal. Hence, the scheduling of these devices is a major optimization problem. From the terminal operator's point of view, one of the main objectives is a high service level for the different modes of transport. Often, the focus is on the quay crane and ship productivity (see Carlo et al. 2014 as well as Grunow et al. 2006), but also service times for truck and train operations gain increasingly in importance (see Park et al. 2010; Stahlbock and Voß 2010 as well as Steenken et al. 2004). For reaching these aims, synchronization of the transport and handling devices constituting the container transport chain on a terminal is necessary, which is a complex problem (see Lau and Zhao 2008). This is illustrated in Fig. 18.3 for a loading transport.

Therefore, a common approach is the decomposition of this problem into smaller subproblems, e.g. the scheduling of the yard cranes of a single yard block or the scheduling of the horizontal transport vehicles. The respective subproblem can be modeled in more detail and can be specifically optimized, but on the other hand, direct usage of the above-mentioned terminal operator's objectives is often not possible, e.g. when quay cranes are not part of the considered terminal devices, their productivity cannot be optimized directly. In this case, due dates can be calculated for the transfer times between the interacting devices and their violation or the productivity of the devices, e.g. yard cranes, can be used as an objective of the subproblem (see Choe et al. 2007). Nevertheless, a good solution of the entire problem cannot be guaranteed by this decomposition approach (see Chen et al. 2013) and Briskorn et al. 2006 find that direct optimization criteria are preferable.

In this work, two different approaches are compared: The detailed scheduling of the yard cranes of each single yard block (decomposition, see continuous red rectangle in Fig. 18.4) and the integrated scheduling of all yard blocks, the waterside horizontal transport and the quay cranes (see dotted green frame in Fig. 18.4). While the first approach means to consider a subproblem in the sense described above, the second approach allows for a direct consideration of the terminal objectives and an integrated optimization of the container transfer operations between the transport and handling devices involved. With this approach, the composition of different

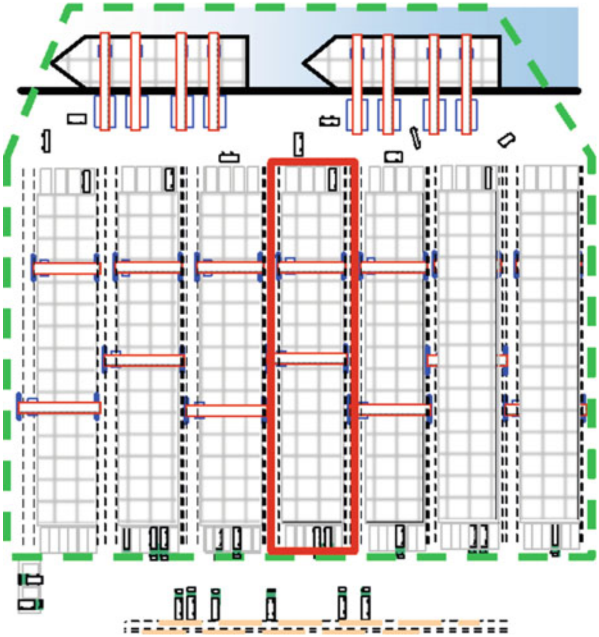

Fig. 18.4 Focus of the scheduling: block-wise approach (continuous red frame) and integrated approach (dotted green frame)

subproblem solutions is avoided. On the other hand, integrated approaches may have issues with higher complexity of the problem and resulting (longer) computation times.

18.2.3 Problem Definition

Taking into account the previous considerations, the scheduling problem for this work can be defined as follows:

A set of terminal devices, containing yard cranes, quay cranes and horizontal transport equipment, and a set of jobs for these devices are given. The problem is to find a feasible assignment of the jobs to the devices and a sequence of jobs for each device that is feasible according to given predecessor relations (e.g. for reshuffle moves at yard cranes and for loading moves at quay cranes), such that the weighted sum of a set of objectives is optimized.

For the integrated problem, the set of objectives contains the maximization of quay crane productivities and the minimization of the quay cranes' makespan, the yard cranes' cycle times and the lateness for hinterland moves. In case of problem decomposition, if the quay cranes are not part of the considered devices (for the block-wise optimization), the quay cranes' productivities and makespan are substituted by the minimization of yard cranes' lateness relative to due dates, which are derived from the quay crane work sequences. As at a terminal not all relevant jobs are given from the beginning, but become only known over time, the problem can be considered to be an "online problem" (Grötschel et al. 2001), requiring information updates on a regular basis.

18.3 Literature Review

A lot of research has been done on the optimization of container terminals in recent years. Steenken et al. (2004) were among the first to give an extensive overview and a widely accepted classification of the relevant optimization problems. Stahlbock and Voß (2008) provide an update, which focuses more on automation and newer technologies like dual cycle operations. Furthermore, the authors present an overview of crane scheduling approaches for yard cranes. An overview of current research on yard handling equipment and optimization strategies is presented by Carlo et al. (2014). They give a classification of the different approaches with respect to several aspects like yard crane layout, crane system and objectives of optimization.

18.3.1 Comparison of Automated Yard Crane Systems

Only a few authors compare the different automated crane systems which were described in Sect. 18.2. Saanen and van Valkengoed (2005) identify land requirements and flexibility of the crane systems as important decision criteria. They find that Twin RMGs allow for a higher throughput capacity on a given terminal space than DRMGs. Kemme (2012) as well as Kemme (2013) considers all four variants of the automated RMG system and describes their main characteristics. Furthermore, a simulation model is used to compare the RMG system variants with respect to their service times for various yard block dimensions. It turns out that Twin RMG systems attain lower service times than the DRMG system for wider yard blocks, while TRMGs outperform the other crane systems, especially for longer yard blocks.

18.3.2 Scheduling Approaches for Different Yard Crane Systems

Different scheduling approaches and results on crane scheduling have been presented in the literature. Choe et al. (2007) as well as Park et al. (2010) compare different algorithms for the scheduling of Twin RMGs by means of waiting times of the horizontal transport. They discover that treating reshuffles as independent moves has a positive effect on service times.

Stahlbock and Voß (2010) as well as Speer et al. (2011) evaluate the scheduling of DRMGs using the example of the CTA. Both integrate the minimization of lateness and empty drives into the objective. Moreover, Speer et al. (2011) compare cycle times with operational data from CTA and emphasize that crane interference is a considerable part of the cycle times, especially in situations with technical breakdowns.

In contrast to this, Vis and Carlo (2010) develop a mixed-integer linear program for the scheduling of DRMGs and use the makespan as the only objective. They neglect reshuffles and assume that the sequence of jobs has no influence on their duration. The authors develop a heuristic based on simulated annealing and state that only few crane interferences occur with their test data. This might be due to the special assumption that the small crane can pass while the large crane is working on the stack.

Dorndorf and Schneider (2010) describe a beam search algorithm in which the weighted sum of the mean tardiness, crane driving and interference times is considered as the objective. They attain an increase of yard crane productivity between 20 and 30% compared to simple priority rules.

Petering et al. (2009) use a simulation model to compare different priority rules for the yard crane scheduling problem. Major findings are that retrieval moves should be prioritized against the storage of containers and that consideration of truck arrivals is an important issue for yard crane scheduling.

Speer and Fischer (2016) use a branch-and-bound procedure with an adapted search strategy and apply this approach to all four RMG system variants described in Sect. 18.2. This procedure is one of the optimization approaches for which simulation results are presented in Sect. 18.6. A similar approach is used by Guo et al. (2011), who suggest a tree search algorithm for the scheduling of a Single RTG.

18.3.3 Integrated Optimization Approaches

As stated above, integrated optimization approaches combine more than one optimization problem and aim to find a good (or optimal) solution for the entire problem. One integrated approach in the field of container terminals is the integrated optimization of handling equipment and stacking allocation in the container yard. Gharehgozli et al. (2013) suggest such an algorithm for Twin RMG scheduling and determination of stacking positions for inbound containers using the makespan as the objective. Lee et al. (2011) as well as Ya et al. (2010) provide a similar approach for RTGs which have special requirements for stacking positions. Lee et al. (2011) use a simulated annealing approach while Ya et al. (2010) use a Lagrange relaxation-based procedure.

Another option is the integrated optimization of yard cranes and other handling equipment, e.g. horizontal transport and quay cranes. Lau and Zhao (2008) develop a mixed-integer linear program for this problem and use the minimization of AGV- and yard crane driving times and of the quay cranes' delays as the objectives in a multi-criteria approach. Fereidoonian and Mirzazadeh (2012), He et al. (2015) as well as Chen et al. (2007) and Chen et al. (2013) also develop approaches for similar three-stage problems and use genetic algorithms or a decomposition of the problem for the solution.

18.3.4 Conclusions from the Literature Review

As can be concluded from the literature review above, the different crane systems for container terminals have been studied in various degrees of detail, but hardly any comparison of all automated RMG system variants exists, apart from Kemme (2011) and Kemme (2012), who mainly studies the influence of the block size on performance. In particular, the relevance of crane interference and disturbances on the system's performance has not yet been studied, nor have integrated and non-integrated optimization approaches been compared. These aspects are in the focus of the study presented below.

18.4 Scheduling Approaches

In this section, the scheduling approaches and some important assumptions are described which are used to derive the results presented in Sect. 18.6. The scheduling approaches are on the one hand, two priority rules which are used as a reference, and on the other hand, the two optimization approaches already mentioned in Sect. 18.2.2. For the latter two, also a combination is provided.

Priority Rules

1. FIFO: An advanced FIFO algorithm (*F*irst-*I*N-*F*irst-*O*UT) is used for the scheduling of all terminal devices. Within this rule, the oldest job is always assigned to the next free device (see Petering et al. (2009)). If more than one device is free, the job is assigned to the device with the shortest empty drive that is needed to reach the starting position of the job.
2. EDD: An advanced EDD algorithm (*E*arliest *D*ue *D*ate) is used for the scheduling of all terminal devices. Within this rule, the most urgent job is always assigned to the next free device (see Lau and Zhao (2008)). If more than one device is free, the job is assigned to the device with the shortest empty drive needed to reach the starting position of the job.

Optimization Approaches

3. BBCI (*B*ranch-and-*B*ound procedure for block-wise optimization considering *C*rane *I*nterference, combined with advanced FIFO algorithm for horizontal transport): A branch-and-bound procedure is used for the assignment of the jobs to the yard cranes. All feasible job sequences for the six most urgent jobs for each yard block are evaluated (or discarded during the branch-and-bound process) by use of an iterative construction of job sequences. Job duration and the resulting lateness are estimated with a high degree of detail for each job (bounding), e.g. taking driving times and crane interference into account. A separate optimization is carried out for each yard block. The advanced FIFO algorithm is used for the assignment of jobs to horizontal transport vehicles. Further details of the branch-and-bound procedure can be found in Speer and Fischer (2016).
4. IntOpt (*Int*egrated *Opt*imization of RMGs, quay cranes and AGVs): A mixed-integer linear model is formulated and solved with CPLEX.[1] The model includes up to 200 container moves which are known to be executed at the terminal. The solution is used to construct job sequences for the yard cranes of all blocks, the waterside horizontal transport and the quay cranes (assuming that the quay crane's job sequence can be changed to a certain degree for loading and horizontal transport devices are exchangeable for discharging moves). The approach is based on the assumption that all yard jobs can be carried out by all cranes of the respective block which prohibits its application for the Twin and TRMG system. Further details of the integrated optimization approach can be found in Speer (2017).
5. IntOpt_BBCI: A combination of the IntOpt approach and the branch-and-bound procedure for each block is used for the scheduling. The integrated optimization of equipment is used for the scheduling of jobs for horizontal transport devices and quay cranes. Furthermore, tentative job sequences and due dates for the yard cranes' jobs are generated and used as input for the branch-and-bound procedure for each yard block. Yard cranes are scheduled according to the results of this method, which allows the application of the IntOpt_BBCI approach also for Twin and TRMG. Further details for the combined optimization approach are provided by Speer (2017).

The scheduling problem described in Sect. 18.2.3 is a multi-objective problem. There are usually several non-dominated solutions for such problems (Ehrgott 2006) and a human operator is needed to choose one of them. However, this approach to problem solving is not reasonable for an automated terminal, where due to the real time requirements of the problems, a solution is needed within several seconds to avoid waiting times (see Grötschel et al. 2001 as well as Kemme 2011).

For the optimization approaches described above, the weighting method is used to transform the problem into a single-objective problem (see Ehrgott 2006, p. 345). As the solution of this problem is a non-dominated solution for the respective multi-

[1]CPLEX is a commercial optimization software package (standard solver). The software is named for the simplex method being implemented in the C programming language.

objective problem (see Ehrgott 2006, pp. 244–245), it can be used for the automated scheduling. This approach is also discussed by Carlo et al. (2014) and used, e.g. by Lee et al. (2011) as well as Skinner et al. (2013). Suitable weights for the weighting method can be determined by a sensitivity analysis which is presented by Speer (2017).

18.5 Simulation Model

The simulation model which is used to evaluate the different optimization approaches is described briefly in this section. Simulation has become a standard tool to evaluate planning and optimization approaches on terminals, as an analytical examination is hardly possible due to the high complexity of the problems and the many interdependencies between the different transport and handling devices on a terminal. In contrast to field experiments which are only possible for existing terminals, computer simulations guarantee reproducible starting conditions without external influences. Hence, they allow for an efficient (quantitative) evaluation of optimization approaches and crane systems in realistic data settings (see Saanen and van Valkengoed 2005). Moreover, data settings for future scenarios can be used to consider estimated changes of cargo volumes or changes of the vessel call pattern (see Hartmann 2004).

In the simulation setting used in this work, there are eight quay cranes at a berth of 800 m length available for the loading and unloading of the containers. For the horizontal transport between the quay and ten yard blocks, an AGV system with synchronous transfer is used. Each block is fitted with an automated RMG system and containers are stacked perpendicularly to the quay wall in 37 bays and 10 rows, up to 4 containers high. Four AGV/RMG transfer lanes are installed on the quayside of each block, while on the landside, there are three transfer lanes for internal rail chassis and four lanes for external trucks. Relevant parameter settings as well as scenario descriptions can be found in Speer and Fischer (2016). Further implementation details are given in Speer (2017).

All simulation results presented in the following section were derived as the mean of five simulation runs, as it turned out that five runs already produced very stable results. In each run, 5000 container moves were executed on a pre-allocated container yard. The performance results did not vary much after the first 1000 moves for the 5 repetitions, and therefore sufficient reliability of the results is given (see Lorscheid et al. 2012).

18.6 Comparison of Crane Systems and Scheduling Approaches

18.6.1 Planning Horizon, Stability and Computing Times

Prior to comparing the scheduling approaches, the planning horizon for the scheduling – i.e. the number of jobs to be taken into account in the branch-and-bound procedure – has to be defined. On the one hand, a longer horizon allows more "freedom" for the optimization as it extends the solution space, and hence may lead to better results. On the other hand, the number of possible solutions grows factorial with the number of jobs (see Speer 2017) which can make it difficult to find an optimal solution and leads to increasing computing times.

Speer and Fischer (2016) show that at least three jobs per crane should be considered to exhaust the potential of the branch-and-bound procedure (i.e. 6 jobs for a DRMG block, see Sect. 18.4) and that in this case computing times stay on a moderate level of only a few seconds. Considering more jobs leads to raising computing times, but the results do not improve significantly.

Moreover, due to the online aspects of the problem, information about future jobs (e.g. their likely start times and durations) becomes more and more uncertain for longer planning horizons and additional jobs may occur. This results in a higher probability that calculated job sequences will not remain stable in the future. Grunow et al. (2006), Petering et al. (2009) as well as Speer and Fischer (2016) address further features of the online problem, e.g. the importance of arrival information for horizontal traffic, and deadlock problems.

The aspects discussed above become visible in Table 18.2 where the stability of job sequences which have been calculated with the branch-and-bound procedure is shown for the DRMG. The results illustrate that taking into account too many jobs when planning the job sequences does not make sense, as most of the jobs do not remain at the position of the sequence for which they were originally scheduled. For example, the sixth position in a sequence will only be determined in 0.3% of all cases, and this will also be the final position of the respective job in only 18.8% of these cases, while in all other cases, the position will change again. Hence, calculating long job sequences is not useful, as often the jobs' positions will change again later in the procedure.

Table 18.2 Stability of job sequences of the branch-and-bound procedure

Position in sequence	2	3	4	5	6
Determined in schedule	99.8%	90.1%	47.5%	7.5%	0.3%
Correct	61.5%	34.1%	22.0%	19.0%	18.8%
Swapped with other crane	0.1%	0.1%	0.1%	0.0%	0.0%
Wrong	38.4%	65.8%	77.9%	81.0%	81.3%

Due to the low stability of (longer) job sequences, the branch-and-bound procedure is executed each time a crane finishes a job or when a new job comes up while a crane is available. This approach is also suggested by Grötschel et al. (2001) who call it "replan".

For the integrated and combined optimization approach, this replan approach is not possible because the computing times for a solution with acceptable quality increase to 30 to 40 s (see Speer 2017). Hence, the related algorithm is executed every 60 s only. In the meantime, the results of the last optimization run are used for job assignments when a device becomes available (see ignore-strategy at Grötschel et al. 2001). In many cases, an optimal solution cannot be found in the time mentioned above and the gap between the solution's objective function value and the bound calculated by CPLEX would allow for further improvement of the results. Future research can focus on this issue. Nevertheless, the non-optimal solutions found by the integrated optimization approach can be used to estimate its minimal potential and to compare it with the other approaches in the following section.

18.6.2 Comparison of Different Scheduling Approaches

As quay crane productivity is one of the most important optimization criteria in terminal optimization, this aspect is the first to be considered.

In Fig. 18.5, the efficient quay crane productivities resulting from the different scheduling approaches are shown for the DRMG and varying numbers of AGVs. For this key figure only the productive time of a quay crane (i.e. times when a job exists for a crane) are taken into account for the denominator of the productivity quotient. This allows for the application of this measurement to realistic scenarios in which not all quay cranes are continuously busy.

In Fig. 18.5, the numbers of quay crane moves per hour which are achieved by the different approaches are shown below the graph in the very same order as the procedures are listed in the figure's legend. It is obvious that all three approaches presented in this work (BBCI as well as IntOpt and IntOpt_BBCI approach) are superior to the advanced FIFO algorithm and lead to an 8–30% higher productivity.

For large numbers of AGVs, the BBCI approach (3) shows the best productivity results. This makes sense as in this situation the RMGs are the bottleneck of the terminal and hence a specific RMG optimization can be most effective. For low numbers of AGVs, i.e. when the AGVs constitute the bottleneck, the IntOpt approach (4) shows (slightly) better results than BBCI, while for large numbers of AGVs the integrated optimization of equipment is not particularly successful. For small and average AGV numbers, the combined IntOpt_BBCI (5) shows the highest performance and leads to an increase of 21–30% in productivity, compared to the FIFO algorithm, and it is only slightly worse than BBCI in the situation with a large number of AGVs. The latter may be due to the fact that transfer lanes are not explicitly modeled in the integrated optimization approach, which becomes an issue for large numbers of AGVs in particular. Analysis has shown that sometimes

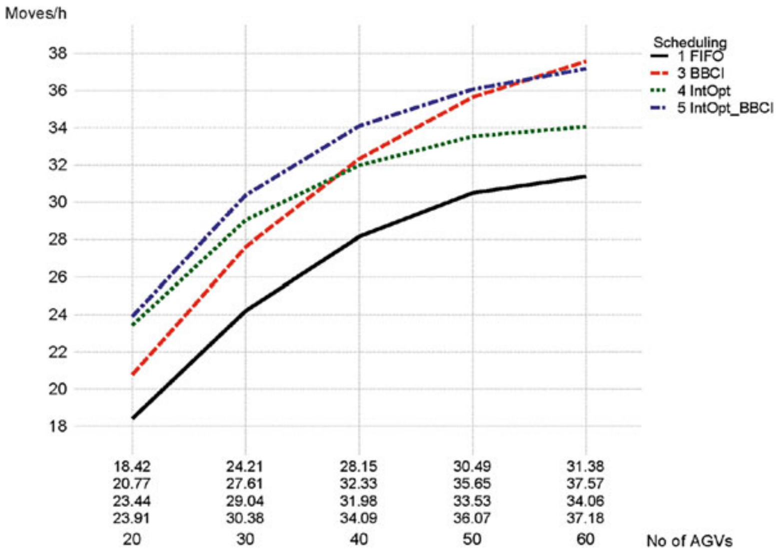

Fig. 18.5 Efficient productivity of quay crane in relation to number of AGVs for the different optimization approaches for the DRMG

more AGVs are sent to a yard block by the IntOpt approach than transfer lanes are available in the simulation and this limits the loading productivity of quay cranes compared with the BBCI. Nevertheless, the combined optimization approach (5) dominates the other approaches for most settings.

18.6.3 Comparison of Different RMG System Variants

In this section, the effect of the different optimization approaches on quay crane productivity is studied for all yard crane systems (see Sect. 18.2.1), keeping the number of AGVs constant (40). The IntOpt approach is not considered here because it is not applicable for Twin and TRMG systems (see Sect. 18.4). Instead of that, the EDD algorithm (earliest due date) is added as a more realistic reference.

It turns out that the efficient productivity of the QCs increases with the capabilities of the crane system, as the TRMG reaches the highest, and the Single RMG leads to the lowest QC productivity (see Fig. 18.6). Twin- and DRMG are to be found in between, with the DRMG being better than the Twin system.

As also can be seen from Fig. 18.6, the productivities of the priority rules FIFO and EDD differ only a little, with the EDD being slightly superior. Productivity increases for all four crane systems when BBCI is used, but this is less pronounced for the Twin system than for the remaining RMG systems.

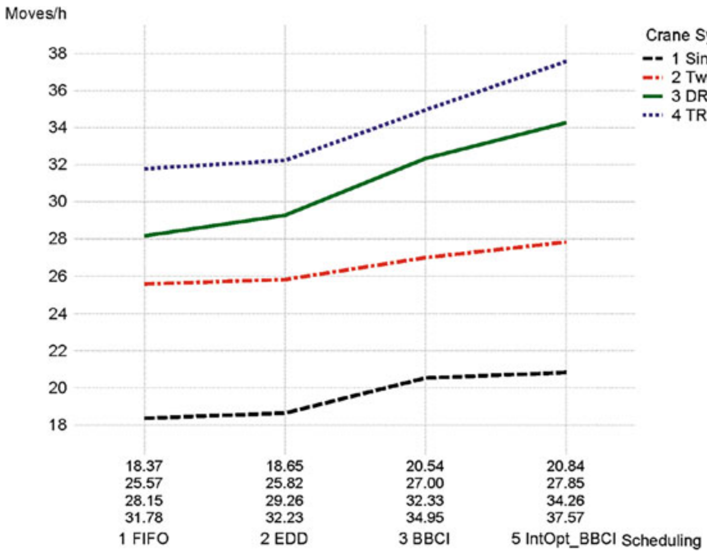

Fig. 18.6 Efficient productivity per quay crane for different RMG systems and for various optimization approaches

The combined optimization approach (5) only leads to further (significant) improvements for the DRMG and the TRMG, while it does hardly have an effect for the Single RMG, as in this case the RMG is the bottleneck of the terminal (due to its low capability) anyway. Also for the Twin system, the positive effect is less pronounced. The reason may be the assumption of the IntOpt approach that all jobs can be carried out by all cranes, which does not hold for this system, and may lead to unrealistic sequences and due dates as input for the branch-and-bound procedure. However, the productivity improvement that can be achieved through the IntOpt_BBCI approach compared to the priority rules (1, 2) is between 8% for the Twin RMG and 17% for the DRMG and TRMG. Hence, it turns out that the crane systems with an overtaking option show a clearly higher optimization potential.

For a comprehensive assessment of the productivity gains shown above, the waiting times in the hinterland also have to be considered. Since this is also an important key figure of the terminal, the water side gain must not be at the expense of the land side. Analysis has shown that the truck waiting times are very sensitive to changes in the weight of the respective objective and long waiting times can occur. A dynamic adjustment of the weight, i.e. a higher weight of the objective for jobs which are already delayed, could be shown to be a good approach to resolve this issue. Hence, it was used for the results presented in this work; this leads to lower truck waiting times than the advanced EDD algorithm. Details for the dynamic weighting and simulation results for the waiting times are found in Speer (2017).

18.6.4 System Behaviour Under Disruptions

Both, the BBCI and the IntOpt approach, highly rely on the accurate estimation of job durations. But due to temporary disruptions, traffic disturbances on the AGV-Layout, different weather conditions and human interactions, correct estimations are actually impossible under real conditions. Hence, in this section the effect of disruptions on crane productivity is examined using the example of DRMGs. In the simulation, this is carried out by successively raising the probability of RMG and AGV breakdowns, i.e. reducing the devices' availability.

Crane breakdowns and incorrect estimations of crane driving times may result in more crane interferences. Therefore, the number of crane interferences per move is illustrated in Fig. 18.7 for the different scheduling (optimization) approaches.

As expected, the number of RMG interferences grows with the number of disruptions. Nevertheless, the growth is only moderate. Furthermore, it becomes obvious that the branch-and-bound procedure, no matter if in combination with IntOpt or with FIFO, leads to considerable reductions of interferences. Hence, it can be stated that the branch-and-bound procedure leads to unhindered work and productive RMG behaviour, even if disruptions occur. This fits in with the results of Speer et al. (2011) and Grunow et al. (2006), who also note that the algorithms they study are rather robust with respect to bad data prognoses and large variations in the devices' driving times.

Figure 18.8 shows the productivity of the QCs in relation to RMG availability. The combined optimization approach (5) leads to the highest productivity in all

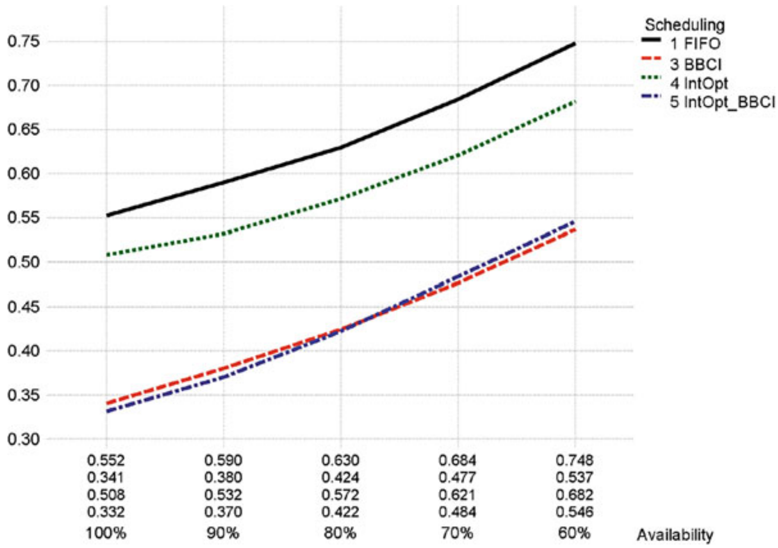

Fig. 18.7 Average number of RMG interferences for different availability of the devices and the different optimization approaches for the DRMG

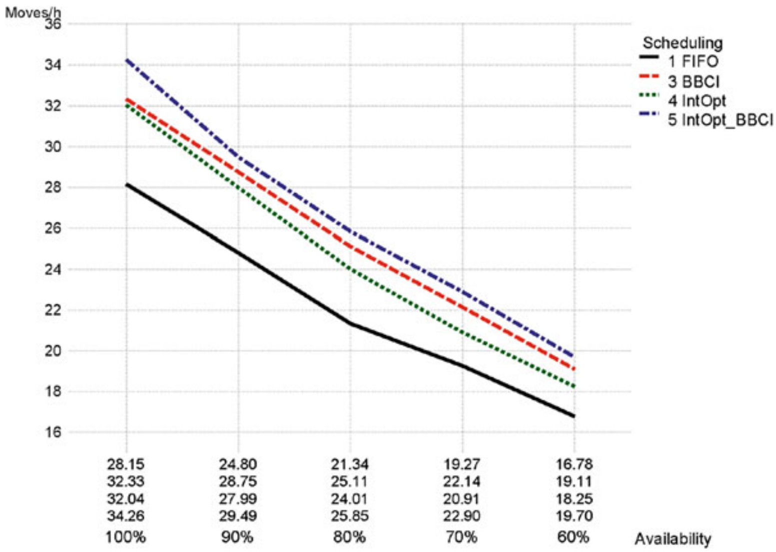

Fig. 18.8 Efficient productivity per quay crane for different availability rates of the devices and the different optimization approaches for the DRMG

cases, also in the case of disruptions. However, the improvement that can be gained by this approach compared to FIFO decreases from 22% (without disruptions, i.e. 100% availability) to 17.5% in the case of low (60%) availability, i.e. disruptions have a negative impact on performance enhancement. Again, the BBCI approach performs very well in all cases, leading to 14–15% better results than FIFO with and without disruptions.

18.7 Summary and Future Research Prospects

The optimization approaches discussed in this work show a large potential with respect to increase in quay crane productivity. For the branch-and-bound procedure, the consideration and integration of crane driving times and the resulting interferences into a more sophisticated procedure are worthwhile and lead to considerably less interferences and improved crane productivity for all systems with more than one crane, compared to the well-known priority rules.

When RMGs are the bottleneck, the branch-and-bound procedure for single yard block optimization (combined with FIFO) is advantageous, while the integrated optimization of equipment leads to better results when the means of horizontal transport (here: AGVs) are scarce. However, compared to the advanced FIFO algorithm, with DRMGs both optimization approaches lead to gains in productivity of at least 10% for the quay cranes. Hence, both ideas, the detailed optimization of the yard cranes (as the potential bottleneck of the terminal) as well as the integrated optimization which results in more freedom for the assignment of jobs, but also leads to a more complex problem, are successful and promising.

When the integrated optimization approach and the branch-and-bound procedure are combined, the advantages of both procedures can be exploited, leading to productivity increases of the quay cranes (compared to the priority rule FIFO) of about 20 to 25% for the DRMG.

For TRMG, the potential for productivity enhancement is in a similar range, while it is significantly lower for the Single and Twin RMG. This is due to the higher flexibility of the crane systems with overtaking possibility. This ability can be exploited best when more sophisticated optimization approaches are used, and hence, these approaches work best for the respective crane systems. Due to the higher flexibility and efficiency, the crane systems with overtaking possibility are a good option especially for transshipment terminals where high workloads occur on one side of the block. Moreover, when the yard cranes become a bottleneck of such a terminal, it may be advantageous to first advance their optimization before building additional yard blocks.

As a conclusion, control and optimization aspects – although they often seem not to be important for the planning phase of the terminal and become relevant only after the operational startup – should be considered in the choice of the yard crane system and the TOS from the very beginning. The approaches presented in this study strongly rely on accurate forecasts for the devices' job durations, but nevertheless, they provide robust results even when disturbances occur. Due to the particularly detailed modeling of the storage yard, of the container transfers between different devices, of yard crane interferences in the simulation model and because of the realistic scenario used, the results are readily applicable in practice.

A limitation of the integrated optimization approach is the missing feasibility check of job assignments to yard cranes. Hence, further research should focus on this issue. Furthermore, a special optimization algorithm instead of the application of a standard solver (CPLEX) for implementing the integrated approach can help to solve the optimization problem faster and with a lower optimality gap, and therefore to exploit the potential of the approach in practice. On the contrary, a consideration of longer job chains or a longer planning horizon does not appear to be meaningful since the optimized job chains become unstable due to the online character of the problem.

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Chapter 19
Optimal Stack Layout Configurations at Automated Container Terminals Using Queuing Network Models

Debjit Roy and René de Koster

Abstract A well-designed stack layout is crucial for container terminals to maximize both the internal efficiency and the responsiveness to customers (such as vessels, trucks, and trains). One key performance indicator influencing both efficiency and responsiveness is the container seaside lead time for unloading a container from the vessel, transporting it to the stack area and storing it in a stack block, or vice versa, loading it in a vessel. The terminal performance depends not only on operational variables such as the location of the container in the stack, but also on design decisions, such as the type and the number of stacking cranes per stack, the type and number of internal transport vehicles, the layout of the stack (parallel or perpendicular to the quay), and the dimensions of the stack. In this chapter, we present an overview of analytical models that rely on queueing network theory, for analyzing stack layout decisions in automated container terminals and summarize the design and operational insights.

19.1 Background and Motivation

Due to growth in international trade and better accessibility to the major seaports via deep-sea vessels, containerized freight movement is today the dominant mode for global break-bulk cargo transport with around 400 container shipping companies and 5,100 container ships worldwide (see Sia Partners 2015a). With the arrival of slow steaming ultra-vessels, with a capacity of 20,000 TEU (and more) and consuming 50% less fuel compared with the average, the cost per container transport

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has been reduced drastically (see Statista 2019). This cost reduction will further boost the growth in containerized trade. In December 2018, the combined capacity of container ships worldwide is expected to be around 22.9 million twenty-foot equivalent units (see Sia Partners 2015b). With the increase in container traffic, several new deep-sea as well as inland container terminals are being designed across continents. Several of the larger ones are considering automation to improve the terminal efficiency.

Making the right container terminal design decision is crucial as the investments involved are huge (between 0.5 and a few billion euros), the time frame is long (e.g., in case of greenfield projects, the land and the port often have to be created), and the payback period varies between 15 and 30 years (see Wiegmans et al. 2002). The design of the container terminal includes strategic design choices such as the terminal layout at the stackside, choice of equipment for container handling and transport at the seaside and landside, and type of equipment for container storing (or retrieving) in (or from) the stack. However, the process to arrive at an optimal design is extremely complex due to several reasons. They are: (1) physical constraints such as variations in ground conditions and topology of the terminal area, (2) large number of design parameters and corresponding solution search space, and (3) stochastic interactions among the main terminal processes (seaside, stackside, and landside).[1]

The layout decisions at a terminal such as the horizontal spacing between the quay cranes and the container stack affects the travel time for internal transport. Likewise, the number of stack blocks, and the number of rows, columns, and tiers within each stack block affects the lead time at the stack side. The layout decisions in the container terminal areas are interdependent because of the interactions of the different flows. For example, the import containers that arrive at the quayside form the box flows towards the landside terminal interfaces requiring internal transport at seaside from *Q*uay *C*ranes (QC) to the stack. Quayside flows consist of internal flows from quayside to the stackside. Likewise, the export containers that arrive at the landside terminal (e.g., by external trucks or trains) form the box flows towards the quayside. After temporary storing in the stack, at seaside, internal container transport is required from the stacks to the QCs at the quay wall. Further, the choice of technology for one type of equipment influences other equipment choices. For example, if a *R*ubber-*T*yred *G*antry (RTG) crane system is adopted at the stackside, then terminal trucks are typically adopted for the internal transport as well.

[1]The whole container handling process is composed of seaside and landside processes. The seaside processes include the container handling at the quayside and internal transport between the quayside and the stackside, i.e., the container handover at the stack buffer lane position for storage in the stack, and container handling and retrieving on/from the storage positions within the stack area. The landside processes include the internal transport between the stack (i.e., the stack handover and/or storage positions and the landside terminal interfaces, i.e., truck gate, rail head, and barge berths) and container handling at the landside terminal interfaces (rail head and barge berths).

Recently, a new generation of fully automated terminal equipment has been put into operation. Remotely controlled QCs equipped with two trolleys have been introduced, where each QC is capable of handling two or even more containers at the same time (e.g., at the Port of Rotterdam by APM terminals on the Maasvlakte II). Automated terminals with *R*ail-*M*ounted *G*antry (RMG) yard cranes use one, two, or even three *A*utomated *S*tacking *C*ranes (ASC) in every stack block to retrieve and store containers, and depending on the design of the stack blocks and ASCs, the ASCs can or cannot pass each other. New automated vehicles such as *A*utomated *G*uided *V*ehicles (AGV) or *A*utomated *L*ifting *V*ehicles (ALV) are developed for internal container transport. The vehicles of conventional AGV systems do not have self-lifting capabilities and they need to be synchronized with the QCs at the quayside and with the ASCs at the stackside to pick-up or drop-off the containers. On the other hand, ALVs have self-lifting capability and decouple container handling at the quayside and the stackside. Figure 19.1a shows the functional areas of an automated container terminal with stacks oriented perpendicular to the quay

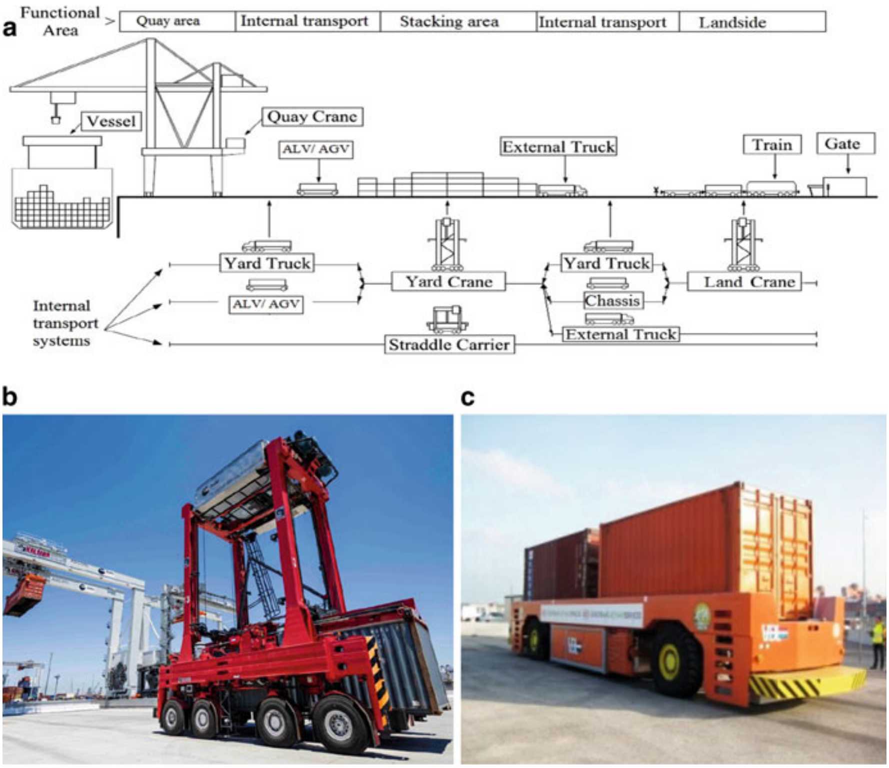

Fig. 19.1 (**a**) Functional areas and resources at an automated container terminal, Brinkmann (2011) and Meisel (2009), (**b**) illustration of an ALV (see Kalmar 2019), ALVs can lift up (set down) the container directly from (to) the ground, and (**c**) illustration of an AGV (see VDL 2019), AGVs cannot lift up (set down) the container directly from (to) the ground

wall, and equipment automation in the container yard and at the seaside transport area. The quayside, internal transport, and the stackside operations of automated container terminals (denoted as seaside operations) represent the scope of this research. Related processes include the handling activities by quay cranes, internal transport between QCs and stack as well as container handling in the stack area with container storage and retrieval. Figure 19.1b shows an ALV and Fig. 19.1c shows an AGV transporting containers in the yard area. An ALV and an AGV are typically considered for internal seaside transport at automated terminals with yard gantry cranes.

Traditionally, the main research focus has been on building simulation and optimization models to address strategic and tactical issues such as the container stowage on ships and in the stack, as well as on operational issues such as vehicle dispatching rules and quay crane scheduling (see de Koster et al. 2004; Liang et al. 2009). Practitioners also have developed detailed simulation models to design new terminals or improve the efficiency of existing terminal operations. While simulation provides detailed performance measures, it limits the design search procedure due to long model development time and high costs. In this research, we discuss analytical models, which enable the terminal operator to analyze alternate configurations rapidly.

Analytical models have also been built to analyze specific system design aspects. For instance, Canonaco et al. (2008) developed a queuing network model to analyze the container discharge and loading at any given berthing point. Hoshino et al. (2007) proposed a design methodology for an AGV transportation system by using a closed queuing network model. However, in literature, integrated analytical models that consider the system level interactions among the seaside and landside processes for analyzing the performance of container loading and unloading operations by considering some of the stochastic inputs are scarce (see Gharehgozli et al. 2016; Gorman et al. 2014; Stahlbock and Voß 2008; Steenken et al. 2004; Vis and de Koster 2003).

In this chapter, we particularly focus on the stack layout design at an automated sea container terminal characterized by automation of stack operations and internal container transport at seaside. For analysis purposes, integrated analytical models are used that consider at least vessel un(loading), container transport from or to the quayside processes for incoming or outgoing containers. Stack layouts are typically perpendicular or parallel with respect to the quay (see Fig. 19.2). It should be noted that, today (2018), no automated container terminals are in operation with gantry cranes and parallel oriented stacks in the yard, although the technology for automation of the processes is available. While many non-automated sea terminals in Asia (such as in Pusan, Korea or Yangshan, Shanghai) have parallel orientation of the stacks, many large sea terminals in Europe (such as the ECT Delta terminal in Rotterdam) have a perpendicular stack orientation and are automated with RMG yard cranes. Perpendicular layouts (operated by gantry cranes) are good in decoupling manual landside operations from automated seaside operations. In this chapter, we investigate the stack layout decisions with ALVs for container transport between QCs and yard. Further, for simplicity of exposition, we

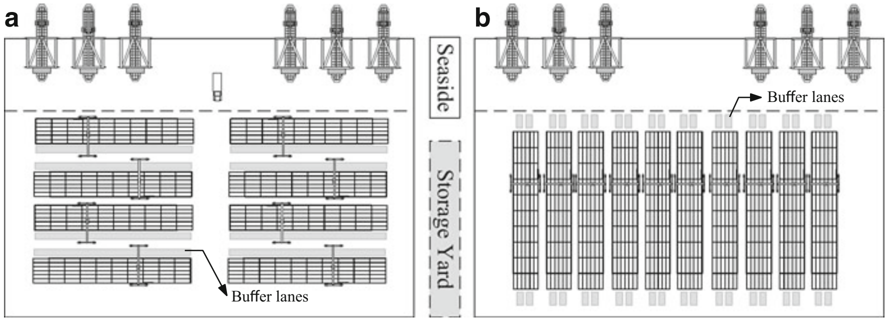

Fig. 19.2 Illustration of a parallel (**a**) and a perpendicular stack layout (**b**), see Wiese et al. (2013)

consider only "single" mode QC operations: either handling of import containers (vessel unloading) or handling of export containers (loading). We discuss two model variants in this chapter:

1. perpendicular stack layout with ALVs for internal transport (see Roy and de Koster 2014, 2018) and
2. parallel stack layout with ALVs for internal transport (see Gupta et al. 2017).

Note that the seaside process time to unload and store incoming containers as well as to retrieve and load outgoing containers depends on several variables such as the location of the container in the stack, the type, and the number of stack cranes per block, layout of the stack (parallel or perpendicular to quay), and dimensions of the stack (number of rows, bays, and tiers). We discuss analytical queuing network models that can help to analyze the effect of such design and operational policy parameters. Such queuing network models have been widely adopted for performance analysis of manufacturing and computer systems (e.g., see Lazowska 1984; Suri et al. 1993). In particular, we compare optimal parallel and perpendicular stack layouts for seaside lead time performance. We adopt our models to analyze different terminal layouts by varying the number of stack blocks, number of rows, bays, and tiers per stack block, and vehicle path dimensions, and arrive at a layout that minimizes seaside lead times. Note that while the vessel sojourn time is a key measure from the shipping line (vessel owner's) perspective, the export or import container's seaside lead time in a terminal, which is the container repositioning time from the stack to the ship (export) or repositioning time from the ship to the stack (import), is an important measure from the terminal operator's perspective. In addition, the container seaside lead time has an impact on the vessel sojourn time.

Queuing network models can be used to rapidly analyze alternate terminal layout configurations by varying the stackside configuration (number of stack blocks, rows, bays, and height), and vehicle transport configuration (number of vehicles and travel path dimensions and topology). Each configuration may impact the vehicle guide path and hence the travel times. In case of perpendicular-oriented stacks, the stack

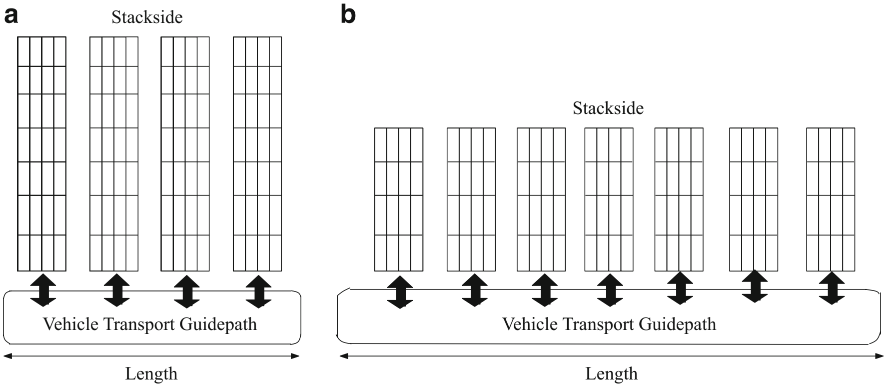

Fig. 19.3 Alternate terminal layout configurations (**a**) small number of stack blocks and large number of bays (**b**) large number of stack blocks and small number of bays

layout configuration also influences the traveling path length of stack cranes and so the time for container storing/retrieving. For instance, by increasing the number of stack blocks being assigned to a berth for vessel processing, the length of the vehicle guide path also increases (refer Fig. 19.3). The total number of stack blocks (assuming constant storage capacity) has a direct impact on the stackside length as the existing capacity requirements are to be met in any configuration. Therefore, the stacking time per stack block may decrease, whereas the vehicle transport time may increase. Hence, the configuration of an optimal stack layout is not obvious. Perpendicular stack layouts typically use ASCs. Although parallel stack layouts use manually operated gantry cranes for stacking operations (sometimes RMG but mostly RTG cranes), in order to be able to compare the layouts, we assume they also use ASCs (which indeed is possible in practice as the necessary automation technology is available). We discuss the models and analyze the layout by considering container unloading process from the vessel only. A similar analysis can be conducted with the vessel loading process under consideration. For the analysis of layouts with overlapping operations, the reader is advised to refer Roy and de Koster (2018).

The rest of this chapter is organized as follows. Literature on integrated container terminal models and alternate stack layout configurations is discussed in Sect. 19.2. The terminal layout adopted for discussion is described in Sect. 19.3. The modeling approach and the resulting queuing network models for terminal operations with ALVs are provided in Sect. 19.4. The results obtained from numerical experimentation and model insights are included in Sect. 19.5. The conclusions of this study are drawn in Sect. 19.6.

19.2 Literature Review

Many researchers have focused on performance analysis of specific container terminal design aspects. For an overview of the literature on container terminal modeling, see Gorman et al. (2014), Gharehgozli et al. (2016), Carlo et al. (2014), Carlo et al. (2015), Steenken et al. (2004), or Vis and de Koster (2003). Many studies just focus on QC modeling and allocation of QCs to vessels. However, little research has focused on integrated modeling of container terminals, particularly using ALVs for internal transport. In the present contribution, the integrated models consider at least vessel (un)loading, seaside transport, and stack operations.

Integrated Models for Seaside Operation

Researchers have either adopted detailed simulation or analytical models for performance evaluation. Using detailed simulation models, researchers have studied the performance and cost trade-offs using different types of vehicles for internal terminal container transport: multi-trailers, automated guided vehicles (AGVs), or ALVs (see Duinkerken et al. 2007; Vis and Harika 2004). Simulation models developed to analyze operational rules such as the effect of vehicle dispatching policies, e.g., by de Koster et al. (2004). Briskorn et al. (2007) show that an inventory-based vehicle dispatching policy is more robust than a due-date based vehicle dispatching policy. Bae et al. (2011) compare the operational performance of an integrated system with two types of vehicles (ALVs and AGVs). Through simulation experiments, they show that the ALVs reach the same productivity level as the AGVs using fewer vehicles due to the self-lifting capability. Detailed simulation models have also been developed to analyze strategies for controlling transport vehicles and yard crane systems in real time within a fully integrated, stochastic container terminal environment (see Kemme 2012; Petering 2009b, 2010; Petering et al. 2009; Speer and Fischer 2016). Some researchers have focused on developing an analytical approach for integrated operations. In Table 19.1, we classify the integrated models from the literature for container terminals based on the type of QC operation (single mode versus overlapping operation), the type of seaside transport vehicles (ALV or AGV or terminal trucks), the orientation of the yard block relative to the QCs (perpendicular versus parallel), and the research method (analytical versus simulation). Li and Vairaktarakis (2004) develop algorithms to optimize the time needed for simultaneous loading and unloading operations with a fleet of terminal trucks that move the containers from the quayside (single mode QC operations) to the stackside and vice versa. Bish (2003) examines the vehicle dispatching problem for loading and unloading containers to and from ships and develops greedy heuristic algorithms to determine job schedules, which are also exact (optimal) for a single ship-single crane combination, and minimizes the overall dwell time of a ship at the terminal. Analytical models have also been developed to analyze terminal design decisions. For instance, Hoshino et al. (2007) propose an optimal design methodology for an AGV transportation system by using a combination of closed queueing networks. Roy and de Koster (2014) develop an integrated analytical model of a container terminal, focusing on either loading

Table 19.1 Classification of literature in integrated models for container terminals

Citation	Type of operation	Type of vehicle	Type of stack layout	Research method
Bae et al. (2011)	Single	AGV and ALV	Perpendicular	Simulation
Vis and Harika (2004)	Single	AGV and ALV	Perpendicular	Simulation
de Koster et al. (2004)	Single	ALV	Perpendicular	Simulation
Petering et al. (2009)	Overlapping	Yard trucks	Parallel	Simulation
Petering (2009b)	Overlapping	Yard trucks	Parallel	Simulation
Petering (2010)	Overlapping	Yard trucks	Parallel	Simulation
Kemme (2012)	Overlapping	AGV	Perpendicular	Simulation
Hoshino et al. (2007)	Single	AGV	Perpendicular	Analytical
Roy and de Koster (2014)	Single	AGV and ALV	Perpendicular	Analytical
Dhingra et al. (2015)	Single	AGV	Perpendicular	Analytical
Roy et al. (2016)	Single	AGV	Perpendicular	Analytical
Roy and de Koster (2018)	Overlapping	ALV	Perpendicular	Analytical
Gupta et al. (2017)	Single	ALV	Parallel	Analytical

Internal transport vehicle type	Coupled (AGV, Yard truck)		Decoupled (ALV)	
Performance measure	External transaction waiting time	Maximum throughput	External transaction waiting time	Maximum throughput
Modeling approach	Semi-open queuing network	Closed queuing network	Open queuing network	Travel time analysis

Fig. 19.4 Framework for performance analysis of automated container terminal operations

or unloading operations. Using an analytical model, they identified the optimal location for the terminal vehicle to park,[2] the optimal layout of the yard, and the vehicle guide path. Dhingra et al. (2015) develop a two-stage stochastic model to estimate the vessel sojourn time at a container terminal. They propose an integrated framework where the interactions among the QCs, AGVs, and ASCs are captured in the lower level model and vessel sojourn time is estimated using a continuous-time Markov chain model. However, this model does not capture the overlapping operations. Roy et al. (2016) develop a closed queueing network model to capture the traffic congestion of the AGVs on the travel path and at the crane buffer locations. Again, this model considers only single mode QC operations. However, many deep-sea vessels spend substantial time in the overlapping phase, when some QCs may still be unloading the vessel while others have already started loading certain bays of the vessel. It is important to start loading the vessel as early as possible to minimize berthing time. Roy and de Koster (2018) model the overlapping mode QC operations at a terminal using an analytical model.

As discussed earlier, depending on the performance measure of interest and the equipment technology, the type of analytical models vary (see Fig. 19.4). For example, ALVs can decouple transport from the stack operations and hence, an open queuing network model captures the stochastic interactions among the three terminal areas. Note that once the hand-off of the container and ALV is decoupled, the QC can drop-off the container to a buffer location and continue with another unloading cycle. Hence, the container can wait at the buffer for an ALV to be available. The container waiting times for an ALV can be modeled using an open queue. On the other hand, AGVs tightly couple transport with stack or QC operations and hence, synchronization among resources is an essential element of the analytical models (see Roy 2016). Note that once the hand-off of the container and AGV is coupled, the QC has to transfer the container to the resource and can only then continue with another unloading cycle. In coupled systems, the container cannot wait at the buffer for transport because coupled vehicles cannot pick-up the

[2] The parking location for a terminal vehicle is also known as the dwell point of the vehicle. A good choice of the dwell point can improve the terminal responsiveness by minimizing the time taken to reach the pick-up location after receiving a container transport request.

container of their own. The seaside processes are modeled with a closed queuing network models, where the vehicles circulate and jointly perform the unloading operations with the QC at the seaside and with the ASC at the stackside. Therefore, integrated models with AGVs typically use closed queueing network for estimating maximum throughput or using semi-open queuing network for estimating external transaction waiting times. For the container unloading process, the external waiting time includes the time, a container waits in the vessel before being accessed by the quay crane.

Models for Analyzing Layout Structure

Although several studies analyze yard layouts, the focus has mostly been restricted to space planning in the yard (see Han et al. 2008), container re-handling operations in the yards (also known as the remarshaling problem – see Caserta et al. 2011), or estimating ASC handling times for a different stack block height, width, and length (see Lee et al. 2011). Some papers study different layout configurations. Kim et al. (2008) develop an integer programming model to determine the layout type (parallel or perpendicular stack layouts), the yard layout, and the number of vertical and horizontal aisles in the stack by considering the stack layout interaction with both landside and seaside operations. They conclude that parallel layouts are superior to perpendicular layouts when the objective is to minimize travel and container relocation (number of re-handles while container retrieving) costs using RTG cranes.

Liu et al. (2004) show that the perpendicular layout is superior with respect to QC moves per hour and the number of horizontal transport vehicles needed. Petering and Murty (2009) develop a simulation model for a vessel-to-vessel transhipment terminal over a several week period. By keeping the QCs busy, they minimize the makespan of the ship schedule considering different stack lengths. They find out that in order to keep QCs busy and minimize the makespan of the schedule of ships, the block length should be limited between 56 TEU and 72 TEU. Petering (2009a) extends the simulation study to include decision support for yard capacity, fleet composition, truck substitutability, and scalability issues. Wiese et al. (2013) develop a decision support model to study parallel vs perpendicular stack layouts with different driving and compensation (loss of ground area due to additional transfer lanes) strategies. Note that additional driving lanes may result in quick access to the stack but then due to loss of ground area, the stack height may need to be increased or the yard area need to be increased for additional storage space. These options to accommodate storage of additional containers due to addition of a driving lane are called compensation strategies. They conclude that both parallel and perpendicular layout may outperform each other under different design parameter settings. Kemme (2012) develops a simulation study to evaluate the effects of four RMG crane systems and 385 yard block layouts, differing in block length, width, and height, on the yard and terminal performance. Lee and Kim (2013) compare a perpendicular layout with a parallel layout considering different cost factors such as construction cost of the ground space, fixed overhead cost of yard cranes, and the operating costs of stack cranes and transporters. They find that an optimal parallel stack layout has a comparatively large number of bays and a small number of rows in each stack. They also determine that shorter and wider blocks are more efficient in a perpendicular layout. In addition, Lee and Kim (2013) state that a parallel layout requires fewer ASCs and it performs superior to a perpendicular layout in terms of cost.

In Table 19.2, we classify the literature on the impact of stack layout structure on terminal performance measures. The classification criteria are the choice of stackside equipment, scope of the research, performance measures, research outcome, and broad area of the research method. The paper closest to our work is that by Wiese et al. (2013), who also compare parallel and perpendicular stack layouts. They find that the design configuration (stack length and depth, vehicle velocity, and possible driving strategies) substantially affects the layout preference and shows that the parallel stack layout outperforms the perpendicular stack layout for most parameter settings. This paper is largely based on Gupta et al. (2017). The specific contribution of this paper is the selection of analytical model for optimizing stack layout dimensions and summarizing the insights from our previous studies in container terminals. We add to this literature by optimizing the layouts first separately and then comparing the top configurations.

19.3 Container Terminal Layout and Process Description of Terminal Seaside Using ALV

The perpendicular layout shown in Fig. 19.5 broadly comprises three areas: quayside, vehicle transport, and stackside (refer Table 19.3 for a description of the notations used in Fig. 19.5). The quayside area includes N_q quay cranes that are spaced equidistant from each other. The vehicle transport area includes a guided path that supports the movement of V vehicles. The unidirectional travel path joins the quayside buffer lanes and the stackside buffer lanes. Note that there are two parallel tracks in front of the stacks and in the backreach of the QCs. The inner track that is farther away from the cranes allows fast vehicle travel in comparison to the outer one that is closer to the cranes. The travel path has a set of shortcuts that reduces travel time from quayside to stackside. There is one shortcut corresponding to each QC and each shortcut originates from each QC buffer. The shortcut paths run from quayside to stackside, but not in the opposite direction. There are N_s stack blocks, each operated by a single ASC. Further, differences in container sizes (20 ft, 40 ft, 45 ft) are not explicitly modeled in this chapter. A similar parallel layout is shown in Fig. 19.8.

In this research, seaside lead time is used as the primary measure used for assessing the terminal system performance. During unloading operations, a container typically goes through six handling phases: (1) it waits on the vessel for the QC to handle it, (2) it is unloaded by the QC, (3) it is positioned at the quayside buffer or placed on the vehicle platform, (4) it is transported by the vehicle, (5) it waits on

Table 19.2 Classification of stack layout literature where outcomes are (1) the orientation of the stack blocks (parallel to the quay or perpendicular to the quay), (2) the number of stack blocks for a fixed number of storage locations, (3) the organization of the stack blocks (number of horizontal and vertical modules for the parallel stack layout), and (4) the dimensions of each stack block, which is expressed as a function of number of rows per block, bays per block, and tiers per block, adapted from Gupta et al. (2017)

Citation	Stackside equipment	Scope	Performance measures	Outcome	Research method
Liu et al. (2004)	Yard cranes with AGVs for both parallel and perpendicular stack	Seaside, loading and unloading	Seaside lead time	1,2,3	Simulation
Kim et al. (2008)	Transfer crane for both parallel and perpendicular stack	Seaside and landside, loading and unloading	Expected travel distance of yard trucks	1,3,4	Integer program
Lee and Kim (2010)	RTGs or RMGs for both parallel and perpendicular stack	Seaside, loading and unloading	Optimal block size (*length, height and width of block*)	1,4	Integer program
Petering (2009b)	RMGs for parallel stack	Seaside, loading and unloading	Gross crane rate (*average numbers of containers lift per hour by each QC*)	3,4	Simulation
Petering and Murty (2009)	RMGs for parallel stack	Seaside, loading and unloading	Gross crane rate	2,3	Simulation
Wiese et al. (2011)	RMGs or RTGs for both parallel and perpendicular stack	Seaside and landside loading and unloading	Minimize the time needed to store the containers into blocks	1,2	Integer program
Wiese et al. (2013)	Straddle carrier for both parallel and perpendicular	Seaside and landside, unloading	Minimize the estimated average straddle carrier cycle time for loading/unloading operation	1,2,3,4	Optimization
Lee and Kim (2013)	RMGs or RTGs for perpendicular and parallel stack	Seaside and landside, loading and unloading	Installation cost and cycle time for loading/unloading operation	3,4	Integer program
Gupta et al. (2017)	RMGs for both parallel and perpendicular stack	Seaside, unloading	Seaside lead time	1,2,3,4	Queuing, integer program

Table 19.3 Notations used in Fig. 19.5 used to obtain the service time expressions for the vehicle transport

Term	Description
V	Number of ALVs
W_s	Width of a stack block
D_s	Length of a stack block
W_{bs}	Width between stack blocks
D_e	Distance between last stack block along X-axis (both ends)
W_{bl}	Distance between two ALV lanes
W_{bq}	Distance between two buffer lanes at quayside
D_{ex}	Distance between entrance and exit of each shortcut
D_{in}	Distance between exit of one shortcut and entrance of another shortcut
D_{sl}	Length of buffer lane at stackside
L_r	Length of path after last shortcut
L_l	Length of path before first shortcut
W_l	Width of overall ALV path

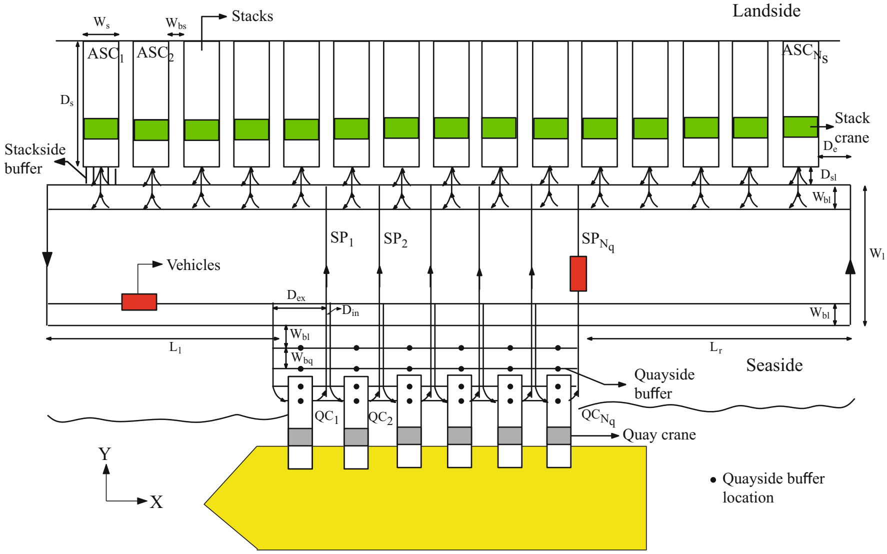

Fig. 19.5 Perpendicular layout of the container terminal used in this chapter

the ground in a stackside buffer for ASC service or picked-up by the ASC directly, and (6) it is loaded by the ASC and put into the stack.

During loading operations, a container typically goes through six handling phases. They are: (1) the container first waits in the stack for the ASC to handle it, (2) it is picked-up by the ASC, (3) it is positioned at a stackside buffer or set down on the vehicle platform, (4) it is transported by the vehicle, (5) it waits on the ground in a quayside buffer for QC service or directly picked-up by the QC, and (6) it is then put down by the QC into the vessel. Note that we do not consider remarshalling of containers at the stackside during loading and unloading operations.

The load and unload seaside lead times include the time spent by the container during the six phases. We now state the modeling assumptions for the processes of the terminal areas.

Modeling of the Quayside Process The extent of variability in the container inter-arrival times for unloading containers is captured using a *C*oefficient of *V*ariation (CV) value of 1 or greater than 1. We consider QCs with only one trolley. QCs perform single cycle operations only, i.e., they either unload or load containers during the entire cycle. All QCs perform the same operation. Each QC resource is modeled as a single server queue. In queuing network models, the resources are modeled as servers and customers join a resource queue for service, if the resource is busy serving other customers on arrival. In this case each QC is a single server resource and the containers wait at the QC queue for service. The service time of the QC (server) could be quite variable due to considerable differing skills of the QC drivers, different locations of the containers in the vessel, etc. We use real QC service times data obtained from TBA (a supplier of container emulation and control software) and estimate the first and second moment of the service times.

Though containers arrive in bulk on a vessel, several sources of uncertainties influence the container availability at the quayside (for unloading) as well as at the stackside operations (for loading). For instance, the time to unlash the containers on the vessel before discharging is variable (typically outsourced to a third-party company), the time to remove the hatch covers and open the twist locks varies, or the stowage plan at the port of origin impacts the number of container restows before the target container can be discharged. This large variability in the timing of individual container availability can be modeled using a Poisson arrival process with λ_a^u denoting the average arrival rates at the quayside for unloading containers (see Fig. 19.6 for an illustration of container arrivals). We use the subscript a to denote the arrival process and the superscript u to denote the unloading process.

The containers to be unloaded are randomly assigned to any QC allocated to process unloading operations. Likewise, the containers to be loaded are randomly assigned to any QC allocated to process loading operations. The dwell point of the

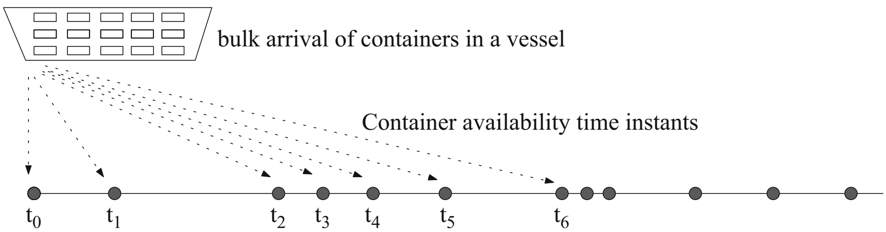

Fig. 19.6 Illustration of container availability for the QCs (adapted from Roy and de Koster 2018)

QC trolley is the point of service completion; i.e., it idles at the last point where the trolley discharges the container near the buffer lane. Though we consider a finite number of buffer lanes under a QC (see Fig. 19.5), each buffer is assumed to have infinite buffer lane space for vehicles parking near the quay cranes. This infinite buffer space assumption is quite reasonable because there are typically 2–3 vehicles allocated to transfer containers from each QC. Also, the vehicles can park near the quay cranes if there is no availability in the buffer space.

Modeling of the Vehicle Transport Process ALVs can autonomously pick-up and set down containers in the absence of other equipment. ALVs have a carrying capacity of one container. ALVs are not dedicated to QCs; they are allowed to process either loading or unloading operations (single cycles). Idle ALVs are assigned to container jobs in a FCFS basis. ALVs follow a point-of-service-completion dwell point policy, i.e., they dwell at the stackside after processing unloading requests and dwell at the quayside after processing loading requests. In case, AGVs are used for transport they also follow a point-of-service-completion dwell point policy. In both cases, the vehicle pool is modeled using a multi-server queue, where each vehicle is a single server and any vehicle can serve any waiting transaction if idle. The distribution of the service times is obtained by considering the travel time between all possible combinations of the QC buffer and the ASC buffer positions. For both the loading and unloading process, the distribution of the travel times is identical (from quayside to the stackside and return in the case of loading operations, and from stackside to the quayside and return in the case of unloading operations; the shortcut paths are unidirectional). The first and second moment of the service times are then derived from the distribution and used as inputs in the multi-server vehicle queue.

Modeling of the Stackside Process We assume one ASC per stack block, which can either process loading or unloading operations in a single-command cycle. Containers are randomly assigned to any ASC during loading and unloading operations so that the workload is uniformly distributed among ASCs. The total number of storage locations in the terminal is essentially fixed, but we vary the number of stack blocks (N_s), number of rows per stack block (N_r), bays per stack block (N_b), and tiers per stack block (N_t). To capture the variation in service time of ASC operations (hoisting, lowering, trolleying, and gantrying) involved in placing containers in the stack block, we generate a random storage location (stack block, row, bay, and tier) for each unloaded and loaded container. Note that we do not consider any reshuffling moves during the container retrieval process. For processing a container unloading request, variability in the ASC service time is introduced by the originating location of the crane within the stack block, the pick-up buffer location, and the destination location of the crane for container drop-off. Likewise, for processing a container loading request, variability in the ASC service time is introduced by the originating location of the crane within the stack block, the pick-up location within the stack block, and the destination location of the crane for container drop-off at the ASC buffer lane. Similar to the QCs, ASCs are also modeled as single server queues. The dwell point of the ASCs is the point of service completion, i.e., the crane raises the trolley and idles at the last location in the stack block. We assume an infinite buffer space for container drop-off at each ASC location.

To determine the optimal stack layout of the terminal, the number of container storage locations, the number of vehicles (V), and the number of quay cranes (N_q) are fixed; we vary the number of stack blocks and ASCs (N_s), number of rows per stack block (N_r), bays per stack block (N_b), and tiers per stack block (N_t). By varying the four parameters, N_s, N_r, N_b, and N_t, the length of the vehicle guide path is also altered (Fig. 19.5), which affects the unload seaside lead time, CT_u. CT_u is composed of container waiting time and the processing time at the three processes (the quayside, the vehicle transport, and the stackside processes). The optimization formulation to determine the optimal combination of the four design variables is presented in Eq. 19.1. The objective function is to minimize $E[CT_u]$, subject to the network stability constraint,[3] fixed locations constraint (C),[4] vehicle utilization constraint ($U(V)$),[5] and upper and lower bound constraints for the decision variables. Other constraints on QC and ASC resources can also be added. To determine the optimal terminal layout configuration for unloading operations with ALVs, we analyze alternate configurations for different combinations of design parameter settings using the integrated queuing network model (described in the following section). Note that the formulation to minimize the seaside lead time for loading containers is similar.

$$
\begin{aligned}
\underset{N_t, N_s, N_r, N_b}{\text{minimize}} \quad & E[CT_u]\left(N_q, N_t, N_s, N_r, N_b, V\right) \\
\text{subject to} \quad & \text{Network stability condition} \\
& N_t N_s N_r N_b = C \\
& U(V) \geq U_{min} \\
& N_{t_{min}} \leq N_t \leq N_{t_{max}} \\
& N_{r_{min}} \leq N_r \leq N_{r_{max}} \\
& N_{b_{min}} \leq N_b \leq N_{b_{max}} \\
& N_{s_{min}} \leq N_s \leq N_{s_{max}} \\
& N_t, N_s, N_r, N_b \in \mathbb{Z}^+
\end{aligned}
\tag{19.1}
$$

[3]To ensure that the number of waiting containers do not grow continuously and the queues empty at times, the utilization of all resources should be strictly less than 100%.

[4]The number of storage slot locations in the yard is kept constant to enable comparison among the layouts.

[5]To ensure that the vehicles are utilized at least for a specific percent of time, a lower limit to the utilization is included.

19.4 Queuing Network Model for Terminal Operations with ALV

In this section, we include a discussion of the queuing network model for terminal unloading operations with ALVs. Note that the approach for modeling the terminal loading operations is identical to that of terminal unloading operations, i.e., the quayside, vehicle transport, and stackside resources are modeled in a similar manner. However, the flow of containers, which determines the routing of containers begins at one of the ASC queues and proceeds to the QC queues via the ALV queue. The model details for single mode QC unloading operations for a perpendicular and parallel layout are available in Roy and de Koster (2014) and Gupta et al. (2017), respectively, whereas the model details for overlapping mode QC operations for a perpendicular layout are available in Roy and de Koster (2018). Figure 19.7 describes the integrated queuing model of the container unloading operations from the vessel. The model is analyzed using a parametric-decomposition approach where the output process from the upstream queue forms the input process to the downstream queue.[6] On arrival, the containers wait at their respective $GI/G/1$ QC queue ($QC_i, i = 1, \ldots, N_q$). The SCV of the inter-departure times from the QC queue form the SCV of the inter-arrival times to the multi-vehicle server representing the ALV transport between QCs and the handover positions of the stack blocks. They can be obtained from Whitt (1983), as he provides the formulas to estimate the SCV of inter-departure times from both single and multi-server queues. Since there are N_q QCs, the departures from each QC are merged to form the

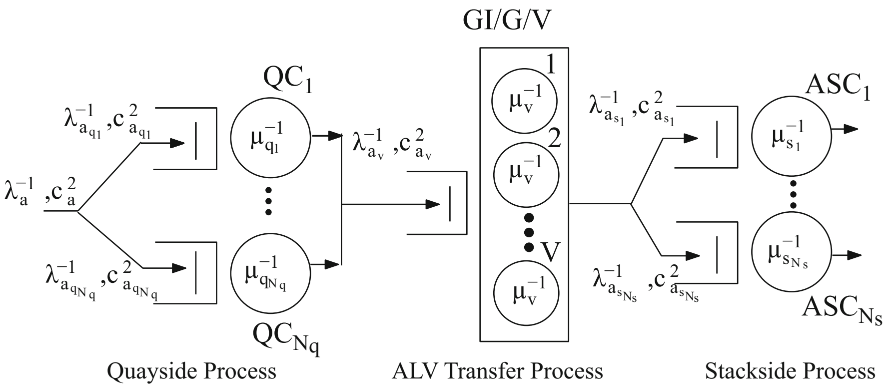

Fig. 19.7 Open queuing network model of the container unloading process with ALV

[6]In this approach, all queues are separated and analyzed in separation. Then the performance measure from each queue is aggregated to obtain the integrated performance measure for the seaside. Each queue is analyzed by using the first and second moment of the inter-arrival times and the service times, see Whitt (1983).

arrival stream to the multi-vehicle server station for internal transport. After service completion, the container joins one of the $GI/G/1$ ASC queues, corresponding to each stack block ($ASC_i, i = 1, \ldots, N_s$). Therefore, the departure process of the multi-server vehicle station forms the arrival process to the $GI/G/1$ ASC queues. From Whitt (1983), we obtain the SCV of the inter-arrival times for the ALV transport and the ASC processes. After the ASC stores the container at a bay location, the container unloading operation is complete. Note that we use $GI/G/1$ queues because the general distribution of the container inter-arrival times and the service times gives us additional flexibility to model the degree of variation in the arrival and the service processes.

Once the expected value of the waiting times at the QCs, ALVs, and ASCs is obtained, Little's law can be used to estimate the expected queue lengths (the average number of containers waiting at the QCs, ALVs, and ASCs). Note that the APM Terminals at Rotterdam (Masvlaakte 1) work only with perpendicular-oriented yard stacks allowing for container in/out at the end of the stack blocks. In Fig. 19.8, we show the layout for the terminal with parallel stack blocks. The operations at the parallel oriented stack blocks are different. Here, ALVs/tractor trailer units/external trucks are loaded and unloaded within the yard area directly next to the container storage position. Therefore, gantry cranes (working with parallel stack blocks) have totally different container storing and retrieving times in comparison to gantry cranes that work perpendicular stack blocks. The ASC service times for parallel stack blocks are estimated with buffers that are located directly next to the container storage position. The queuing model for both configurations remains identical. However, the service time expressions have to be adapted based on the layout dimensions and ALV movement. Note that there are several path possibilities from the QCs to the ASCs in a parallel layout. In such cases, we consider the shortest travel path. For purpose of comparison, we ensure that the total number of storage locations in both layouts are same.

19.5 Insights Based on Numerical Experiments and Layout Comparisons Using ALV

In this section, we summarize the validation results of the analytical models for unloading operations with ALVs discussed in this chapter. The data behind the terminal layout with perpendicular and parallel stack blocks, which include the speed of the vehicles, ASCs, QCs, clearance between the stack blocks, etc., are obtained from the APM Terminal operation in Rotterdam (also refer Roy and de Koster 2014 and Gupta et al. 2017). The analytical model is validated using detailed simulations and the container arrival rates vary at different levels such that vehicle/QC utilization lies between 60 and 90%. Each simulation experiment is run for 15 replications with a 1 day warm-up period and 20 day run time. The confidence intervals for the performance measures are all within 3% of the means.

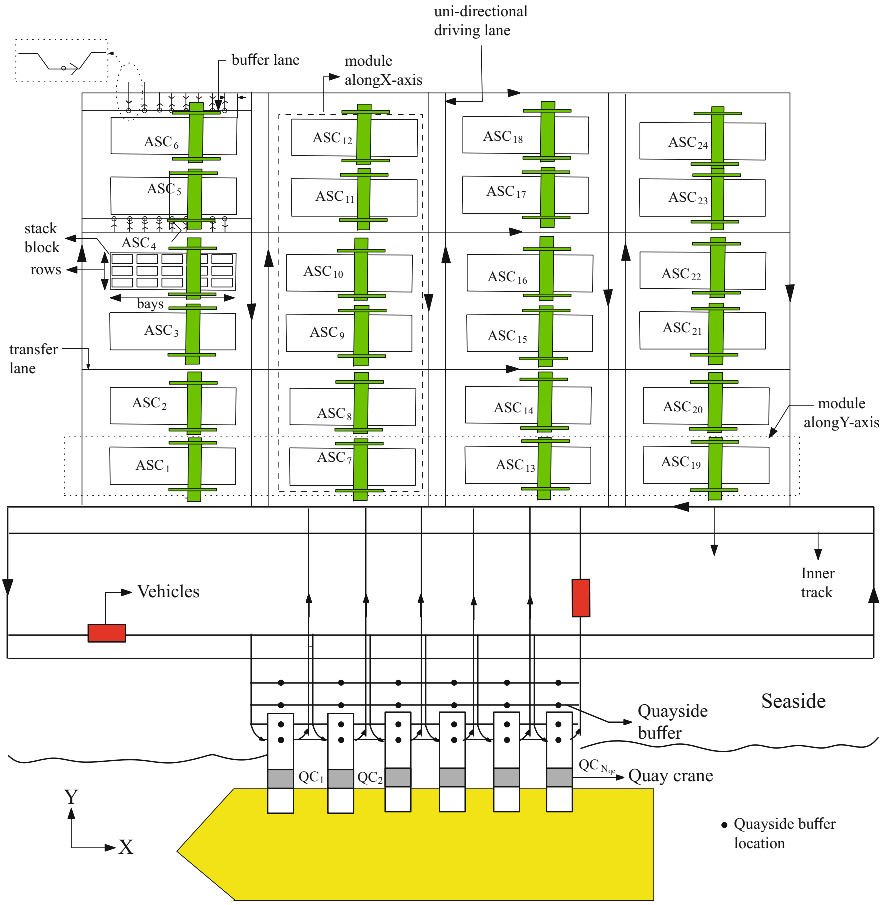

Fig. 19.8 Illustration of a container terminal with parallel yard layout

The performance measures considered are the expected seaside lead time for each of the three processes of quayside ($\mathbb{T}_q$), vehicle transport ($\mathbb{T}_v$), and stackside ($\mathbb{T}_s$) operations, the utilizations of the QCs (U_q), vehicles (U_v), and ASCs (U_s) and the average number of containers waiting in the queues at the quayside (L_q), at quay buffer lanes (L_v), and at the stackside buffer lanes (L_s). The average percentage errors (the error between the results being based on the analytical models with respect to the simulation results) for all of the performance measures are taken over all the different configurations. The percentage errors are quite low (upto 5%) for the expected seaside lead times and resource utilization. However, the errors are somewhat larger upto 10% for expected queue length measures.

To validate the analytical models, we create a three-dimensional simulation model in AutoMod software (see AutoMod 2019). Using this software, we develop precise travel path layouts, and capture the operational capabilities of the QCs and the ASCs. The seaside processes are modeled in the simulation. To compare the performance of the analytical model, we make the infinite buffer assumptions in the simulation model as well, i.e., the vehicles are not blocked in the terminal for lack of physical space. We validate the equipment utilization, queue length, and the lead time measures.

We perform experiments with varying levels of the number of ALVs, container arrival rates, and number of storage locations. We consider two levels of the number of ALVs: 15 and 20 and two arrival rates for the containers 108 and 126 containers/hr. We identify efficient stack layouts for: 28,800, 36,000, and 48,000 stack storage locations. Each location corresponds to 1 TEU storage space. Therefore, we consider a design of 12 ($3 \times 2 \times 2$) experiments. For each experiment, we vary the number of stacks, the stack modules, and the design parameters of each stack block such as the number of rows, number of tiers, and number of bays per stack block (for details, see Gupta et al. 2017).

The number of stack blocks is varied between 4 and 32 with increments of 4 such that the number of stack block modules along the X-axis is varied between 2 and 8 with increments of 2. The number of rows per stack block is varied between 4 and 10 with increments of 1. The number of tiers is varied between 3 and 5 with increments of 1. We compare parallel stack layout configurations to perpendicular stack layout configurations based on lead times ($\mathbb{CT}_u$). The analytical model for the perpendicular stack layout is adopted from Roy and de Koster (2014). We perform 12 experiments based on the design parameters discussed in the previous section. Since the stack blocks are perpendicular to quay, we use a wide range for varying the number of stack blocks: from 10 to 120. The other design settings remain the same.

Optimal Stack Layout with Parallel Stacks and ALVs

We consider the influence of different yard layout parameter values such as the number of stack blocks, number of stack block modules along the x and the y axis, number of tiers, number of bays on seaside lead times for the parallel stack layout. In all scenarios, we vary these stack layout parameters. Other design parameters such as the number of ALVs and the total number of stack locations remain unchanged. Note that we maintain a constant throughput rate for different layouts but only the expected flow time of containers during the discharging becomes shorter or longer depending on the layout configuration. For each configuration, network stability condition is enforced, i.e., the utilization of all resources is less than 100%. Note that we investigate stack layout configurations for one deep-sea vessel berth (only).

We find that stack layout configurations with fewer modules along the x-axis (2, 3) and more modules along the y-axis (8, 9) are better than the stack layout configurations with more modules along the x-axis and less modules along the y-axis. Also the ratio between the number of bays to the number of rows for good configurations is about 2:1. For a stack layout with 48,000 storage locations, 2 modules along the x-axis, 9 modules along the y-axis, 10 rows, 30 bays, 5 tiers, and 32 stack blocks perform significantly better (about 100% in container seaside lead time) than the layout with 2 modules along the x-axis, 5 modules along the

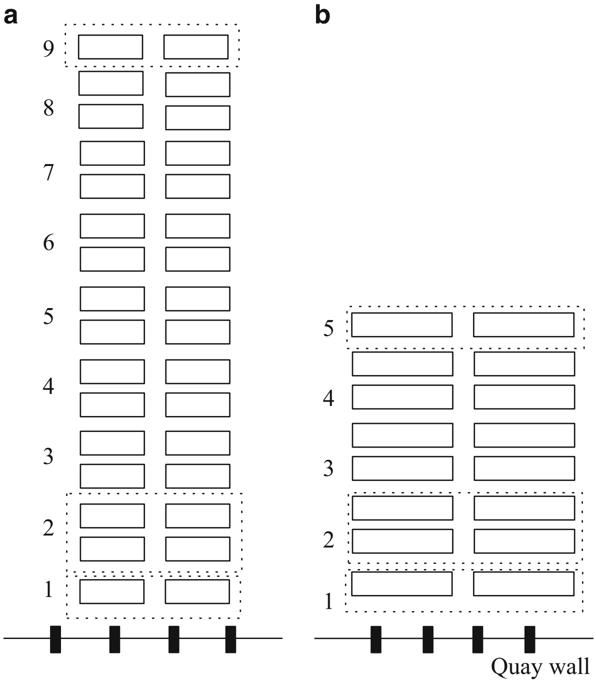

Fig. 19.9 Top view of two parallel stack layouts: (**a**) 2 modules along the x-axis, 9 modules along the y-axis, each stack block has 10 rows, 30 bays, 5 tiers, and (**b**) 2 modules along the x-axis, 5 modules along the y-axis, each stack block has 9 rows, 67 bays, 5 tiers

y-axis, 9 rows, 67 bays, 5 tiers, and 16 stack blocks (see Fig. 19.9 for a comparison on the two layout configurations).

Optimal Stack Layout with Perpendicular Stacks and ALVs

We find that stack blocks with large number of bays and small number of rows perform poorly compared to stack blocks with small number of bays and large number of rows. For example, for a yard with 48,000 yard slots, a layout with 30 stack blocks each with 10 rows, 32 bays, and 5 tiers performs significantly better ($>$100% in container seaside lead time) than a layout with 20 stack blocks each with 6 rows, 80 bays, and 5 tiers. The analytical model with AGVs with hard coupling can be developed in a similar fashion. Similar results also hold for yard configurations with AGVs (see Roy and de Koster 2012). Note that all layout configurations may not have exactly the same number of yard slots because of integrality constraints. For similar storage capacity, we find that the expected container seaside lead times are at least 4% lower in the case of parallel stack layout than for the perpendicular stack layout (see Table 19.4 for the performance gaps between the two layouts). However, we expect that by also including the landside operations, the seaside lead

Table 19.4 Percentage expected seaside lead time difference obtained from optimal parallel vs optimal perpendicular stack layout for unloading operations

V	Locations	λ_a (per hour)	N_r, N_b, N_t, N_s (Parallel)	$\mathbb{CT}_u^*$ (Parallel)	N_r, N_b, N_t, N_s (Perpendicular)	$\mathbb{CT}_u^*$ (Perpendicular)	% Diff.
15	28, 800	126	(10, 18, 5, 32)	597.0	(10, 29, 5, 20)	621.6	4%
20	28, 800	126	(10, 18, 5, 32)	595.7	(10, 29, 5, 20)	621.1	4%
15	28, 800	108	(10, 18, 5, 32)	545.9	(10, 29, 5, 20)	590.1	8%
20	28, 800	108	(10, 18, 5, 32)	545.5	(10, 29, 5, 20)	590.0	8%
15	36, 000	126	(10, 23, 5, 32)	624.0	(8, 30, 5, 30)	664.7	7%
20	36, 000	126	(10, 23, 5, 32)	621.4	(8, 30, 5, 30)	664.7	7%
15	36, 000	108	(10, 23, 5, 32)	571.9	(8, 30, 5, 30)	630.2	10%
20	36, 000	108	(10, 23, 5, 32)	571.0	(8, 30, 5, 30)	630.1	10%
15	48, 000	126	(10, 30, 5, 32)	664.4	(8, 40, 5, 30)	715.5	8%
20	48, 000	126	(10, 30, 5, 32)	657.7	(10, 32, 5, 30)	707.3	8%
15	48, 000	108	(10, 30, 5, 32)	609.4	(9, 36, 5, 30)	681.8	12%
20	48, 000	108	(10, 30, 5, 32)	609.4	(10, 32, 5, 30)	679.6	12%

All layouts are evaluated with six QCs. The unit of lead time is seconds. (see Gupta et al. 2017) time in the case of parallel stack layout may increase due to additional congestion along the driving lanes.

Parallel stacks appear to offer greater flexibility in terms of routing vehicles to the destination stack block. However, they may actually increase the travel times to reach the destination stack block buffer lane from the quayside. In the perpendicular layout, the travel time to the stack block may be marginally lower in comparison to the optimal parallel stack layout. However, stack blocks are shorter and wider in parallel stacks in comparison to perpendicular stacks. Therefore, the cranes of parallel stack blocks have basically shorter container storing/retrieving times than gantry cranes operating perpendicular stack blocks. Hence, the stack crane seaside lead times are higher in the case of perpendicular layouts in comparison to parallel stacks.

19.6 Conclusions

In this research, we summarize integrated analytical models for the unloading operations in the container terminal using Automated Lifting Vehicles for both parallel and perpendicular stacks. The type of queuing network model differs based on the type of vehicle and the terminal process under consideration. The analytical models can be customized to accommodate large variations in the number of resources such as QCs, vehicles, and ASCs, and also the topological variations such as the length of travel path. Detailed simulations of several operational scenarios indicate that the analytical models can be used to identify high potential layout configurations during the terminal design phase. Numerical results with analysis of unloading operations suggest that the optimal parallel stack layout is marginally better than the optimal perpendicular stack layouts. However, more studies need to be performed by considering only loading operations and considering overlapping operations. Further, the landside congestion is not accounted at the stack blocks in the parallel layout and only one gantry crane per stack block has been considered for both layout types. For parallel stack layouts, we show that configurations with fewer modules along the x-axis and more modules along the y-axis are better than the stack layout with more modules along the x-axis and less modules along the y-axis. For perpendicular stack layouts, we find that stack blocks with small number of bays and large number of rows perform better than stack blocks with large number of bays and small number of rows.

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Part V
Planning Area: Terminal Landside and Hinterland Access

Chapter 20
Port Feeder Barges as a Means to Improve Intra-Port Container Logistics in Multi-Terminal Ports

Ulrich Malchow

Abstract The unique *P*ort *F*eeder *B*arge (PFB) can be considered as a "green logistic innovation" for container ports. The self-propelled and self-sustained container pontoon of double-ended configuration (capacity: 168 TEU) can release the terminal gates from queuing trucks and the terminal ship-to-shore gantry cranes from inefficiently serving small inland barges. The PFB can be employed in three business fields: Shifting container haulage within ports from road to waterway, supporting feeder operation, and loading and discharging inland barges. The PFB can be easily integrated in the container logistics within a port. In congested ports or ports with limited water depth and/or insufficient container handling capability even deep-sea vessels can be directly served midstream by the PFB. Hence the PFB can also be used as an emergency response vessel to quickly lighter grounded container vessels. The green potential of the vessel can be further exploited by using LNG as fuel.

20.1 Introduction

Within multi-terminal ports, such as Hamburg, Antwerp, Rotterdam, New York, or even Santos (Brazil), a lot of intra-port container haulage has to be organized. It is not only between the various deep-sea terminals but also between terminals and other container-related facilities like depots, packing stations (stuffing/stripping), and repair shops. For example, in Hamburg, it is estimated that 540,000 TEU are moved just within the port during the year 2015 (see Malchow 2016), which is done almost completely by truck causing congestion on the roads within the port, at the terminal gates and unwanted emissions. Especially the Köhlbrand Bridge (one of Hamburg's landmarks) which connects the eastern and western part of the port has

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to be crossed by 50% of the intra-port container trucking and serves as a major bottleneck (see Bönning 2009).

Beside the deep-sea terminals of container ports, also on-site located intermodal terminals (see, e.g., PoRA 2017c) and minor container-related facilities[1] are partly equipped with their own quay and can be accessed by water, i.e., at least by inland barges. Hence, it seems to be quite useful to look for a water-based alternative to container trucking within and around multi-terminal ports.

However, deploying conventional inland barges (or pontoons) for intra-port haulage would mean that the big *S*hip-*T*o-*S*hore (STS) gantry cranes of the deep-sea terminals had to be used for loading and discharging the small barges. Unfortunately, one single move by such crane is already as costly as approx. the entire trucking within the port.[2] That is why container haulage by conventional inland barges is at least twice as expensive as trucking. Additionally barges enjoy only the last priority at the deep-sea terminals causing significant delays in their port turn-around. Hence haulage by truck is much faster. Minor container handling facilities sometimes even do not have their own crane equipment.

Both aspects led to the conclusion that a self-propelled harbor vessel of sufficient container capacity which is equipped with its own full-size container crane would be a useful tool if waterborne intra-port container haulage had to be realized. However, such type of vessel does not exist yet.

20.2 The Port Feeder Barge Concept

The internationally patented *P*ort *F*eeder *B*arge (PFB) is a self-propelled container pontoon with a capacity of 168 TEU (completely stowed on the weather deck), equipped with its own state-of-the-art container crane mounted on a high column (see Fig. 20.1). The crane is equipped with an automatic spreader, extendable from 20 ft to 45 ft, and a turning device. A telescopic over-height frame is also carried on board. The PFB is of double-ended configuration, intended to make it extremely flexible in connection with the sideward mounted crane. Due to the big width of the vessel no operational restrictions (stability) for the crane shall occur (see Table 20.1).

The PFB crane has a capacity of 40 t under the spreader, at an outreach of 27 m (maximum outreach: 29 m). The vessel is equipped with 2 electrically driven rudder propellers at each end in order to achieve excellent maneuvrability and the same speed in both directions. Hence the vessel can easily turn on the spot. While half

[1]For example, empty container depots (see, e.g., PoHM 2017a and PoRA 2017a) or container packing stations (see, e.g., CPA 2017).

[2]Depending on the liner shipping company, the terminal handling charges for 20 ft and 40 ft standard containers amount to about 225 EUR at the port of Hamburg and about 205 EUR at the port Rotterdam (winter 2016/17).

Fig. 20.1 Port Feeder Barge (artist impression)

Table 20.1 Port Feeder Barge – main data

Type	Self-propelled, self-sustained, double-ended container barge
Length (overall)	63.90 m
Width (overall)	21.20 m
Height to main deck	4.80 m
Max. draft (as harbor vessel)	3.10 m
Deadweight (as harbor vessel)	2500 t
Gross tonnage	Approx. 2000 BRZ
Power generation	Diesel/gas electric
Propulsion	2 × 2 electrical rudder propeller of 4 × 280 kW
Speed	7 knots at 3.1 m draft
Class	GL ✠ 100 A5 K20 Barge, equipped for the carriage of containers, Solas II-2, Rule 19 ✠ MC Aut
Capacity	168 TEU (thereof 50% in cellguides), 14 reefer plugs
Crane	LIEBHERR CBW 49(39)/27(29) Litronic (49 t at 27 m outreach)
Spreader	Automatic, telescopic, six flippers, turning device, over-height frame
Accommodation	Six persons (in single cabins)

of the containers are secured by cell guides, the other half is not, enabling the vessel to carry also containers in excess of 40 ft length as well as over-dimensional boxes or break bulk cargo. Fourteen reefer plugs allow for the overnight stowage of electrically driven temperature controlled containers.

The PFB shall fulfill the highest environmental standards. A diesel- or even gas-electric engine plant with very low emissions has been chosen to supply the power

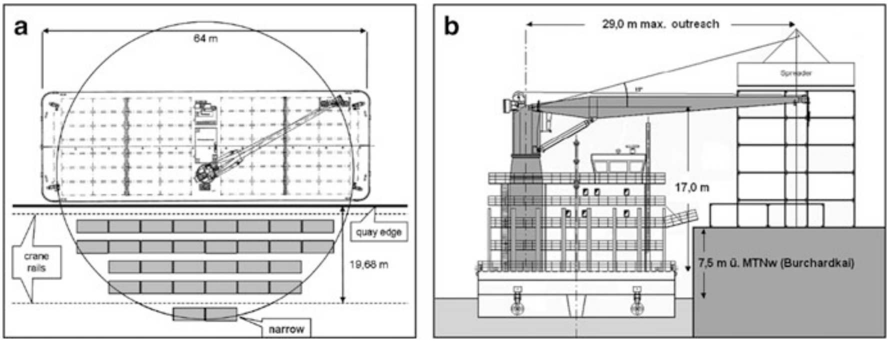

Fig. 20.2 (**a**) Turning cycle of crane, (**b**) Outreach of crane

either for propulsion or crane operation. The vessel can be operated by a minimum crew of 3 whereas in total 6 persons can be accommodated in single cabins.

The key element of the worldwide unique PFB concept is its own full-scale heavy duty container crane. All its mechanical components have been especially designed for continuous operation – unlike standard shipboard cranes, which are designed for operation only every few weeks when the vessel is in port. Due to its nature the load cycle requirements of the PFB are even higher than for many quayside cranes, which has a significant impact on the design of the mechanical components of the crane. When berthed the PFB is able, without being shifted along the quay, to load or discharge 84 TEU in three layers between the rails of typical quayside gantry cranes (see Fig. 20.2a). This is more than sufficient, with a total loading capacity of 168 TEU.

That is why the full outreach of the crane is not always needed. Berthing the barge with the crane on the opposite side of the quay (see Figs. 20.2b and 20.3) would speed up crane operation as the turning time of the outrigger is minimized. Depending on the specific conditions and the driver's ability the crane productivity is estimated to at least 18 moves/h.

The height of the crane column is sufficient to serve even high quays in open tidewater ports at low tide while stacking the containers still in several layers on the quay (or to serve even deep-sea vessels directly, see Fig. 20.6). Due to its short length of 64 m the PFB needs only a small quayside gap between two deep-sea vessels for self-sustained operation (see Fig. 20.3).

The operation of the PFB is not limited to inside a seaport or its neighborhood. As the hull is classified according to DNV-GL's class notification for seagoing vessels, the operation in (sheltered) open waters off the coast is also possible which opens some interesting opportunities for additional employment (see, e.g., Sect. 20.4.1). Considering intra-port container haulage the PFB shall ply between all the major and minor waterfront container handling facilities, including a dedicated berth to meet with the inland waterway vessels which can even be located somewhere at the dolphins.

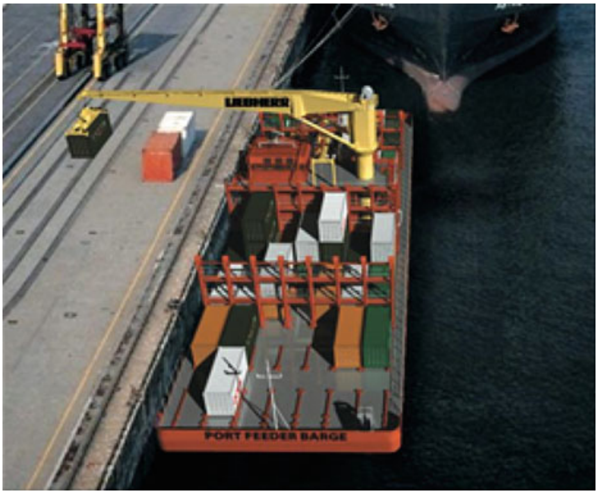

Fig. 20.3 The PFB is working independently from quayside equipment at a deep-sea terminal requiring only a small gap between two deep-sea vessels (artist impression)

20.3 Business Fields

20.3.1 Intra-Port Haulage on the Example of the Port of Hamburg

The PFB shall serve as a “floating truck” in the course of its daily round voyage throughout the port, i.e., shuttling containers between the various container facilities. Hence container trucking within the port can be substantially reduced.

It is estimated that in 2015 within the port of Hamburg approx. 290,000 containers, i.e., approx. 88% of the total volume, have been carried by truck (which is corresponding to approx. 475,000 TEU, Malchow 2016).[3] The remaining 12% have been already carried on the water by ordinary inland barges. The reason for the poor share of conventional barging is very simple: In most cases intra-port barging of standard containers is not competitive unless the liftings by the quayside gantries were subsidized by the terminals which cannot be expected.

According to industry sources one-third of the road haulage within the port of Hamburg is between two (out of four) deep-sea terminals while more than half is between the deep-sea terminals and off-dock facilities (like depots, packing stations, repair shops, etc.) of which some have their own water access (see Malchow 2016). Taking into account all aspects, e.g., no complete water access of all minor facilities and required cut-off time for the booking procedure, the present cargo potential

[3] According to the Port of Hamburg Marketing Board the average TEU ratio at the port of Hamburg was approx. 1.6 TEU/box in 2015.

Fig. 20.4 Typical view on Hamburg's Köhlbrand bridge linking the port's eastern and western part (German Press Agency)

for the PFB out of the intra-port haulage in Hamburg is estimated to roughly 95,000 containers p.a. (corresponding to approx. 150,000 TEU). At present approx. 50% (!) of all intra-port container trucking has to pass the frequently congested Köhlbrand Bridge (see Bönning 2009 as well as Fig. 20.4).

Considering the advantages discussed in Sect. 20.2, the PFB offers a more competitive service than the trucks can do. Beside lots consisting out of many standard containers, this especially applies to over-sized boxes like flats with over-width/-height and also boxes containing dangerous goods whose trucking requires special-licensed but very rare drivers. Hence the PFB operation can contribute to less congestion at vital bottlenecks on the roads within port areas and is a viable and much more environment-friendly alternative compared to trucking.

20.3.2 Feeder Operation

In multi-terminal ports common feeder services have to receive and deliver containers from/to all facilities of the port where deep-sea vessels are berthing. For this reason the feeder vessels have to call at all such terminals within the port – sometimes even if only a few boxes have to be handled.

For example, in the port of Hamburg the daily business of feeder operators shows that each of their vessels has to call in average at four different facilities (incl. waiting berths, see Behrend 2016 and Malchow 2015). In order to save some berth shiftings the companies make already intensive use of road haulage services. Otherwise the number of shiftings within the port would have been even higher. From the experience of deep-sea terminal operators, vessels with less than approx. 100 boxes to handle are critical with respect to profitability (see Meyer and Wörnlein 2008). However, at the port of Hamburg a big portion of all terminal calls of feeder vessels are below that figure. Smooth and efficient feeder operation is essential for the port's economic well-being as its entire container throughput relies to more than one-third on transhipment (about 36% in 2015, PoHM 2017b).

As the feeder operators are usually an important customer of the trucking companies for intra-port haulage the PFB can replace trucking for collecting and distributing containers in multi-terminal ports. With its cost advantage it is expected that the PFB will be used by feeder operators more intensively than truck services at present enabling the concentration of feeder calls on fewer terminals. This reduces the number of berth shiftings as well as the port time of the feeder vessels and related costs. Furthermore, it leads to increasing terminal and berth efficiency and is associated with significant improvements in safety (danger of ship collisions).

20.3.3 Inland Navigation

In general, inland navigation is facing a dilemma as far as the hinterland transport of containers to and from seaports is concerned. On the one hand, there is a common understanding that its share in hinterland transport has to be substantially increased – for capacity and environmental reasons. On the other hand, inland waterway vessels in sea ports have to berth at the facilities which are tailor-made for the biggest container vessels sailing on the seven seas (with a capacity of 22,000 TEU and possibly even more in the future). Hence the efficiency of the big STS gantry cranes is rather low when serving the small inland barges. It comes as no surprise (but is most disadvantageous) that inland navigation enjoys the last priority when it comes to berth allocation at deep-sea facilities (see Malchow 2007).

Inland barges suffer even more than feeder vessels as they have to call at more facilities. For example, the port of Rotterdam has approx. 30 terminals and depots (see PoRA 2017b, PoRA 2017c and PoRA 2017a) which are frequently served by inland barges (the barge share of hinterland container transport is steadily above 30% during the last decade, see, e.g., Pastori 2015, p. 9).

The average number of terminal calls per barge is about 10 whereas in 50% of all cases less than 6 containers are handled (see Konings 2007 and Konings 2005). This kind of inefficient and hardly coordinated "terminal hopping" is very time-consuming and each delay at a single terminal results in inacceptable accumulated waiting time during the entire port stay. Actually, roughly one-third of the time in port is only spent for productive loading/unloading (see Konings 2007).

In Hamburg – where inland navigation has still a poor share of approx. 2% in hinterland container transport (see PoHM 2017b) – the inefficient operation has been identified as one of the major reasons for such small share. Some Dutch and German studies regarding the problems of transhipment procedures between inland barges and deep-sea vessels have been already published (see Beyer and Pistol 2009; Konings 2005, 2007 as well as Menist 2008). One common recommendation is that container handling for inland navigation and container liner shipping should be separated from each other. In other words: Inland barges should not call at the deep-sea facilities any more.

It has been already proposed to introduce dedicated berths at the deep-sea terminals for processing inland barges. However, most terminals simply do not have any shallow draught waterfront left where such berths could be meaningfully arranged. Transforming existing valuable deep-sea quays to exclusive barge berths with smaller gantry cranes does not pay off for the terminals as such a measure would reduce their core revenue earning capacity. For smooth inland navigation, the introduction of a central (dedicated) terminal within a port, where all inland barges call only once, has also been proposed to spare the barges their inefficient "terminal hopping." However, this would burden the most environment-friendly and economical mode of hinterland transport with the costs of two further quayside crane moves and one additional haulage within the port (either on the water or even by truck). The opposite of more waterborne containers in hinterland transport would be the consequence. Nevertheless, a few facilities for processing non-deep-sea vessels have been put into operation at container ports in recent years. For example, since 2009 the ECT Delta complex at the port of Rotterdam is equipped with a 800 m quay wall and three smaller STS gantry cranes exclusively dedicated for feeder and barge processing (see ECT (2016)).

Hence increasing the share of inland navigation in hinterland transport of containers is frequently facing a dilemma in many major container ports. To overcome such a dilemma the PFB can act as a dedicated "floating terminal" for inland barges. During its envisaged daily round voyage throughout a multi-terminal port the PFB shall collect and distribute the containers also for inland navigation. Once (or several times) a day, the PFB will call at a dedicated berth to meet with the inland barges where the containers shall be exchanged ship-to-ship by the PFB's own gear, independently from any terminal equipment (virtual terminal call). Not even a quay is required but the transhipment operation can take place somewhere midstream at the dolphins (see Fig. 20.5). Such kind of operation would mean that the terminals would delegate their obligation towards their customers to serve also the inland barges partly or completely to the PFB.

A "floating terminal" provided by the PFB will strengthen the competitiveness of inland navigation and contribute to increase the share of the most environment-friendly mode of hinterland transport. Employing one or more PFBs as a "floating terminal" is less costly and much quicker and easier to realize than the erection of any equivalent quay-based facilities (not to mention that less parties have to be involved for approval and that operational flexibility increases appreciably). The entire PFB investment is in the range of the procurement costs of a single STS gantry crane which is designed to serve huge deep-sea vessels.

As ports can avoid heavy land-based investments and with that land consumption as well as changes in townscape, it is apparent that such a terminal concept not only provides economic and environmental advantages but beneficially affects urban issues as well. Considering all this positive impact, a "floating terminal" is much smarter than any land-based facility.

Fig. 20.5 The PFB is serving a conventional inland barge midstream (artist impression)

20.4 Further Applications

20.4.1 Emergency Response

The PFB can also help to keep consequences of maritime averages at a minimum. When container vessels are grounded in coastal zones they mostly have to be lightered very quickly to set them afloat again in order to avoid further damage to the vessel's hull, the environment, and in extreme cases to sustain even the accessibility of a port at all. However, it has to be conceded that most container ports are not really prepared for such a situation and do not have suitable floating cranes (if any) available to quickly lighter big container vessels.

Despite its small size the base version of the PFB (168 TEU) can rapidly lighter grounded container vessels of up to 6000 TEU capacity by working from both sides (Fig. 20.6). For bigger vessels the crane has to be mounted on a higher column and the crane's outrigger has to be lengthened. The average of M/V "CSCL Indian Ocean" in 2016 (see Fig. 20.7) has dramatically demonstrated that adequate salvage equipment is generally missing. If the containers from the ninth deck layer of such a grounded 19,000 TEU vessel had quickly to be lightered a floating crane would have been needed with a hook height of at least 60 m. Such equipment is worldwide very rare and hence was not quickly available in this special case. Unlike some other heavy floating equipment, the PFB can navigate in very shallow waters due to its light ship draught of only 1.2 m (base version).

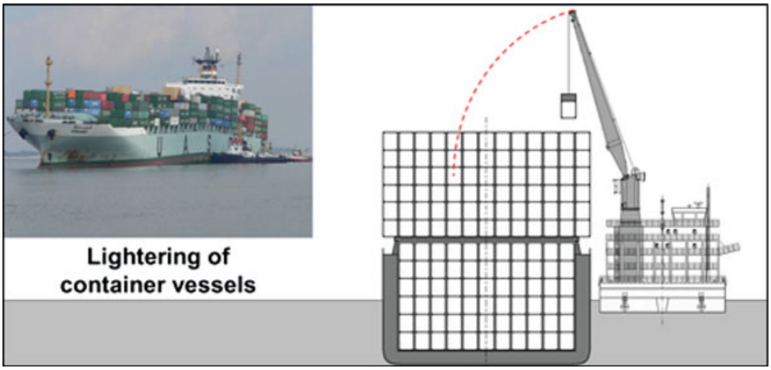

Fig. 20.6 Grounded Panamax container vessel on Schelde river in 2005 and how it could have been quickly lightered by a PFB

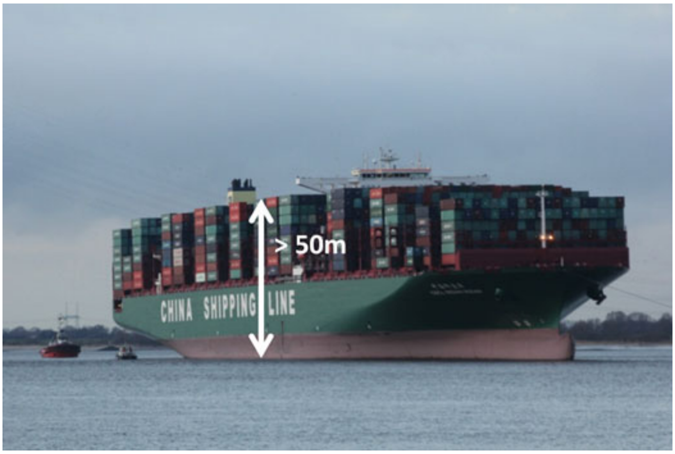

Fig. 20.7 M/V "CSCL Indian Ocean" (19,000 TEU) grounded in Feb. 2016 on Elbe river heading for Hamburg

20.4.2 Hong Kong Style Midstream Operation

In Hong Kong a considerable portion of the huge port's container throughput still relies on floating units directly serving deep-sea vessels while laying at anchor (see Fig. 20.8). These traditional midstream barges are equipped with their own cargo gear, but the handling method is far from being sophisticated. The A-frame derricks have a single beam just controlled by wires and are not even fitted with a spreader. Instead, steel wires are fitted manually to the corner castings of the containers. In fact, this cargo handling technology is from the 1950s and complies hardly with international port labor safety standards. Such midstream barges are only operating in Hong Kong (except a few in Angola and Vietnam). Still in the 1990s, up to

Fig. 20.8 Typical midstream operations in Hong Kong

ten fatal accidents per year were officially reported, whereas the handling method has not been improved since then (see Buddle 1998). Quite apart from the health and safety issues, they are not self-propelled (not even pushed but towed). The midstream share of the total Hong Kong container throughput has continuously decreased to less than 10% at present (see HKMOA 2017, MD Hong Kong 2017 as well as Wan 2009).

PFBs would significantly improve such ship-to-ship operation with regard to safety, efficiency, speed, flexibility, and accessible ship sizes. At other places of the world where terminal facilities are insufficient or congested or water depth is limited such advanced midstream operation provided by PFBs would be a viable alternative to the long lasting construction of costly land-based deep-sea terminal facilities. Beside pure container operation the PFB can also be used as a flexible floating unit with handling, storage, and transport capabilities. With a crane mounted on a column of 17 m and a capacity of 49 t under the hook (40 t under the spreader) complemented by sufficient deck space for any kind of cargo (other than containers), the PFB can also be used as an ordinary floating crane.

20.5 The LNG Option

All costly measures to be taken to keep the exhaust emissions of the diesel-electric engine plant at an envisaged minimum (e.g., exhaust scrubbers, urea injection, filters, etc.) could be saved when choosing LNG as fuel. The PFB can serve as an ideal demonstrator for LNG as ship fuel:

- As a harbor vessel it does not rely on a network of bunker stations. Only one supply facility is sufficient. As the power demand is relatively low the vessel could even be supplied out of a tank truck at the initial stage (a standard 50 m^3 truck load was sufficient for approx. 14 days of operation).
- Due to its pontoon type there is plenty of void space below the weather deck. Hence the accommodation of the voluminous LNG tanks would not be a problem at all which is not the case with most of the other types of harbor vessels. Approx. 500 m^3 of tank capacity could be theoretically installed which is by far more than sufficient as this quantity is good for several months of continuous operation (see Fig. 20.9).

As in the meantime ISO tank container for LNG are available (see Fig. 20.10) such units could also be used for bunkering purposes while making use of an environmental-friendly intermodal supply chain (instead of pure trucking). If the regulations allow, the units could be even loaded on the PFB with its own crane to serve as the vessel's fuel tank.

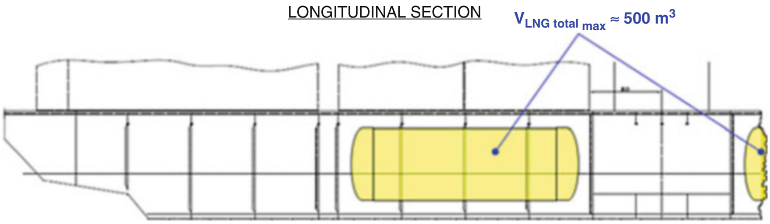

Fig. 20.9 LNG tank arrangement

Fig. 20.10 ISO tank container for LNG

20.6 Interface Between PFB and Terminal

Many discussions with all parties involved have shown that terminal operators' acceptance of self-sustained cargo operation at their facilities is a major hurdle for the PFB operation. Especially the unions of the terminal's labor force might oppose such cargo handling operation "from outside."

When the PFB calls at various container facilities within a port it has to be ensured that the entire operation is following well-established procedures. Such procedures have to be agreed upon in detail between the PFB operator and each individual facility in beforehand. The more sophisticated the terminal operation the more changes in the existing terminal routines have to be implemented. The following aspects have to be agreed upon:

- berthing procedures,
- physical box handling,
- data exchange, and
- commercial issues.

Firstly, it has to be checked whether the envisaged berths are suitable for the entire *berthing procedures* with the PFB. For example, the position of the quay fenders needs to be checked (considering all tide levels) and whether additional bollards for mooring the PFB are to be arranged in the quay wall. Furthermore, the procedure of berth allocation has to be determined at all terminals to be called at (e.g., how much time in advance).

With regard to the *physical box handling*, the relevant safety regulations have to be observed which most probably do not allow for simultaneous straddle carrier operation during any self-sustained cargo operation by the PFB (contrary to STS gantry crane operation serving conventional barges). That means that all boxes which have to be loaded by the PFB have to be put down on the quayside by the terminal before the PFB starts cargo operation with its own crane. Vice versa all boxes which have been discharged by the PFB can only be taken away from the quayside after the cargo operation of the PFB has been accomplished. Although the terminal does not need to use their own STS gantry cranes (incl. their crew) to serve small barges anymore, the relevant quayside might be blocked for a longer time than with "conventional" gantry crane operation. However, many terminals have berths of less occupation where such aspect is actually not relevant. Furthermore, there has to be an agreement on how the boxes have to be put down on the quayside by the terminal and by the PFB. (e.g., regarding the order, distances between the boxes, number of layers, etc.)

As a part of an adequate *data exchange*, there has to be an agreement on the minimum notice time which the PFB has to meet to inform the terminal in advance on the details of the containers to be handled. The necessary data flow, its format, and scope have to be fixed before the PFB operation commences. Depending on the terminal's general standard, such procedures can either be organized manually (in a "jumble of bits of paper style") or rather sophisticated by making use of wireless data exchange between the various facilities of call and the PFB and its operation center, respectively. The containers which are going to be loaded or have been discharged by the PFB need to be checked on their condition and whether they have a seal or not. If such data input is intended to be done by handheld devices, it has to be ensured that they can operate independently from any STS gantry crane where the respective receiving antennas are often located.

Commercial issues mostly refer to the so-called gate charge which the terminals are charging from their customers (container lines) for container receipt and delivery depending on the modes of pre- and on-carriage (truck, train, or barge). Compared to truck and train the gate charge for the pre-/on-carriage by (conventional) barges is much higher as STS gantry cranes (incl. their crews) are involved. In order to achieve the necessary competitiveness compared to intra-port haulage by truck it is essential that the gate charge for the self-sustained PFB is not higher than for trucks. However, this has to be agreed upon between the terminals and their customers, i.e., the container shipping companies. In case the PFB acts also as a “floating terminal” for the inland barges, a further agreement has to be made on the remuneration of such delegation of original terminal duties.

20.7 Conclusion

As there is no doubt that container volumes will certainly continue to increase – however on a smaller rate – ports and their terminals have to prepare to ease already experienced and foreseeable bottleneck situations and to reduce the environmental impact of container transhipment procedures at the quay wall. The PFB concept is a “green logistic innovation” for sea ports whose inherent beneficial effects to the environment can even be further increased by using LNG as fuel. The use of PFBs generally helps

- to shift container trucking within sea ports from road to waterway with all the positive effects on the traffic flow, emissions, and road safety (e.g., less dangerous goods on the roads),
- to ease feeder and transhipment operation within multi-terminal ports,
- to improve the intermodal connectivity of inland navigation within sea ports as well as
- to be prepared for lightering of even very big grounded container vessels.

In particular also the terminals would benefit:

- Their gates would be released from queuing trucks.
- They would gain flexibility in labor organization for checking incoming and outgoing containers.
- Their STS gantry cranes would be released from inefficiently serving small inland barges.

Furthermore, at places with insufficient or congested terminal facilities and/or shallow water restrictions (like in many developing countries) the PFB could facilitate the handling of deep-sea container vessels at anchorage.

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Chapter 21
Drayage Port: City Trucking

Jens Froese

Abstract Ports close to cities or even embedded within a city increasingly suffer from truck traffic to and from the terminals. Especially container drayage causes high traffic peaks to serve ultra large container vessels. Citizens complain about traffic jams, hazardous emissions and noise, forcing politicians to think about restricting rules and regulations having an impact on port productivity. Sustainable mobility is not at all a new idea; however, applicable technologies to make heavy port traffic more environmentally friendly without losing efficiency are just emerging. Most of the solutions described here are either in their early phase of introduction or currently under consideration. This explains the fact that the topic is a very dynamic one and there is a lack of references to proven applications. As new technologies might finally show deficiencies once deployed and others, not yet considered, may come up, this chapter will certainly require frequent updating during the next few years.

21.1 Introduction

Port hinterland connectivity represents a key selection criterion for liner shipping companies. From the modal split of hinterland transportation by

– truck,
– railway
– and barge,

truck transportation usually has the biggest share in most ports. Considering further increase in global trade as it is expected (see WTO 2018), both, the absolute and also the relative share of road transportation will even increase as it is the most flexible means of transport allowing door-to-door carriage without additional cargo

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handling. The growth of the rail segment is frequently restricted by lack of capacity which cannot easily become increased, requiring availability of land and high investment for infrastructure. Growth of inland waterway volume is particularly restricted by comparatively long transport times and limited access to customers sites in most regions, but also reliability problems arise as both, too high and too low water levels impair continuous transport flows, turning routing into a challenge.

Trucks may move almost the whole spectrum of commodities, from liquid and dry bulk via heavy loads and project cargo to containers, however, huge and still increasing container volumes cause the main headache in planning and control of transportation in and around ports. For long distance haulage, trucks are competing to railways and inland navigation barges, whereas short distance trips, i.e., the transportation between terminals and nearby consignees/shippers, freight stations, ware-houses, storages, cargo distribution centres and dry ports, require a very high degree of flexibility and therefore are mainly provided by truck services. This truck transportation segment is called *drayage*.

Port truck services, however, have become victims of own success resulting in traffic jams and increasing emissions. Effective drayage operation therefore is a key indicator for port efficiency, influencing shipping line decisions about port rotation.

21.2 Development of Port Volumes

Before the world trade recession in 2008 hub terminals in peak times moved over 6000 boxes (imports and exports) per vessel of about 12,000 TEU carriage capacity. This figure decreased in the following years and since about 2014 is continuously increasing, in 2017 reaching again the 2008-level and beyond (see WTO 2018). What vessel sizes and box transfer volumes have to be expected in the foreseeable future?

Almost 22,000 TEU vessels are already reality (2018) and up to 30,000 TEU vessels appear technically and economically feasible. An increase of the number of ports in a service string's port rotation is not expected as consolidation contributes to reduction of liner costs and accordingly longer rotation times are avoided. Hence, the number of boxes to be handled at one terminal will further increase.

*U*ltra *L*arge *C*ontainer *V*essels (ULCV) of about 400 m of length (24 bays) theoretically allow a crane intensity[1] of up to 12 *S*hip-*T*o-*S*hore (STS) cranes, depending on the distribution of bays between forecastle, bridge superstructure, funnel segment and stern. However, distribution of boxes over the bays and the associated crane split usually does not allow to engage more than 9 cranes economically. Furthermore, this also prevents from congestions of horizontal transport vehicles under the cranes, resulting in crane waiting times and hence reducing overall productivity. Based on the author's experience, currently, 5–7 STS cranes per ULCV can generally

[1]Number of cranes working on a vessel on average.

be assumed resulting in a total number of container moves per port stay of about 4000 on average and between 6000 and 7000 in peak conditions. In the view of 22,000 TEU vessels coming soon into operation and assuming increasing global trade, terminals need to be prepared to handle about 10,000 container moves per vessel and port stay in the near future.

It is difficult to estimate trade and transport volumes beyond a decade; however, there are indications that container vessel capacities will not increase over 30,000 TEU and might even stay well below. Besides ship design restrictions, where length is an operational key factor, this is not a question of trade volumes, which is expected to grow sufficiently to feed bigger ships, but necessary high investments into port and waterway infrastructure and of container handling equipment are seen to kill business models. Concentration on only a few "super-hub" terminals could be a solution to allow extreme big vessels; however, costs for the vessel call and cargo distribution, resulting in increasing distances by sea, road, railway and inland waterways need to be balanced out.

Also when considering about 10,000 container per vessel and port stay, shipping lines usually expect port stay duration not to exceed 36 h (requiring a gross berth productivity of about 280 container moves/hour) and in any case it should remain less than 48 h. Depending on the terminal, this is currently only achievable with a crane intensity of 8–9 cranes per vessel and a crane split allowing smooth engagement of all cranes during almost the whole discharging and loading operation. Noting that such a handling scenario has a quite theoretical nature from the operational point of view. Additionally, there are a limited number of terminals being able to work more than two ULCVs with at least 5 cranes per ship simultaneously. Thus, a realistic volume calculation to determine drayage requirements for a common terminal may be based on the assumption of total about 8000 container moves over 36 h for two vessels worked in parallel for the time being and about 15,000 containers as a perspective for the next decade. Progressive terminals are well advised to aim at the ability to handle up to 20,000 container moves working simultaneously on two ULCVs. Bigger ports with more than one container terminal need to calculate the accumulated volumes for the whole port.

Usually 3–4 days before the vessel arrival and 3–4 days after the departure, the majority of boxes is supplied to the yard and picked up again, resulting in traffic peaks. To determine drayage volume upon total terminal throughput one must know the

- transhipment volume, i.e., the number of containers going from ship-to-ship and in between they are stored at the yard,
- feeder factor, i.e., the percentage of boxes to be transhipped to and from feeder vessels,
- volume of long-distance road haulage,
- railway volume and the
- inland barge volume.

Then the modal split and hence the number of boxes, being moved to and from the yard from and to local port and hinterland sites by *truck*, can be calculated. Frequently, volumes are only provided in TEU. To determine the number of boxes, in these cases, the TEU figures need to be divided by the TEU factor, providing the ratio of TEU volume to box volume. As a rough estimation currently (2018) a TEU factor of 1.6 is applicable in many container ports. As the share of 40 ft and 45 ft boxes compared to 20 ft boxes is still increasing, the TEU factor will further increase, too. The flow of (full) hinterland boxes to and from the yard does not yet indicate the total port container transport, additional transportation of

- *empties* (MT) from an MT depot within the port area to an enterprise or freight station to be packed or vice versa after stripping from an enterprise to an MT depot,
- MTs from depots to terminals to be shipped back resulting from asymmetric transport flows,
- repositioning of full boxes between different port terminals.

need to be counted. As container transport processes and the modal split do not change rapidly, determining the ratio of

the annual container moves by truck generated on
transport relations between port terminal and hinterland
vs.
the annual container moves by crane counted at terminal quay wall

results in a useful parameter for port traffic planning. According to the author's experiences, for most Northern European tri-modal container terminals in seaports, around 60% of the boxes moved by STS cranes come from or end up on a truck.

21.3 Truck Traffic Annoyances

Truck drayage in port cities increasingly comes under pressure because of being seen as a significant cause of traffic jams, hazardous emissions and noise (see Lange et al. 2017; Mongelluzzo 2018). In terms of environmental impact, trucks and buses are responsible for about a quarter of carbon dioxide (CO_2) emissions from road transport in the *E*uropean *U*nion (EU) and for some 6% of total EU emissions (see EU 2017). Air pollution remains the number one environmental cause of death in the EU, still leading to about 400,000 premature deaths each year in the EU due to elevated levels of fine particles and ozone (see EU 2018). Nitrogen oxides (NO_x), however, meanwhile overtook particulate matter (PM) as number one killer. One of the German cities frequently having difficulties to maintain the EU clean air requirements is Stuttgart. To identify emission sources and conditions and to allow for mitigation, a comprehensive monitoring system was established. Air analysis in the city centre showed that about 50% of PM comes from traffic, about 25% from fire places, the remaining 25% come from agriculture, pollen, dust from construction sites, bulk cargo transfer and other sources (see Schadwinkel and Stockrahm 2017). Of course different cities will show different measurement results, however, it can be taken as a rough indication.

Traffic-induced PM is not only caused by combustion engines, significant sources are abrasion from clutches, brakes, tires and asphalt, resulting in dust which continuously is raised by the traffic (see Asendorpf 2016). The conclusion is, that even when all diesel- and petrol-fueled vehicles are replaced by electric propulsion the cities would be left with about 75% of the current PM pollution. This is of course not an argument to stay passive but it helps to prioritize combating targets according to significance. As public and private capital is restricted and not all problems can be solved at once, it is important to determine an optimized roadmap.

Diesel-fuel results in higher NO_x emissions than from petrol but in a lower carbon footprint. There is no common understanding how to assess emissions, the USA and Europe have quite different views resulting in diverse allowances. The plea to policy makers is to first measure true impact on environment and investigate causes thoroughly before deciding on rules and regulations.

Another aspect making it difficult to compare measures and effects is, that there is no uniform method to measure Air is not a static medium but swirls around, the positions of the measurement sensors have a significant impact on results. Moving a sensor by a few hundred of meters can change the situation form "clean air" to "above all limits". Furthermore, medical science meanwhile proved that particle sizes of less than 0.1 μ ($PM_{0.1}$) of aerodynamic diameter, i.e., ultrafine particles, are dramatically more lethal than the bigger fractions but only PM_{10} and $PM_{2.5}$ are currently being measured and covered by regulations.

There is no doubt, diesel- and petrol-fueled vehicles in cities present a serious health hazard but before requesting countermeasures one should exactly know where the most dangerous enemies are and how to combat best. Premature regulations do not only miss targets, they also hinder further research to find better solutions. This is not advocating ports to lean back and wait. The first necessary step also for ports is to measure and analyse, means to

- install a close-mesh sensor grid to capture traffic and emissions,
- explore sources and sinks of trucks and nature of load, either by statistically significant numbers of interviews or by transponders to be read automatically, 0.1 cm
- investigate the cause and effect chain and conditions to control it.

Only then it is possible to rationally discuss mitigation measures and to allow timely preparation to meet future requirements in an effective and efficient way.

Protection of environment is subject to quite distinct technical, social and political views frequently lacking comprehensive competence but focusing on niches or following individual needs. The only way for ports to not get into a punching ball role between different interests is to either develop own competence or to cooperate with competent institutions. To ensure sustainability of port operations is a challenge and measures to meet upcoming requirements will cause high investments if not properly anticipated and organized. However, no terminal or port enterprise should walk alone, involvement of all port stakeholders (including opponents) will pave the way for accepted sustainable operations solving conflicts between economy, ecology and society. Bundling resources will improve the cost-benefit ratio.

21.4 Opportunities to Mitigate Annoyance

There are opportunities to make container drayage more sustainable depending on the urgency (time-scale), budgets and technologies. The following catalogue categorizes promising organizational and technology-based measures for improving drayage operations in this regard. Furthermore, Lange et al. (2017) provide a classification of literature especially dealing with concepts, methods and IT driven solutions on the organizational level.

21.4.1 Capacity Utilization

On short term by far the biggest effect could be achieved by simply reducing transportation by better exploiting available transport capacities. The following catalogue of possible measures mirrors the discussion currently ongoing in a number of port cities confronted with annoyances from road hinterland traffic:

Gate Slot Systems
Some terminals apply gate slot allocation already but it must be understood that this will only reduce long waiting queues at the gates resulting in the trucks must find another place to wait and there is no relief for port traffic in general.

Chassis Exchange Stations
Often it is not possible to carry a box from pick up point (terminal, consigner/shipper) directly to point of delivery (consignee, terminal), thus the trucks must wait somewhere. Providing secure (to meet requirements of carrier liability) buffer areas allowing to drop or pick up a (loaded) chassis would avoid waiting times of the trucks and thus increase productivity of the transport system as a whole.

Ramp Access 24/7
Figure 21.1 shows the distribution of container truck arrivals and departures of a typical northern European container terminal concentrating between 05:00 and 19:00, due to working hours of drivers but also because ramp access at most warehouses is restricted. It will not be easy to convince ramp owners to provide pick up and reception services 24/7 but there are organizational-technical solutions available to ensure secure box delivery and pick up without support of ramp staff. Figure 21.1 shows that average in-/outbound truck peaks will be reduced by about 40% when distributing the traffic equally over 24 h a day (uniform distribution). In practice,

uniform distribution will never be feasible but, based on the author's experiences, also a conservative estimation results in about 20% average peak reduction as potential.

Transport Order Management

A traffic survey in the port of Hamburg (see Ehrler and Wolfermann 2012), interviewing 1086 truck drivers, resulted in only 39% of all trucks carry a box in and out of the gate, the other 61% go one trip empty (see Fig. 21.2). This is a result of free competition where each trucking company individually chases transport orders. The ideal solution would be a transport order management system virtually merging all trucking companies to allow to optimize exploitation of capacities, i.e., minimizing empty trips without distorting fair competition. Thus, new business models are required for the haulage industry enabling joint operations planning for better utilization of truck fleets, for example.

Improved Planning Ahead

*T*erminal *O*perating *S*ystems (TOS) have the potential to estimate availability of an import box to be picked up by truck rather accurate and hence could contribute to control the flow of trucks. However, as the nominal cargo owner decides when a box shall be picked up or delivered, this potential can only become tapped jointly with the cargo owners. There are still a few problems to overcome in order to invent push services (terminal in control of box pick up) instead of the current pull services (cargo owner decides on box pick up). Of course, close cooperation of terminals, haulage companies and consignees would be the prerequisite but this does not automatically mean higher workload for them as intelligent interoperability of existing IT-systems could provide automated solutions. To the knowledge of the author, there are TOS developers already working on features for mutual planning of the yard operations system and (external) transportation systems.

Separating Truck Traffic from Individual Car Traffic

Terminal employees and port workers nowadays usually commute by private car. Thus, during morning and afternoon hours and before and after shift changeovers, ports experiences peaks of individual traffic. If this coincides with peaks in truck traffic, which usually is the case around the afternoon shift changeover, traffic jams are the result. In most cases, ports will not be in the comfortable situation to provide double road connections in and out of the port, one for trucks and the other for private cars, however, an alternative could be to combine voluntary change of traffic attitude of commuters with regulatory measures, e.g., by providing an excellent and comfortable waterborne ferry service from (toll-free) park garages at the port periphery, shuttle buses for the last mile in the port and inventing a (time-dependent) toll-system for private cars using port roads.

Assigning One-Way Roads Including the Terminal Gates

Thus allowing for round trips of trucks instead of bidirectional traffic. One-way roads should provide at least two lanes to prevent from blocking the whole road in case of accidents. Noting that related measures presuppose enough road capacity or space, respectively.

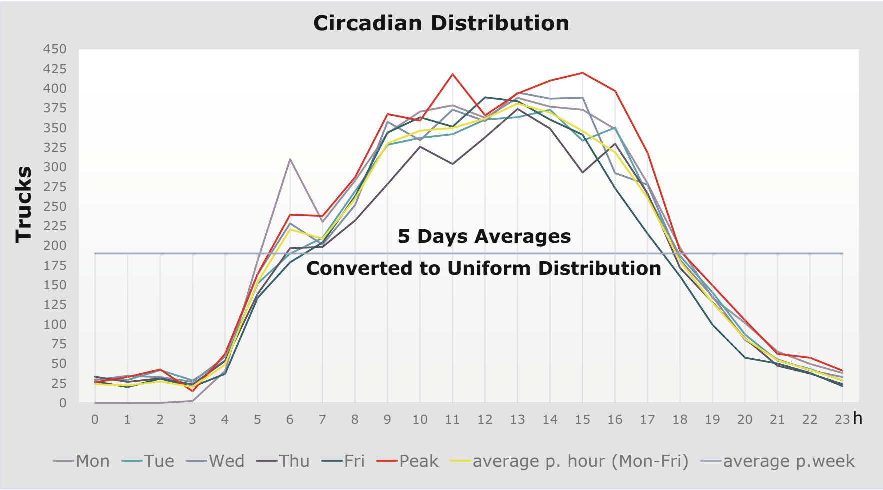

Fig. 21.1 Number of in-/outbound trucks per hour at a Northern European container terminal – including the circadian distribution for all working days as well as the circadian distribution of 5-days peak (red) and 5-days average (yellow) and a uniform distribution assuming an equal number of arrivals from Monday to Friday (grey), see Froese and Töter (2016)

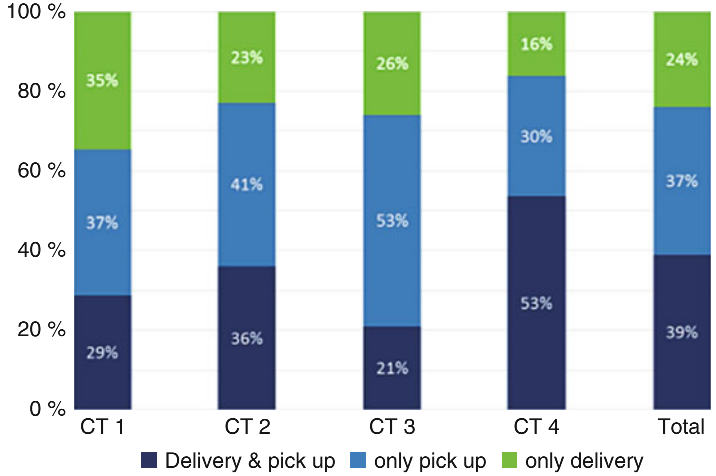

Fig. 21.2 Delivery and pick up of boxes at container terminals in Hamburg (see Ehrler and Wolfermann 2012, modified)

Empty Container Depots
To be established in areas where the impact of container transports by truck on common port traffic is minimum.

Time Slots for Transports of Empty Boxes
To avoid queuing trucks at MT depots blocking terminal access and port cross roads.

Empty Boxes Exchange Between Carriers
To allow feed of MTs from and to terminals from the most appropriate depot.

21.4.2 Alternative Fuel

Emissions of primary concern from burning conventional fossil fuels (diesel and gasoline) include hydrocarbons, NO_x, carbon monoxide (CO), CO_2 and PM. Methane[2] (CH_4) as fuel for combustion engines results in significantly less emissions. PM is reduced by about 95% and carbon dioxide by about 10%. Because of the higher calorific value, consumption is about 10% lower and it results in a slightly lower noise level. Regarding carbon footprint savings, it very much depends on the engine effectiveness and the way of refuelling. As unburned methane escapes to the atmosphere by the tailpipe and during the refuelling process the advantage may easily turn into a disadvantage. Noting that the global warming potential of methane is about 23 times higher than that of carbon dioxide. Pre-dominant methane source is purified naturally occurring *hydrocarbon gas*. Also organic waste can serve to produce bio-methane. In vehicle tanks, methane can be stored under pressure of about 230 bar (*C*ompressed *N*atural *G*as: CNG), requiring high pressure tanks, or liquefied (*L*iquefied *N*atural *G*as: LNG) under extreme low temperatures (about −162 °C), requiring cryogenic tanks.

There is currently no satisfying overage of CNG and LNG refuelling stations, hindering a quick introduction of natural gas as fuel. However, as drayage operations mostly occur in rather limited areas requiring only a few refuelling stations, conditions in ports and the nearby hinterland are favourable to drive on natural gas as an environment-friendly fuel. Methane-fuelled trucks are available on the market but the comparatively high purchase price is still a major impediment for wider dissemination in the transport sector. Furthermore, ports also expected to benefit from the increasing usage of LNG to fuel ships, hence availability in ports will increase.

From the environment-friendly point of view hydrogen (H_2) is even more favourable than methane, however, production is expensive and flammability is higher. Additionally, it is more corrosive and has lower leak tightness due to a lower molecular weight, hence, requiring special materials for engines and tanks.

[2]Methane accounts for by far the largest share in natural gas. Depending on the place of discovery the share ranges from 75 to 99 mole-%. Therefore, the gases are frequently treated as being the same.

In coastal areas with generation of wind energy often excessive production occurs which does not find consumers, the surplus energy can serve for decomposition of water (H_2O) into oxygen (O_2) and H_2. As only a few refuelling stations would be required to supply drayage trucks, hydrogen may well serve in ports, too. For both, methane and hydrogen, ports may consider to use these fuels comprehensively for trucks, terminal equipment, tugs, port barges, etc., hence gaining from economies of scale.

Other alternative fuels like bio-diesel (nowadays mostly used as an additive to diesel) ethanol and methanol can serve to fuel combustion engines. However, there are currently (2017) no significant applications for trucks.

21.4.3 Electric and Fuel Cell Drivetrains

21.4.3.1 eTrucks

E-vehicles run on battery power and are not per se more environment-friendly than diesel vehicles; however driving an electric car results in shifting where the environmental impacts are allocated. Environmental impacts from e-cars are mainly caused by battery and power production.

Life-cycle assessment, from “cradle to grave”, does currently not result in favour of e-vehicles. Of course the *global warming potential*, i.e., the carbon footprint, of e-vehicles is about 23% lower than of combustion engines but the *human toxicity potential* is about 3 times larger (see Brennan and Barder 2016). This, however, does not call for stopping e-vehicle development. It very much depends on the production of electric energy. If the percentage of regenerative energies used for recharging is very high, the e-vehicle gets into the pole position (see Asendorpf 2015). Exploiting the innovation potential in battery-techniques, reducing vehicle weight and charging by power from regenerative sources only, on the long run will justify e-vehicles. There are already big advantages of e-vehicles:

- Emissions do not pollute cities as power generation and consumption is de-coupled.
- Emissions producing power plants may be far away.
- There is low noise emission, which means e-trucks may also serve inner-city areas with noise restrictions at night. However, also e-trucks are not noiseless as tires emit noise when driving, the noise level very much depends on the tire profiles, the asphalt and on weather conditions.

There are currently (2017) no tractor trucks with electric propulsion available to fully meet requirements for container drayage. For example, BMW jointly with Terberg in 2015 successfully tested a modified terminal tractor as e-tractor truck capable to serve about 100 km distance before requiring recharging, allowing for a maximum speed of 40 km/h (see Kohagen and Hector 2016, Fig. 21.3). The speed is slightly too slow to serve an adjacent city area or the nearby port hinterland

Fig. 21.3 40t e-tractor truck, Terberg and BMW (J.Reichel/Logistik Heute)

Fig. 21.4 Urban eTruck (see Daimler.com)

but the performance does meet already short distance transports, e.g., to handle internal transports between a terminal's container yard and its MT depot.

In 2017, for example, Mercedes-Benz commenced production of the "Urban eTruck" in small quantities, the full production is planned for 2020. With a payload of 12,8 t this truck is more a van-type and not adequate to serve for container drayage (see Fig. 21.4). However, it will certainly not last long until e-trucks become capable to serve for drayage. The high investment costs for e-trucks, said to still be considerably higher than conventional trucks, currently prevents from quick market penetration. As costs can only go down with large numbers produced, there is a hen and egg problem.

Fig. 21.5 Urban eTruck (Scania/Siemens)

21.4.3.2 Catenary Trucks

To benefit from electric propulsion without the disadvantages of heavy battery-packs requiring continuous recharging or to search for hydrogen refuelling stations, a very old technology is being revitalized in Germany: catenary powered trucks within an advanced transportation concept called *eHighway* (see Siemens 2017, Fig. 21.5).

A first testbed had been successfully installed to serve the Swedish port of Gävle and another port-oriented testbed is currently under development for San Pedro Bay, the ports of Los Angeles and Long Beach (see Roether 2017). Additional test installations for other than port services are currently (2017) realized in Germany, expected to come into operation in 2019.

The trucks, Scania in Sweden and Volvo in San Pedro Bay, are hybrid trucks allowing to automatically switch to diesel traction once the catenary connection is not available. This allows, e.g., to overtake on the highway even if only one lane provides catenary service, or to manoeuvre at a terminal yard.

There are obvious benefits of the system, which could be installed along dedicated roads between terminals and a city or a railway terminal. The necessary infrastructure for the catenary is seen as a hindrance; however, the drayage conditions are ideal as roads can be dedicated, carriage distances are short and utilization is high to justify the investment.

21.4.3.3 Fuel Cell Trucks

Production of electric energy by fuel cells reverses the process to crack water into hydrogen and oxygen by electrolysis. Hence fuel-cell vehicles require hydrogen to produce electricity. Battery-powered trucks suffer from range problems, even when drayage tours are considered to be short, recharging or replacing batteries requires to drive to dedicated stations and wastes time. Thus the combination of battery and fuel cell can solve this problem assumed that hydrogen fuel stations are available. Development is currently hindered by an egg and chicken problem. As long as there is not a significant number of vehicles using hydrogen, there will be no investment into a fuel station network and because there are only very few hydrogen fuel stations no freight forwarder will risk to run out of hydrogen far from the next fuel station.

San Pedro Bay California, where the ports of Los Angeles and Long Beach are situated, often plays the protagonist role in order to reduce traffic-induced emissions (see Shumaker and Serfas 2017). Under the *California Sustainable Freight Action Plan* in summer 2017 a feasibility study was initiated to test Toyota Motor Corps.'s hydrogen fuel-cell trucks (see PT 2017).

21.4.4 Autonomous Driving

Autonomous driving recently became a buzzword in driving technology. In May 2015, the first self-driving truck was brought on the road in the State of Nevada, United States (see DW 2015), and there have been and still are several tests around the world since. Current testbeds are dealing with *level 3* autonomy (see Fig. 21.6). However, technology development never stops and thus *level 4 tests* on public roads are at the doorstep.[3]

Nevertheless, before autonomous truck driving (on *level 4*) will become reality in every-day-traffic many hurdles must be overcome. The technology appears feasible soon but there are also legal and ethics questions to be answered. The concept, however, should be understood as comprehensive set of driver assistance systems, which only in its final stage will be capable to make a human driver redundant. Today, system components, e.g., for lane keeping and autonomous braking are already state of the art for equipping vehicles. In relation to drayage, in particular, the adaptive speed control feature is of interest, to always adjust driving speed

[3]There are basically classified six levels of autonomous driving. On *level 0* the human driver does all the driving and on *level 5* humans are just passengers and need never be involved in driving (see NHTSA 2018).

Autonomous driving on *level 3*:
An *A*utomated *D*riving *S*ystem (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.
Autonomous driving on *level 4*:
An ADS on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human need not pay attention in those circumstances.

Fig. 21.6 Autonomous driving truck (see thefuturesagency.com)

in order to maintain the optimum flow of whole traffic assumed that there is a comprehensive traffic management system operating.

A vision for ports may be to assign dedicated roads between terminals and buffer parking/chassis swapping areas and thus create the ideal environment for autonomous driving under controlled conditions. Comprehensive traffic management may then serve to permanently optimize traffic flows. A speed pilot can be told to drive, e.g., 7.5 min at a speed of 34.5 km/hr and then accelerate to 42.0 km/hr for another 9 min if appropriate to maintain smooth progress. Human drivers always tend to go at maximum possible speed which results in being forced to brake again and hence creating the so-called caterpillar effect. In other words, they are going fast, breaking and slowly again accelerating being associated with considerable reduced traffic throughput. Autonomous driving features are expected to soon contribute to comprehensive intelligent transport systems managing both, cargo and vehicle flows, in order to maximize usability of resources and sustainability of operations.

21.4.5 Road Infrastructure

There are many ports being squeezed in neighbouring industrial and residential areas, so that all approaches described above may not serve to mitigate annoyances sufficiently. Investing in infrastructure then is the only possible coup to prevent from suffocation. Of course, this requires big budgets but when shipping companies and sea freight forwarder commence to swap ports, it could become the most economic solution.

Even when budgets are available it is not easy to project port access roads in densely settled areas. The only way then might be to use the third dimension, i.e., either construct tunnels (compare, e.g., Port of Dublin) or flyovers (compare ports, e.g., of Genova or Singapore). Considering these options, a rather drastic step is the relocation of the total port infra- and suprastructure to a more advantageous traffic site (with superior accessibility and capacity conditions) as the Port of Rotterdam did it some decades ago by starting the Maasvlakte project (see PoR 2018). It can only be recommended to port and city planners to include these options into their long-term planning as early as possible. Even if not to be realized within the next generation or even never. To foresee such options today may take the headaches away of coming generations.

21.5 Innovative Drayage Solutions

21.5.1 Repositioning of Port Facilities

Main causes of truck drayage contribution to port city traffic problems are originating from lack of space to better distribute traffic flows, thus innovative drayage solutions must result in lesser and better organized traffic within the port area itself as well as to and from the nearby city or hinterland locations, respectively. The roadmap for improvement must be based on a comprehensive picture of sources and sinks and related conditions (like type, time, volume and restrictions of transport flows). Main relevant truck flows are between

- The city (port entrances)
- Terminals
- Freight stations
- Transhipment stations
- MT container depots
- Container weight verification stations
- Customs check stations
- Container scanning stations
- Veterinarian check stations
- Container cleaning and repair station
- Truck parking areas
- LNG and hydrogen refuelling stations (if applicable)

Ports, especially bigger ports, are very heterogeneous industrial structures with quite different enterprises from terminals via logistics service companies to production plants, all aiming to fulfil their own goals. The results therefore frequently lead to mutual conflicts. Accordingly, wherever feasible, traffic sources and sinks within the port area need to become positioned in such a way that excessive overlapping and accumulation of traffic flows can be avoided. This can be achieved by repositioning and/or by time slot allowances, the latter however is complicating truck scheduling.

21.5.2 Advanced Traffic and Transport Management

Smart transport and cargo management technologies are especially provided by two research areas called "Industry 4.0" and "Internet of Things". Related technologies allow for interlinking all operational entities on an ad hoc basis (not restricted to subscribers) and optimizing the whole system in order to achieve maximum overall productivity at minimum exploitation of resources. This means a change of paradigm to establish cooperative resource management in a highly competitive business environment. To ensure data protection, currently the main hindrance in cooperation, trusted third party process brokers might be required.

21.5.2.1 Traffic Management

All cities apply variations of *traffic management*, from simply controlling traffic lights to the optimization of entire traffic flows. Traffic management on road networks does however not influence the point in time of traffic generation.[4] Related systems just try to manage what shows up on the roads. Regarding port induced traffic the following two examples demonstrate that both appears possible, to control the generation of traffic movements over time (incl. drayage) and to manage flows:

- By combination of gate slot allocation, pick up/delivery slots "at the ramp" and buffer parking/chassis exchange a smooth flow of boxes can be organized assumed that there are interoperable IT-systems providing the necessary data to base optimization decisions on. Buffer parking/chassis exchange must always be the second best solution as direct flows from pick up to delivery are the most economical solution (see Sect. 21.4.1).
- Traffic jams in ports, resulting in stop-and-go traffic with continuous acceleration and deceleration is maximizing emissions by both, maximum engine emissions and long exposition times. Reducing travel speed will reduce emissions and relief drivers from stress. Smooth traffic flows also result in higher traffic throughput compared to stop-and-go traffic. But what is the ideal travelling speed to avoid traffic jams?

  In this regard, simulation allows traffic forecasts upon known key parameters, but also can well serve to control actual traffic in real-time, hence always advising on the appropriate speed to ensure optimum flow. This requires a comprehensive fleet management system being able to capture all relevant traffic data and to address trucks and other vehicles.

[4]In contrast to air transport where an airplane will not be allowed to take off before the landing slot is cleared.

21.5.2.2 Intelligent Transport Systems

Directive 2010/40/EU from the European Commission (see EU 2010) provides a rather clear picture of what they expect from intelligent transport systems:

> "*I*ntelligent *T*ransport *S*ystems (ITS) integrate telecommunications, electronics and information technologies with transport engineering in order to plan, design, operate, maintain and manage transport systems. The application of information and communication technologies to the road transport sector and *ITS* interfaces with other modes of transport will make a significant contribution to improving environmental performance, efficiency, including energy efficiency, safety and security of road transport, including the transport of dangerous goods, public security and passenger and freight mobility, whilst at the same time ensuring the functioning of the internal market as well as increased levels of competitiveness and employment."

Optimizing truck drayage in order to reduce traffic by truck-miles driven, not by volumes carried, requires efficient IT-systems and reliable interoperability of all relevant systems equipped with sensors. Necessary technologies are available or under development under the topics "industry 4.0" (automation) and "internet of things" (machine-to-machine communication). It is expected that this development leads to an increase of data communication volume by factor 10^3 within the next 10 years. Furthermore, estimates say that 50 billion devices will communicate by the year 2020, an important sector will be vehicle-to-vehicle communication. For example, autonomous driving is only possible once extremely reliable real-time communication is available. The current 4G standard in mobile communication will not sufficiently meet these requirements but the new 5G-standard, currently under development appears promising. System solutions "on the local level" based on the WLAN-standard IEEE 802.11p (5.9 GHz) are already feasible, e.g., allowing traffic sensors "talking" to vehicles and traffic management centres.

Severe concern, however, causes IT-security. Experts state that no system can be fully protected against external manipulation, it is only possible to rise the intrusion threshold to reduce the risk. Since hospital systems, for example, have already been hacked (see CBS 2017), it is not unthinkable that intruders try to manipulate transport systems. High standard IT-security must be taken into account from the very beginning of development of applications and this is very costly. The distributed ledger (Blockchain) technology (see e.g. Drescher 2017), however, appears promising to ensure a high degree of cyber security at reasonable costs.

21.6 Conclusion

The pressure on ports by the public and, as consequence, also from policy makers to mitigate annoyance from hinterland road traffic increases. Ports face the task to square the circle by reducing emissions and drayage costs at the same time. This chapter provides the scope of potential measures according to the current state of the art. Optimum solution widely depends on local infrastructural, operative and political conditions. Infrastructural measures are long-term activities requiring high investments and unambiguous conceptions of future operations to really meet these. Purchase of advanced equipment results in high capital expenditures including uncertainties about effectiveness.

It is obvious that ports and drayage operators cannot manage all challenges alone not knowing if the selected concepts are truly future proof. There is currently no unequivocal experts' opinion about the optimum trend to follow.

Comprehensive research and investigation are required to identify technologies contributing to holistic solutions, business and environment equally can benefit from. Politics must create a framework to allow for "living labs" in order to identify best technologies and practices. Public funding is required to award entrepreneurs taking the risk to invest in not yet proven solutions. Last but not least global cooperation and communication is required to avoid fragmented parallel activities but to complement each other in order to identify a comprehensive picture of a sustainable and successful port industry.

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Chapter 22
Port and Dry Port Life Cycles

Aligning Systems Complexity

Gordon Wilmsmeier and Jason Monios

Abstract The aim of this chapter is to revisit in the context of more recent work in the field the work of Cullinane and Wilmsmeier (The contribution of the dry port concept to the extension of port life cycle. In: Böse JW (ed) Handbook of terminal planning. Springer, New York, pp 359–380, 2011) on the contribution of the dry port concept to the extension of the port life cycle. This extension relied on the use of vertically integrated corridors between the port and the dry port to move containers quickly and smoothly from the port to the hinterland for processing and stripping. This chapter brings another layer to this conceptualisation by adding the inland context, applying the intermodal terminal life cycle of Monios and Bergqvist (Intermodal freight terminals: a life cycle governance framework. Routledge, Abingdon, 2016), in order to discuss synchronicities between the port and inland terminal (or dry port) life cycle. Both seaport and dry port in the hinterland have their own institutional governance structures, national and local policy and planning regimes and internal investment strategies regarding infrastructure capacity limits, and these change over time according to the different life cycles. Yet the demand for improved quality of port–hinterland access to facilitate trade means that the two nodes must increasingly work together, which is already demonstrated in increasingly integrated ownership and operational models. However, for port–hinterland transport to function smoothly, it is essential to understand both potential synergies and conflicts between various stages of the port and dry port life cycles.

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22.1 Introduction

The aim of this chapter is to revisit in the context of more recent work in the field the work of Cullinane and Wilmsmeier (2011) on the contribution of the dry port concept to the extension of the port life cycle. In their chapter, the authors showed how dry ports can be used to increase port capacity by shifting containers inland for processing. Fierce port competition in the years leading up to the global economic crisis in 2008 saw ports using dry ports as tools of port competition, using freight facilities in the hinterland not simply for transporting containers inland but also for customs clearance, processing and administration activities (see Notteboom and Rodrigue 2005; Roso et al. 2009; Monios and Wilmsmeier 2013). The onset of recession and dip in freight demand relieved the immediate challenge on port capacity, as did many port expansions that were completed in this period that had been initiated before 2008. Yet processes and models of port–hinterland integration continue to diversify due to several influences and challenges.

The trend towards using dry ports to enlarge the hinterland of the seaport is not new (see van Klink and van den Berg 1998), neither is the integration of logistics services within the transport chain (see Notteboom and Winkelmans 2001). The discussion on port regionalisation of Notteboom and Rodrigue (2005) identified that the hinterland was the new battleground and source of cost savings for large ports in a range that had already achieved similar cost savings and operational efficiencies at the quayside. Graham (1998, p. 135) wrote that “the land-side is characterized by relatively low investment, high operating expenses, little scale incentive to collective operation and a considerable level of unremunerated activity requiring cross payment out of sea freight”, and this remains the case today.

The early port development literature from the 1960s was focused more on spatial development than actor-centric approaches, due in part to the historical industry structure. More recently, the complexity of the port’s interactions with hinterlands and forelands (see Notteboom and Rodrigue 2005; Monios and Wilmsmeier 2013) and their institutional relationships (see Ng and Pallis 2010; Jacobs and Notteboom 2011; Wilmsmeier et al. 2014) have been essential aspects of analysis for understanding the port’s development path.

The five stages of the traditional *P*roduct *L*ife *C*ycle (PLC) are development, introduction, growth, maturity and decline. The adapted PLC applied to ports by Charlier (1992) was based on five stages: growth, maturity, ageing, obsolescence and restructuring. The development and introduction stages are missing because most port sites have been in operation for long time periods, in some cases many 100 years. In the two decades since this model was applied, the development of entirely new ports is more familiar (e.g. China); nevertheless, from a strategic perspective, the interest is on how an ageing port reacts to changes in the market, changes in technology and changes in port competition. Therefore, rather than a simple decline phase, the model focuses on obsolescence (see Charlier 2013). For example, a location may be obsolete due either to the introduction of a competitor port, new structures of world trade meaning that the location is no longer closest or cheapest to sources of demand, or changes in technology meaning that the port berths are no longer deep enough to accommodate larger vessels or the cranes are no longer able to handle containers fast enough to avoid congestion. In contrast to the traditional PLC model, the port life cycle includes a restructuring phase. Ports can restructure in various ways, such as deepening and lengthening berths and adding more and larger cranes to accommodate larger vessels, they can expand the size of the terminal if space permits, they can improve processes to achieve faster transit through the gate or faster processing of containers.

Cullinane and Wilmsmeier (2011) also applied the PLC to ports, and, following Schätzl (1996), argued that this restructuring could take place by “location splitting” as a means to extend the port life cycle when limitations in feasible rationalisation, investment and access are reached. Such creation of a subsidiary in the hinterland provides a potential solution that avoids an inevitable decline, caused either by the emerging inappropriateness of the actual port location (e.g. once-central urban ports) or an increasingly competitive environment. One question that arises is whether location splitting as proposed by these authors can be induced by landside-driven factors as well. This means that terminals in the hinterland are not developed only as a result of port strategies but by cities seeking economic development opportunities or by real estate developers establishing logistics platforms (see Sect. 22.3 for discussion of the (Wilmsmeier et al. 2011) “directional development” model that contrasts port-driven vs. inland-driven models of developing terminals or dry ports in the hinterland).

Cullinane and Wilmsmeier (2011) found a connection between the port’s need to expand to serve growing trade and the increasing vertical integration in the logistics sector. The dry port concept (see next section), in which the inland freight facility is viewed as highly integrated with the port, suggests that vertically integrated corridors between the port and the inland location could improve port efficiency by moving containers quickly and smoothly to the hinterland for processing and stripping, including other functions such as customs (see Beresford and Dubey 1991). The achievement of such a smooth functioning port–hinterland system may help to postpone the decline in the port’s life cycle that may come about due to reaching the limits of infrastructural capacity within the port itself.

22.2 Definitions of Dry Ports and Inland Terminals

Terminology for describing inland freight handling nodes in the hinterland of seaports has become quite confusing in recent years. An early term was *I*nland *C*learance *D*epot (ICD), which focuses on the ability to provide customs clearance at an inland location rather than at the port. Similarly, the term “dry port” has often been used interchangeably with ICD (see Beresford and Dubey 1991; Garnwa et al. 2009) for the same reason – as the goods were legally entering the country at the inland location, it acted as the seaport yet it was not on the water hence “dry port”. As such facilities have grown and are often linked to facilities providing logistics activities where freight is stored or processed, the “dry port” term has more recently been used to describe a kind of integrated logistics facility (see Roso et al. 2009), thus sharing similarities with terms such as “freight village” or “logistics platform” (see also “*G*üter*V*erkehrs*Z*entrum” (GVZ) in Germany, *L*ogistics *A*ctivities *Z*one (ZAL) in Spain or Interporti in Italy).

Discussions can also focus on the operational link between the seaport and the inland site, such as a high capacity link (rail or barge) and a high level of operational integration in the management (see Veenstra et al. 2012). Other terms include inland terminal, intermodal terminal and inland port. Rodrigue et al. (2010) related the multiplicity of terms to the variety of geographical settings, functions, regulatory settings and the related range of relevant actors and proposed that the key distinction is between transport functions (e.g. transloading between modes, satellite overspill terminals or load centres) and supply chain functions (e.g. storage, processing, value-added). Yet some of these terms (e.g. inland port, dry port and several of the logistics terms such as freight village) are used to describe a large site containing both transport and logistics functions. Sometimes a small intermodal road–rail terminal with one rail service per day to/from a port is referred to as a dry port, whereas other times a large logistics platform with several large warehouses and a high capacity road–rail terminal with several services a day to a port is also called a dry port. Other times the former is called an intermodal terminal or inland terminal and the latter a freight village or logistics platform (see discussion in Monios (2015)). A key distinction is that “dry port” is only used in a maritime context (for obvious reasons), thus intermodal terminals not handling cargo from a port would have no reason to use such a term, but they may then start handling maritime flows and introduce customs clearance facilities, hence becoming eligible to use such a term.

For consistency with the (Cullinane and Wilmsmeier 2011) chapter that we are discussing, we primarily use the term “dry port”, but for the most part this can be considered interchangeable with “inland terminal” or “intermodal terminal”, which is the term used in some of the other papers used in our conceptual discussion.

22.3 Directional Development

Wilmsmeier et al. (2011) utilised insights from industrial organisation to examine how different institutional frameworks reveal nuances in the different kinds of integration between seaports and inland terminals or dry ports. They introduced a conceptual approach (directional model) to dry port development contrasting Inside-Out development strategies (land-driven, e.g. developed by rail operators or public bodies) with those that are pursued Outside-In (sea-driven, e.g. developed by port authorities or port terminal operators). While not all site development strategies can be classified solely as one or the other, this broad conceptual distinction highlights conflicting strategies and the importance of port investment if a dry port development is to lead to a successful business, handling port container shuttles for one or more seaports, thus assisting the seaport(s) in developing their hinterlands (see Monios and Wilmsmeier 2012).

This classification is particularly important because it highlights the challenges of port–hinterland integration and the potential conflicts between different actors. Monios and Wilmsmeier (2012, 2013) showed that the assumed levels of integration in intermodal corridors are in many cases at odds with the reality. Their analysis identified several difficulties arising from the nature of intermodal transport that challenge successful implementation of hinterland integration strategies. It is not only that differences can be observed between those developed by ports (Outside-In) and those developed by inland actors (Inside-Out), but that, while rail remains a marginal business, the industry remains fragmented, large shippers refuse consolidation and fragile government subsidy remains the basis of many flows, dry ports cannot become instruments of hinterland capture and control for ports. The integration processes predicted by the port regionalisation concept (see Notteboom and Rodrigue 2005; Monios and Wilmsmeier 2013) cannot happen until the inland logistics system becomes more integrated, and there is insufficient evidence as yet that inland transport is consolidated to the extent that maritime transport (e.g. global shipping lines and port terminal operators) has become over recent years. Moreover, in many cases the complexity of institutional design and the conflict of interest and collective action problems continue to constrain integration between maritime and inland transport systems. For example, precisely how an inland freight facility can be integrated with a port (either by activities or more formally through ownership) and how it can extend the port's life cycle by taking on some formerly port-based activities depend on the specific actions it undertakes and the institutional relationships between the various organisations (e.g. whether the port authority or port terminal operator owns the dry port, whether they own or have any integration with the rail shuttles or with the logistics platform and its activities).

In recent years, some authors have engaged with the directional model and attempted to develop it further, from a binary model covering only the development phase into a matrix with two or more phases and two or more options at each phase. Bask et al. (2014) proposed that, while the development phase can be either Inside-Out or Outside-In, the growth phase could also be bi-directional, involving a high level of equal collaboration between the port and the dry port. Similarly, Raimbault et al. (2016) also took up the directional model, suggesting that only two directions are too simple and both directions can be at play simultaneously in a relational perspective. Their empirical analysis found that dry port development and integration (or not) with seaports is "as much a part of the wider structural changes as the actual retreat of transport activity from waterfront locations". One way to revise the directional model on the basis of this recent work could be to transform it from a binary model (Inside-Out vs. Outside-In) covering only the development phase into a 3×3 matrix, including three phases (development, growth, maturity) and three model types (Inside-Out, Outside-In, bi-directional) at each phase. Yet, this would be rather simplistic and would not capture the complexity of institutional and operational relationships underpinning successful intermodal hinterland corridors linking seaport(s) with dry port(s). Crucially, it also would not account for the later period of the life cycle, where the dry port (and the port) faces decline due to several influences, often infrastructural lacks but also changes in the market structure. The next section will explore these in more detail by turning to the intermodal terminal life cycle.

22.4 Intermodal Terminal Life Cycle

The *I*ntermodal *T*erminal *L*ife *C*ycle (ITLC) was developed by Monios and Bergqvist (2016) and is presented in Table 22.1. While this model was developed for intermodal (primarily road–rail) terminals without explicitly considering their relations with seaports, it can be adapted for use here. The ITLC takes account both of the original product life cycle model and previous applications to seaports (see Charlier 1992) and inland ports (see Leitner and Harrison 2001). The (Monios and Bergqvist 2016) model is based on the concerns raised in the literature regarding the difficulty distinguishing between PLC phases with certainty as well as identifying and measuring the main influences. Therefore, their adapted model is not based on unit sales like the number of containers transported. A model could be constructed based on related traffic figures over time, but the purpose of this model is to guide strategy, which relates to another criticism of the generic PLC model's inability to differentiate clearly between phases. Consequently, the life cycle in this model is divided into observable phases of development and operation rather than on, e.g. container throughput.

If maturity for an intermodal terminal can be defined, as for ports, as "when it cannot provide more space to the customer due to saturation or to impediments that stop further expansion" (see Charlier 2013, pp. 599–600), then this is the trigger to enter the fourth phase, defined by Monios and Bergqvist (2016) as "extension strategy". This term is necessarily broad, because it may include different strategies of restructuring physically (e.g. terminal expansion), operationally (e.g. redesign of the site, different traffic sources and rail operators using the terminal) and institutionally (e.g. new business model, new ownership, integration between terminal and other actors like rail operators or seaport terminal operators). The point of "maturity", then, is not a phase but a trigger for restructuring, which, if successful, will lead to another period of operations until the next challenge arises.

The extension strategy phase is based on the restructuring phase from the port life cycle by Charlier (1992). Transport infrastructure can be upgraded and service portfolios developed to meet changes in the market; on the other hand, the infrastructure will also need to be maintained or simply monitored for long periods of time. Where a regular product or service on the market will simply be withdrawn and cease to be manufactured/offered due to absence of demand, transport infrastructure cannot be removed so easily. Public sector bodies will need to decide what to do with such infrastructure and consider whether it should be retained in the public stock or the land redeveloped for another purpose.

Table 22.1 Main features of each phase of the intermodal terminal life cycle (adapted from Monios and Bergqvist 2016)

	Planning, funding and development	Finding an operator	Operations and governance	Long-term or extension strategy
Link to original PLC phase	*Development*	*Introduction*	*Growth and maturity*	*Decline* (+ potential restructuring, Charlier 1992; Cullinane and Wilmsmeier 2011)
Length	3–10 years	1–2 years	>10 years	>15 years
Main stakeholders	– Public infrastructure stakeholders (e.g. rail authorities, planners, etc.) – Large shippers – Real estate developers – Terminal operators – Rail operators – Ports	– Public infrastructure owners – Terminal owners (if different to the above) – Terminal operators	– Public infrastructure owners – Terminal owners (if different to the above) – Terminal operators – Rail operators	– Public infrastructure owners – Other public stakeholders (e.g. rail authorities, planners, etc.) – Terminal operators
Main activities undertaken	– Planning – Design – Funding sought – Tendering of construction – Construction	– Designing business and ownership model – Tendering for operator – Designing concession agreement – Contract development	– Continuous improvements – Responding to changes in technology and demand	– Renewed terminal concession – Potential changes in business and ownership model – Potential expansion – Ensuring long-term strategy and control – Potential sale and redevelopment of site for new purpose

Table 22.2 4 × 4 dry port development matrix based on the ITLC (Monios and Bergqvist 2016) and the directional model (Wilmsmeier et al. 2011)

Phase	Development	Introduction	Operation	Extension strategy
Direction	Inside-Out	Inside-Out	Inside-Out	Inside-Out
	Outside-In	Outside-In	Outside-In	Outside-In
	Bi-directional	Bi-directional	Bi-directional	Bi-directional
	Inland only	Inland only	Inland only	Inland only

Drawing on the ITLC, the directional model for dry port development via-à-vis seaports can be expanded, including a fourth phase as well as adding a fourth type (inland only with no port involvement) to produce a 4 × 4 matrix (see Table 22.2).

One advantage of drawing on the ITLC is to address concerns raised by Raimbault et al. (2016) that, in addition to the direction of development and the identification of the key public and private actors involved, greater focus is needed on power relations between actors regarding strategic alignment of interests. Furthermore, a dry port facility may be developed under certain assumptions about its business model and traffic sources, with particular expectations of the role it would likely play in the port's ongoing strategic development (e.g. will the port guarantee traffic levels or not, will the port and dry port collaborate in organising rail shuttles or will it be left to the decision of rail operators). But over the years of its operational life the conditions may change and with that the role of the dry port. The dry port may be sold or re-concessioned, it may gain or lose the business of various rail operators (who ultimately are the ones hauling the traffic and using the terminal) or it may require maintenance or upgrades and become involved in contractual disputes over who should fund these investments.

Research shows that much of the time the port actor is a peripheral player in these ongoing day-to-day operational difficulties, even if they maintain a high percentage of ownership in the dry port (see Monios and Bergqvist 2016). Such operational problems may cause, e.g. trains to be delayed or have to wait in sidings, or containers not to be available on time. These problems endanger the high levels of throughout and integration required by a large seaport handling large numbers of container drops and relying on a smooth hinterland transport system. This challenge is exacerbated by the increasing size of container vessels now dropping thousands of containers in a single call. Can a seaport fully rely on their inland connections to such a high degree? Building on these concerns, the next question is what this expanded model (see Table 22.2) means for seaports. How does it enhance or constrain their location splitting options?

22.5 Relevance of Life Cycles to Port and Terminal Planning

Despite an increasing volume of containers being transported inland from ports by rail, the number of dry ports in vertically integrated arrangements producing operationally and institutionally linked seaport–dry port intermodal corridors have not eventuated to the degree forecast a decade ago. Therefore, in mind of the many challenges and strategy fragmentations observed in the governance of dry ports, particularly during the maturity stage in their own later years when they require investment, several questions arise:

- What does this mean for the port life cycle, or as implied above, for a potentially aligned port–hinterland system life cycle?
- Can ports still rely on inland facilities to relieve pressure on their own development?
- Should ports be more proactive in developing and operating dry ports in the hinterland?
- Should ports return to their more traditional focus of expanding their handling capacity in the port?
- How complex is the creation of an alignment of different development strategies and phases?

As shown in the previous section, the different elements of the transport system, whether infrastructure, services or governance models have a certain economic lifetime (see Schätzl 1996) that can be characterised by sets of common phases. In recognition of the system's complexity, a key issue is not only to understand the implications of life cycle development of each of the elements (seaports or dry ports), but also the alignment or potential synchronisation of each of the life cycles.

Since many infrastructure and governance models in transport and economic geography research are generally long term in nature, alignment of different life cycles becomes a strategic issue. Thus, the assumption is that the life cycles run in parallel but are also interconnected. Cullinane and Wilmsmeier (2011) looked at how the dry port extends the port's life cycle, thus taking the Outside-In direction as a single perspective. The previous sections have shown that various combinations of directional development exist. The numerous models and facets of dry port development intrinsically change the complexity of aligning the individual life cycles. This complexity creates vagueness or lack of information for the planner who potentially cannot grasp or register the entirety of the development and its environment. The difficulty in aligning the seaport and dry port life cycles explains why the most successful seaport-inland links tend to be Outside-In developments, where the seaport actor has a better chance of controlling the system, or at least retaining a high level of operational information in order to synchronise their own planning (see Wilmsmeier et al. 2015).

From an Outside-in directional perspective, a port authority or port terminal operator can trigger the expansion of the seaport either with the goal to extend the seaport's life cycle (e.g. Valparaiso, Chile) or to expand the port's hinterland (e.g. ECT, Rotterdam, Netherlands), via a strategy of location splitting. In these cases, the port authority or port terminal operator may decide to initiate a new dry port or enter a strategic alliance with already existing dry ports. From the port life cycle perspective the system is thus extended not only in its spatial reach and capacity volume, but also in a temporal, functional and governance perspective. Yet, many terminals in the hinterland of seaports have an Inside-Out orientation, thus, when considering the influence of the ITLC as discussed in the previous section, these terminals may be at any phase of their own development and facing various challenges and future scenarios of which the port actors may be unaware.

The potential of life cycle extension from a port authority or port terminal operator perspective creates both challenges and opportunities. An understanding of the individual life cycles and their interaction increases the flexibility and development potential of the seaport terminal and its system capacity (i.e. container handling capacity). At the same time, the aligning and interconnection of different life cycles between seaport and dry port allows the expansion of the concept of the "terminal/port production system", offering additional benefits that reach beyond the pure scale increase of logistics activity. Yet they also raise many challenges due to the difficulty of the seaport actor(s) understanding or anticipating the changes taking place at the dry port potentially hundreds or thousands of miles away, even in a different country. Aligning the seaport's life cycle (which is known to the seaport strategist) with a variety of different and potentially unknown dry port life cycles is depicted graphically in Fig. 22.1.

According to the generic product life cycle theory, each life cycle phase needs to be considered, which will be taken from the seaport perspective. However, one key aspect of seaport strategy that is often overlooked in discussions of port–hinterland integration is the role of port governance. Some of the governance issues in dry port development and operation were raised in the ITLC of Monios and Bergqvist (2016), but an analysis of the strategic role of hinterland development in the port life cycle must also consider the evolution of seaport governance models and their impact on investment and expansion strategies.

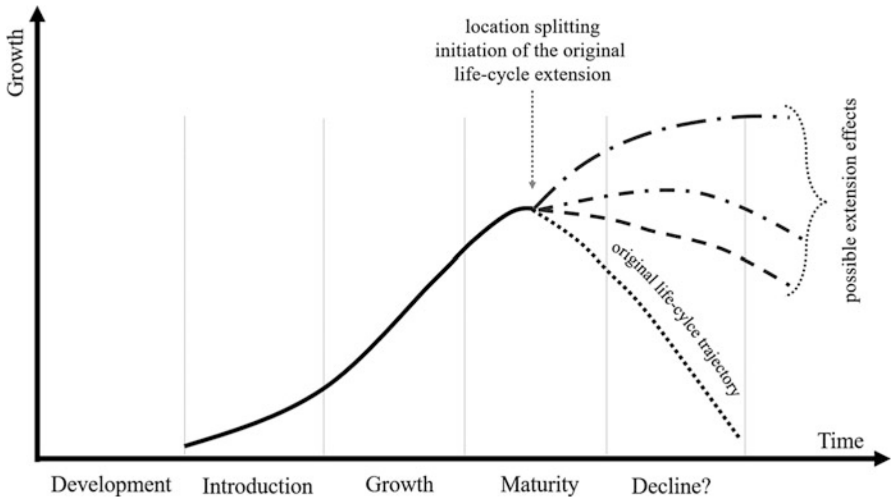

Fig. 22.1 Port life cycle expansion in the context of the dry port life cycle

Over the last decades, the “landlord” model of port governance (subject to regional and local differences), involving seaport terminal concessions, was introduced through port reforms around the world. In other words, the responsibilities for port services are shifted from a monopolistic public supplier, with human capital as the main factor of production, towards a private sector supplier. Changes in the environment and port operations (e.g. towards terminal automation) increased the capital intensity of developments; thus, capital investment to increase efficiency became a principal driver to implement this new governance model. In addition, the institutional responsibilities were in many cases devolved from a national to a local or regional scale (see Wilmsmeier and Monios 2016).

The growth phase mirrors the rapid expansion in international trade activity in which the new governance models allow the realisation of economies of scale by implementing standardisation and process innovation, and private capital investment for technological efficiency gains increasing their importance over human capital. Related governance models and growth prospects initiated an internationalisation of private sector interests, which is also driven by the new capital requirements stemming from emerging needs for infra- and superstructure development and expansion as well as the introduction of new port related activities. In this context, the local and regional (public) institutions, e.g. port authorities, principally manage the fulfilment of the concession contracts and private sector obligations.

In the maturity phase, the main goals of the governance models relying more heavily on the engagement of private sector actors have been achieved by standardisation and technical efficiency and competition in the market increases. Given the demand growth in the previous phase, port authorities typically move towards increasing competition by stimulating new terminal development and by promoting greater private sector involvement. While port activity grows at slower rates, infrastructure approaches physical constraints for further expansion or to create competitive environments. In consequence, investment during the maturity stage focuses on the rationalisation of port services, particularly as land becomes a scarce commodity and commands premium prices or rents. This is paired with a new exposure of local authorities to private international and global operators and an increasing mismatch of power between the locally embedded authority and global players. Further, a certain urgency evolves to change the role of port authorities. During this phase, the local institutions and national authorities are experiencing a potential risk of losing control of the management and development direction of the port, particularly also in relation to port–hinterland development. As market share is lost to competing ports with overlapping hinterlands the limitations of a devolved local governance model become apparent (see Wilmsmeier and Monios 2016).

The decline phase occurs once the point has been reached where the limitations in feasible governance have been reached and no further expansion of the port area or no other efficiency gains are possible at the local level and the supply of port capacity becomes fixed. This is the point where (Cullinane and Wilmsmeier 2011) argued for dry ports being one way to expand the port’s life cycle. However, if the governance model is not adjusted according to the changes in the (competitive) environment of a seaport it can become as obsolete as the infrastructure itself or may lead to stagnation of the future development path of the port.

During the transitional process by which a product moves from the development and introduction phases through the growth, maturity and decline phases of its life cycle, the conditions for production and of the market will change (for terminal operators). Port governance is basically responsive (or reactive) to the demands of their customers (local and national economies). It is reasonable to assert, therefore, that the seaport governance life cycle is very much (functionally) dependent upon the evolution of its social and economic environment. This is a factor which is heavily influenced by the development of the respective seaport and the maritime industry in general.

The life cycle extension success of creating positive expansion effects depends on the alignment of the different life cycles. Existing approaches focus on volume effects, but structural and "production system" effects (e.g. diversification of services) are less considered. The connection of seaport and dry port life cycles can enhance the flexibility and the adaptability of the port–hinterland system, but requires new roles and activities of the port authority (see van den Berg et al. 2012) and the terminal operator, particularly in the area of planning. The architecture of the "integrated production system" increases in its complexity as infrastructure, economic dynamics and governance in the hinterland are becoming more relevant. Accordingly, development decisions need to be based on an analysis of whether implementing a dry port is simply a protectionist measure that would prop up a failing seaport or whether it will be planned as a node of an integrated seaport hinterland system (as argued by Cullinane and Wilmsmeier (2011)).

In recognition that different elements (infrastructure, governance) of related port systems might have reached their maturity stage, the discussion on the "how" of the extension of the current system life cycle seems of high relevance. It might be argued that the currently needed transitions are decisive in the determination of extension of inevitable decline and require, more than ever, a holistic view, without losing the modularity of the system in sight. One reason for the continuing lack of full scale integration between seaports and dry ports is the specific isolated manner of planning and decision-making in the absent (or still only little developed) holistic view, including potentially a lack of understanding of the dynamics and interaction of the various system elements and their life cycles.

As the life cycles of the seaport hinterland system elements might merge in different phases of each of the individual elements, different perspectives complicate planning issues (see Monios and Bergqvist 2016). These range from daily operational challenges in the rail network that may impair regular full shuttles to/from the port (see Bergqvist and Monios 2014) to contractual issues between rail stakeholders (e.g. dry port operators and rail operators using the dry port terminal, see Bergqvist and Monios 2014) and institutional issues regarding port involvement in the dry port (see Wilmsmeier et al. 2015). Thus, a detailed view on a proper understanding of planning and integration issues is necessary to improve efficiency, quality and cost of the integration. The more detailed differentiation between Inside-Out and Outside-In directional development during different phases of the life cycle and the consideration of the governance cycle contributes to the understanding of the complex discussion regarding policies and planning supporting the development of dry ports, as the actors and their overall strategies and aims are potentially different and unaligned.

22.6 Conclusion and Research Agenda

The question thus is not only at which stage of the life cycle a port is at, but rather to understand the interaction of different cycles in order to proactively influence transitions between phases in a coordinated and effective manner. Port–hinterland integration is a reality, but its success in creating positive externalities and reducing negative ones varies significantly across countries and regions. The discussion reveals the system complexity when including the hinterland and its elements (especially the dry port) in the port life cycle perspective, showing that the need for aligning different cycles becomes evident.

From a port authority point of view, various forms of integration with the hinterland are feasible and can offer new market opportunities and create new business areas, such as becoming a logistics cluster manager, deriving strategies to shift negative externalities away from the traditional port boundaries (e.g. modal shift to rail to reduce the environmental impact of truck transport – Gonzalez Aregall et al. (2018)) or even reducing these by increasing the overall efficiency of the system.

From the dry port operator point of view, seaport hinterland integration will allow for extending market reach and competitiveness. However, as the “terminal production system” expands, new complexities in the planning and management of capacity, information flows and cargo flows emerge as well. Since the expansion is intrinsically linked to capacity and structural changes, the potential price for errors or dysfunctionalities in the system becomes greater. While regulation was not discussed in this chapter, ongoing issues of oligopoly in global shipping may also impact on port–hinterland integration, because eventually systems and not individual modes and locations will be competing. Thus market dominance at sea could potentially translate into the hinterland through vertically integrated transport chains. This is a consideration for future research because an inappropriate consideration of the changing competition regimes may lead to significant distortions in resources allocations “in an industry in which residual monopoly power or at least the risks of collusion between a few operators can be quite important” (see Jara-Diaz et al. 2008, p. 1704). This argument applies to the seaport and dry port as well as the maritime and logistics industry.

The argument of this chapter is that such new challenges cannot be identified in the absence of an understanding of the port, shipping and logistics industry and the principles that move their operations. Understanding the system complexity in port–hinterland development contributes to the formulation of realistic policy, planning and regulatory questions, a step towards the development of new theoretical approaches that are less mechanistic and instead flexible and organic in their nature.

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Chapter 23
Flashlight on Intermodal Transport Innovation in European Seaport Hinterland

Thore Arendt

Abstract The chapter describes the characteristics of European intermodal transport in seaport hinterland and pure inland relations (terminal-to-terminal). The market situation in these fields is assessed as well as existing problems of current intermodal services. Based on the apparent limitations of intermodal transport systems, the author describes the requirements of the market and possible factors for a more consumer-oriented intermodal service. The chapter closes with an innovative concept for a prime service as a means of increasing the competitiveness of intermodal hinterland transports in a sustainable way.

23.1 Introduction and Market Situation

Intermodal hinterland transport – also referred to as maritime combined transport – is a specific form of intermodal transport services. Basically, intermodal transport is defined as the use of more than one transport mode within a transport chain, "in which the goods remain within the same loading unit" (see Monios and Bergqvist 2017, p. 3). Characteristically, the hinterland or maritime variant of intermodal transport takes place between a seaport and a customer destination within the catchment area of the port, using almost exclusively standard ISO containers (noting that related destinations are mostly in the same country as the port itself). This type of load carriers (up to a length of 45 ft) can be transported via road without special permit in most European countries, which usually happens in the first or last leg of the related intermodal transport chain. But with regard to space requirements, they are not compatible with the European standard palette. The use of ISO containers in combination with this palette type would lead to inefficient container utilization in intermodal transport services. In Europe, the load carriers of the ISO type therefore can be found almost exclusively in intermodal hinterland transport chains and not,

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for example, in the European continental intermodal transport (also referred to as continental combined transport).

While the deployment of different load carriers is the most apparent difference between continental and maritime *C*ombined *T*ransport (CT), there are differences in the scope of logistical services as well. According to *U*nion *I*nternationale des *C*hemins de Fer (UIC), continental CT mainly forms the basis for inland terminal-to-terminal services which generally include pre- *and* on-carriage by road. Maritime CT on the other hand usually are port-to-door services (i.e., pre- *or* on-carriage by road) including additional logistics services such as customs clearance or empty depot services (see UIC 2017, p. 14).

Intermodal transport was first used in the eighteenth century in England. For intermodal transport services being based on intercontinental sea transport on the main leg, the ISO container became the standard during the 1950s (see AG 2017). Until today, the transports with ISO containers have developed to the most important market segment of intermodal transport in Europe, although the related load carriers are almost only in use in the pre- or on-carriage of maritime CT services. With the increase of containerized transport flows and the privatization of most European rail companies during the 1980s, intermodal hinterland transport chains have established themselves as feasible alternatives to long-distance road transport. Today, about two-thirds of all intermodal transports are hinterland transports in Central Europe, mostly originating or ending in ports of the North range.

It can be speculated that intermodal transport was basically developed as an additional "product" to open new markets for both rail and inland waterway operators, as volumes of traditional mass transportation continuously declined for many years due to the so-called freight structure effect.[1] The continuing containerization positively influenced this development, especially in the field of port hinterland transports.

On a conceptual level, the intermodal hinterland transport can be characterized as a specified system with the purpose of transporting goods according to the customer's requirements. The physical goods and the related information enter the system with the launch of a transport order, are processed and exit the system when reaching the target destination. Due to the numerous different actors executing different roles along the transport chain, the system can be further separated into different subsystems, i.e., the individual legs of the transport chain. These subsystems act more or less autonomously depending on the business model.

While no reliable statistical data exists on the European level to evaluate the volume share of intermodal transport services in total rail freight, it can be assumed that the share is relevant because 10–15% of the rail freight volume in many European countries is transported by intermodal services. In Germany – where specific statistical data is available – the share of intermodal transport of the total rail freight volume is about 25%. Furthermore, 80% of all intermodal volumes are transported via rail in Germany on the main leg, while inland waterway transports

[1]The "freight structure effect" describes the increasing share of high-value consumer or investment goods in transportation replacing traditional mass transportation.

have a total share of 20% (see SGKV 2017, pp. 5). Along European waterways, barges are mainly used for bulk cargo and transport about 9% of the total bulk cargo volume in Europe per year (see Eurostat 2018). The total share of barge and rail transport volume (which includes intermodal services) is about 17–18% in most European countries. In other words, transport by road is still the dominant factor with shares of around 80% in the modal split (see UIC 2017, p. 10).

The market of intermodal transport (maritime and continental CT) is defined by numerous actors in varying roles and relations which interact on different levels, thus creating a complex market structure. According to UIC, the services in the more relevant intermodal rail market (due to the higher market share) are organized by combined transport operators "who act as independent intermediaries or brokers between railway companies, road haulage companies and potential customer groups" (see UIC 2017, p. 14). These operators purchase transport capacity from road haulage and railway companies on behalf of the customers. Volumes on rail range from a wagon-by-wagon basis up to full trains for multiple customers or "company trains" for a single large customer. In recent years, other stakeholder groups such as the railway companies themselves, logistics service providers, shippers, terminal or port operators have acted as operators for intermodal transport services as well. In this regard, the following statement should be noted: "Although the business model of the 'classical' CT operator still prevails in the European market, the trend of past years towards more logistics service providers taking over the operator role continues, particularly in Western Europe" (see UIC 2017, p. 14). Key target customer groups are shippers, shipping lines, logistics service providers, seaports, inland intermodal terminals, and truck companies (see UIC 2017, p. 14).

The fact that intermodal systems for efficient hinterland transport have continuously grown in many European countries but still are unable to take away significant market shares from road transport clearly points to problems in the structure and organization of intermodal transport systems, especially to the lack of sufficient and open interaction between the actors involved in the provision of intermodal transport services along the transport chain.

In the first step, the chapter takes a look at the obstacles and challenges which intermodal hinterland transport services face today (and in most cases in the past as well). Based on that, adaptations and innovations are suggested concerning the structure and organization of the intermodal hinterland transport to overcome existing problems.

23.2 Current Problems of Intermodal Hinterland Transport

Politics both on the national and the European level have tried to enforce the use of intermodal strategies for freight transport along national and international supply chains by means of a variety of legal regulations and research programs.[2] By this way, ecologically viable and sustainable transport solutions are supposed to be developed showing an adequate competitiveness at the transport market as well. However, in recent years it became visible that other factors are also (or more) important for the customer when deciding on (intermodal) transport services – noticing that the modal splits in all European countries currently still have a very high share of road transport. Reasons for this may be different problems of intermodal transport systems on both the level of *implemented structures* and the level of *service organization*.

For intermodal hinterland transport systems, long-term structures in terms of *infrastructure* and *regulations* form the basis for related hinterland connections and are an important or even the central factor for existing problems. This is true for both the inland waterway infrastructure and the rail infrastructure.

Waterways show very different characteristics and spatial extensions in European countries. For example, in the Netherlands, inland waterways play a crucial role in the intermodal transport from and to the seaports, while in Germany a very high share of all water-based intermodal hinterland transports concentrates the River Rhine, which has a sufficient capacity for viable and profitable intermodal services.

The problems in rail transport are more visible throughout the European states, since this infrastructure is present in all states, while the use and importance of inland waterway infrastructure is dependent on the geographical conditions of each country and the development of the network. According to the *U*nion *I*nternationale des Sociétés de Transport Combiné *R*ail-*R*oute (UIRR, see UIRR 2019, p. 9), both infrastructure and regulatory shortcomings basically hinder the further use of rail-based intermodal services (maritime and continental CT). In this regard, typical examples are the following:

- Profile gauge-, train length-, and maintenance backlog-related limitations impede the production process of the rail services.
- Uncoordinated infrastructure design makes cross-border rail freight problematic (e.g., in terms of flexibility).
- General lack of train paths and traffic prioritization in some countries ("passengers before goods") disadvantages intermodal trains.
- Regulatory shortcomings like "diverse national rules (operational as well as safety related), heterogeneous interpretation and implementation of existing European rules, and outdated or missing legislation" translate into obstacles as well (see UIRR 2019, p. 9).

While these *structural deficits* remain a major factor and require continuous financial investments and political efforts of all Europeans states, the efficient use of infrastructure (by appropriate service organization) is rarely discussed. The current

[2]Please compare (Kombiverkehr 2019) for different examples of legal regulations, which apply to most European countries.

challenges for intermodal systems of maritime and continental CT in terms of its *organization* are twofold:

- The need for a better and more efficient use of infrastructure is mandatory due to larger deep-sea vessels (and resulting peak requirements) as well as basically increasing volumes in hinterland transport. The increasing lack of capacity in hinterland transport systems cannot be solely compensated with additional physical infrastructure. A fact which also applies to intermodal transport systems in this area.
- To shift additional volumes to intermodal hinterland services, new customer groups have to be identified and convinced. The cost factor is playing a crucial role in this process and will continue to do so in the future. In addition, the problem arises more and more that "classical" intermodal goods for containerized hinterland transports – which have little sensitivity towards transport time and transparency of the transport process – are becoming less. This is due to the nature of globalized markets, reduced stocks, and the tendency to have digitized information available, e.g., to organize warehousing more efficiently by applying concepts such as "just in time" or "just in sequence."

Simply put, intermodal transport services must adapt to requirements of faster markets by making better and more profitable use of the existing infrastructure for a viable service offer. Suppliers, logistics service providers, and producers, for example, want to build a supply chain that is efficient according to the customers' demand respecting criteria like transparency, flexibility, punctuality, etc. Based on personal experiences of the author, the following criteria can be considered of some relevance for decision-makers when thinking about the use of transport services in general and an intermodal service in particular (see Fig. 23.1).

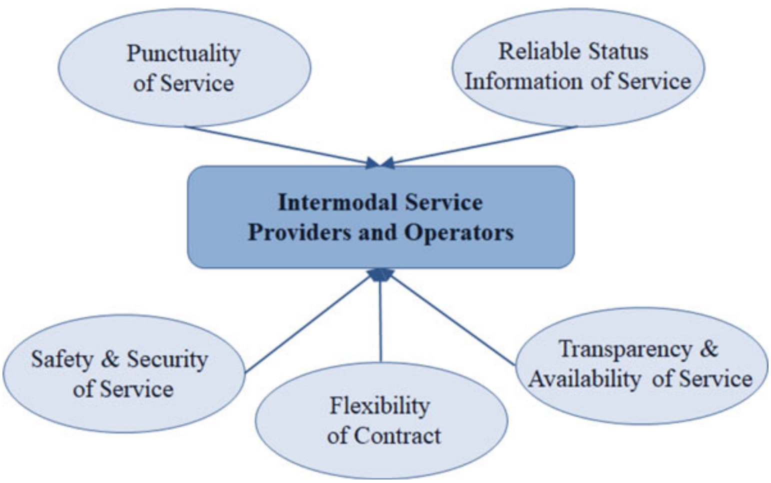

Fig. 23.1 Customer requirements for competitive intermodal transport services

The relevance of these criteria depends on the organization of the underlying transport system:

- **Punctuality**
  Since rail or inland waterway transports are closed systems that (more or less) cannot be influenced by customers regarding departure/arrival times, punctuality (i.e., reaching the transport destination at the promised time) is beside the transport costs among the most important factors when deciding for intermodal service. In several interviews and discussions, the author has done with potential and actual customers, the punctual arrival/departure of the intermodal transport services is an important aspect and one of the reasons customers decide against an intermodal offer, even if it might be cheaper than long-distance road transport. Moreover, many potential customers frequently have an unsubstantiated bias to consider services of rail and/or inland waterway as delayed without actually checking the statistics or enquiring facts about specific relations.
- **Availability of reliable / feasible status information**
  This criterion is closely entwined with the criteria punctuality discussed previously. Today, customers require more in-depth information on the whereabouts, complications, and immediate measures against disturbances during the transport. While such systems do exist, most are closed systems without public interfaces for information provision. In other words, customers have to rely on the information policy of the transport operator or service provider that is controlling the intermodal transport process. As a result, missing information may impede planning processes on the side of the customer and frequently lead to a general aversion to intermodal transport options.
- **Safety and security**
  Many companies transporting dangerous or sensitive goods use intermodal services because the technical safety of related transport chains is comparatively high. In terms of cargo security, due to the anonymity of containerized transports and the reduced accessibility of parked or otherwise stationed trains/barges, transport goods of substantial value are interesting objects for intermodal transport. While *safety* can be considered a "classical" criterion that has appealed, e.g., to the chemical industry since the 1980s, the factor *security* becomes more prominent as global production leads to increased movements of high-value products around the world.
- **Transparency / availability**
  Looking for simple comparable short-term offers, potential customers want to understand the rather complex procedures behind intermodal transport chain to an extend where the customer can make an informed decision. This includes transparent cost structures which can be compared to road transport without time-consuming contract negotiations. Until today, this information is generally not available to the customer. As a rule of thumb, the customer will not "interact" with a transport service that he does not understand. Hence, the need for an interface is evident which improves the transparency of the service complexity in terms of production and cost structure. Another major hindrance for the use of intermodal services is the fact that these services are not displayed on the market

in a way that a potential customer can easily comprehend. By not being able to fully interact with the system's components or subsystems, the client has to trust the mechanics of the system. Of course, due to the fact that customers such as freight forwarders also have responsibility towards their clients, a certain need for control is understandable. Intermodal systems are at times like black boxes to the customers, requiring a high degree of trust. In daily business, this appears to be unattractive to most users.

- **Flexibility**
  The reduction of life-cycle times of products and lean, globalized, and flexible production standards leads to a demand of more flexible, agile logistic systems. Long-running contracts for specific, predictable volumes and destinations are characteristic for mass good transport and traditional intermodal transport services but of little or no benefit for many companies which organize supply chain processes today. Especially train services – as part of the main leg of maritime and continental CT – are traditionally based on long-running contracts for non-time-sensitive goods. But considering today's market requirements, there is a growing tendency of short-term commitments for transport services. The customers do require more flexibility and expect that intermodal services are customizable to the requirements of the production systems, which induce the transport demand.

The abovementioned criteria for the choice of transport mode are not always met by intermodal services in a sufficient way. This is in particular due to the complexity of intermodal systems and the number of independent or semi-independent actors along the intermodal transport chain. Specific limiting characteristics may impact intermodal inland waterway and rail services to various degrees and impede further market penetration (see Fig. 23.2):

- **Domineering actors and hierarchical structures**
  Potentially due to the fact that especially rail services were and frequently are still state-owned companies or departments, a tendency to hierarchical organizational structures exists in most business models for intermodal transport services. This means that generally one actor within the transport chain is dominant insofar as this actor (in many cases a railway company) designs and controls the freight and information flow of the related chain. In many cases, the actor is closely intertwined with the infrastructure and receives financial support from the state for this infrastructure and his business activity. This may further support the hierarchical organization of intermodal transport services.
- **High level of interdependence**
  With multiple actors along the intermodal transport chain the level of interdependence is considered to be high within related systems. All parties involved are being able to act autonomously to a different degree. This interdependent structure only works competitively if its organization can heavily rely on a consistent information flow. If such an open exchange of information is not wanted or possible, the interdependence is purely based on the mutual trust of the participating actors, which further complicates their collaboration in the transport chain.

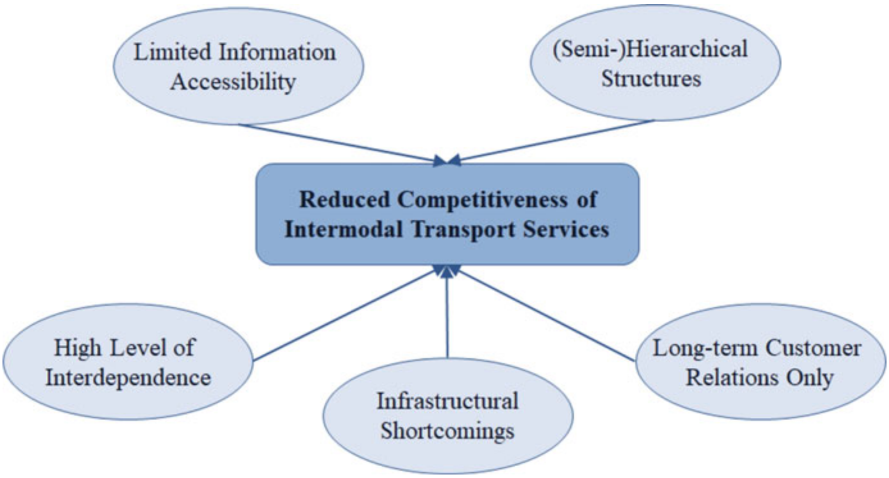

Fig. 23.2 Main limiting characteristics of intermodal transport systems

The impact of "intermodal characteristics" described above is different to every intermodal transport system. It is the domineering actor of each specific intermodal system – whether in maritime or continental CT – that determines the availability of information, control of freight flows, and interdependence with other actors based on its market position and resources power. If potential customers are interviewed on their resentments towards intermodal transport services, there are the abovementioned characteristics being usually the subject of criticism. Nevertheless the providers of current intermodal services – using either rail or inland waterway transport for the main leg – have so far made little or no attempts to reduce the weaknesses of their systems.

23.3 The "Perfect" Intermodal Hinterland Service – Concept for a User-Friendly System

The current share of intermodal services in comparison to road transport, though it has risen substantially during recent years, still offers great potential to acquire new customers and volumes. About 10 years ago, it was a common approach to evaluate whether a region has specific products or goods that are "affectionate" to intermodal transport. Usually such goods were of large volumes, could be containerized, and had little demands in terms of punctuality or flexibility. While such goods do exist today the gross of transported volumes – even though containerized in many cases – use road transport services because it addresses the needs of the transported product more effectively.

Industrial production and its requirements to logistics processes clearly indicate a development towards more flexibility and transparency, especially using the opportunities of digitalization. In many cases, the logistics of industrial production is outsourced and put in the hands of freight forwarders or logistics service providers (e.g., 3PL services). Accordingly, the specific demands of such companies for information in the process of choosing the most appropriate transport mode need to be considered when thinking about options for improving the competitiveness of intermodal transport services:

- Forwarders and logistics service providers usually operate cost-oriented and on a short-term basis. In order to be shortlisted by these companies a quick access to price structures of intermodal services is mandatory.
- It should be possible for customers to check the availability of services in terms of their transport parameters and free capacity for specific connections. Logistics service providers habitually look for existing transport offers. Even though this is less relevant for larger volumes which may require additional trains or barges (and with it an individual offer), the on-demand availability of the information on existing services and its actors is important for a comparison of transport offers on a daily basis.
- Logistics service providers are interested in a high degree of control over the transport chain. In this context, continuous provision of information about the whereabouts of the transport goods is important as related information enables customers to find "fast solutions" if interferences along the transport chain emerge.
- To ensure the most appropriate solution for emerging transport needs, orders are often individually placed nowadays seeking in each case for the best market conditions. Long-time contracts that bind forwarders and logistics service providers to an operator of intermodal transport services are therefore dissuasive to customers. Related business models are inflexible and no longer adequate for today's transport market.

A strategy to basically improve the acceptance of intermodal services in maritime and continental CT must address both physical and information-based interfaces. While physical changes like new infrastructure or better and more equipment require large amounts of money and time, strategies to use existing infrastructure more efficiently may reach the needs of potential customers quicker, at lower costs, and in many cases just as effectively. The question arises, *…what is actually required to attract new customers and volumes?*

Simply put, it is a more open and customer-oriented concept. Due to the complexity of the intermodal production process, this requires testing first to find out how the new system can fit in existing actor-relation-constructs. This can best be validated by using a demonstrator, i.e., a practical solution that is perceived as a positive intermodal example by both the system actors and the customers of the transport chain. One possible option for a demonstrator is a hinterland transport system with a specific range of services and transparent structures considering trains or barges on the main leg and trucks on the first/last leg in the destination/origin area.

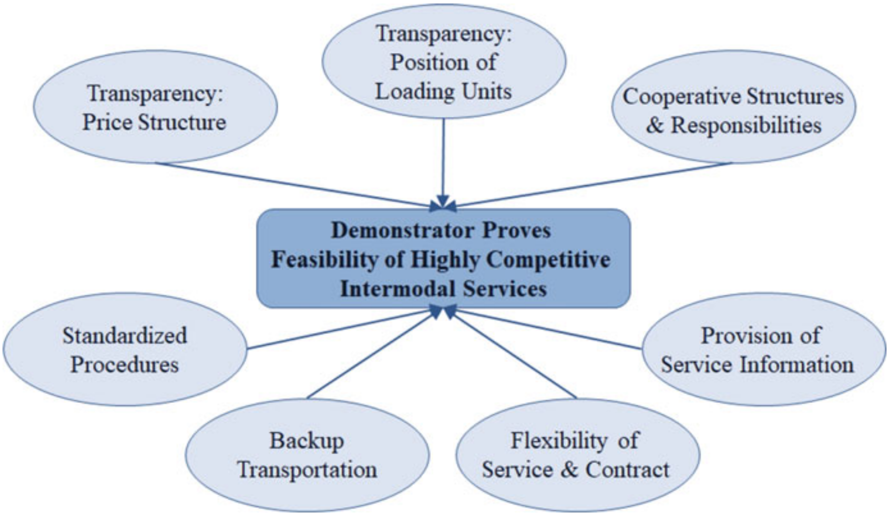

Fig. 23.3 Major components of the prime service demonstrator

Such a demonstrator can be used for field studies to test innovative solutions, e.g., in the area of organizational strategies or information systems improving the interaction of subsystems involved. The proposed demonstrator has the following objectives (see also Fig. 23.3):

- **Increase of transparency (position of loading units)**
  Improvements along the intermodal transport chain can be achieved by positioning of loading units. This requires additional information systems enabling individual unit tracking, e.g., by means of OCR (*O*ptical *C*haracter *R*ecognition) gates which would have to be installed at all terminals involved in the intermodal transport process.
- **Increase of transparency (price structure)**
  The basic prices for individual transports on intermodal hinterland connections are to be made accessible for customers without prior need for negotiation. This represents a stable element in the price structure of the service offer and does not mean that larger transport volumes cannot be negotiated. The publication of a "basic price range" for the individual day-to-day use of intermodal services facilitates the accessibility to the intermodal market for customers.
- **Provision of service information**
  To compare intermodal service offers to long-distance road transports characteristics of the entire transport chain need to be displayed and quantified (i.e., main run plus pre/on-carriage). Customers require sufficient information so that they can comprehend and evaluate the intermodal service offer in comparison to the "road alternative." This particularly includes the abovementioned price structure, possible discounts, and general information on the overall availability (e.g., free

and up-to-date time schedules), involved actors, and operation procedures of the intermodal network. In short, complex structures have to be presented in a way that potential customers can understand their underlying concepts.

- **Improvement of flexibility**
  Customers demand for transport services usually on a short-term basis, which is contradictory to the current policy of most rail or inland waterway services. For example, communicating free slots on a daily basis is a highly effective way to interest customers in intermodal services without forcing the customer into a long-term commitment. In the framework of the proposed demonstrator, such a measure needs to be analyzed based on hard facts (i.e., sales figures) revealing in how far intermodality gains in attractiveness by this way.
- **Varying service levels**
  A demonstrator with more transparency regarding the transport price and processes as well as more flexibility in concluding contracts allows for differentiating the service level according to the inhomogenous requirements of customers. While specific requirements such as punctual trains, guaranteed delivery, or complete tracking may be more expensive, the basic transport service is guaranteed for a fixed base price accessible to all customers.
- **Backup system**
  In case of failure of the transport vehicle used on the main leg of the transport chain (i.e., train or barge), a backup system is required to ensure the transport in the promised quality. The customer needs to be aware of this system and its reliable operation to simply gain trust in the intermodal service. Normally, such a backup system uses third party forwarding services by truck.
- **Agreed cooperation structures along the chain**
  As backbone of an efficiently working intermodal transport system appropriate cooperation structures between the different actors are required. For this purpose, agreed rules and responsibilities as well as standardized procedures can serve as a basis and create a trusted environment. That represents a prerequisite for both smooth operation processes and smooth information exchange with third parties (customers) as well as between the intermodal actors themselves.

To implement a demonstrator as proposed, a rail service is suggested that connects a seaport with specific hinterland destinations showing sufficient volumes to guarantee a basic capacity utilization. An inland waterway service is possible to function as demonstrator as well, but the related transport vehicles have specific disadvantages, e.g., the speed of the service or the physical limitation of handling equipment especially in German seaports where barges are usually processed with equipment used for discharging and loading deep-sea vessels.

In simple terms, such a prime service is to introduce two things: On the one hand, it copies the idea of public transport by offering the customer a chance to decide individually and on a daily basis whether he makes use of the service transport offer. Providing free slots and pursuing a business model that is (at least in part) based on short-term selling these free slots is in fact like “buying a ticket.” On the other hand, giving the customer all necessary information and a backup solution guaranteeing him punctuality and transparency, the intermodal service becomes as powerful and comprehensible as long-distance road services. The demonstrator *prime service* is supposed to offer at least the following customer functions:

- **Tracking and tracing of loading units by the use of OCR systems**
  This technology is inappropriate for continuous position monitoring, but it opens up the opportunity to track and trace each unit in "batches" or "time windows," respectively. In addition, the specific ILU Codes or BIC Codes[3] allow the identification of each unit. Regarding implementation this requires sufficient OCR technology along all terminals of the transport chain. If combined with the railway company's system to track train movements a (more or less) continuous position monitoring becomes possible for the loading units.
- **Online-booking system (free slots)**
  Such a booking system allows customers to access the intermodal transport service on a day-to-day basis, booking slots for fixed prices. That is, the underlying business model must ensure that these slots are offered on a reliable, regular basis.
- **Online pricing system**
  The basic tariffs, additional costs for specific services, and quantity- or time-related discounts are displayed online and allow for short-term use of the intermodal transport services. The related web frontend represents a "barrier-free" entry point to the offerings of the prime service.
- **Prove of quality**
  A backup system that at least regulates the compensation of system failures or delays on a financial level is also required to gain trust in the service.

In the light of the aforesaid, the key structure behind the prime service needs to be paperless, highly IT-based, and smoothly organized in terms of freight transport on the route and freight handling in the access/exit points (terminals) by a limited number of partners. These partners are bound by "rules" that have to be negotiated before the service becomes operational. The set of rules regulates interactions, responsibilities, and reactions to system failures between the partners. Only if the role of each actor is clearly determined and repercussions are fixed if the interaction is disturbed by one of the actors a trusted environment can be organized. This provides the basis for efficient and customer-oriented operation processes as well as open flow of information between all involved parties which is substantial to attract new customers.

[3]Both the ILU Code and the BIC Code are systems to identify the owner of a loading unit and the loading unit itself, by providing a unique code that is visibly applied to each unit. Regarding more information see UIRR (2011) for the EU inland intermodal code and see BIC (2019) for the BIC Code system which is more relevant to intercontinental transports (seaborne).

23.4 Conclusions

In the past, the use of intermodal systems for hinterland transport can be considered to be the right step to make transports of general cargo more time- and cost-efficient (by comparison to non-containerized cargo). Today, on the brink of worldwide digitalization, it needs to take a second step that improves flexibility and transparency of related systems. This may lead to more volumes for intermodal transport services which is beneficial to everyone – in economic, social, and environmental respects. The strategy for a successful introduction of more advanced intermodal services to the market of hinterland transports has to be twofold: First it needs a sufficient infrastructure in the port hinterland. Second existing infrastructure especially requires strategies on the operational level to make better and more efficient use of it.

To achieve higher flexibility, there is a need for changes in the historically closed and "uncommunicative" structure of business models underlying many intermodal hinterland services even today. Central to this approach are transport services that are paperless, traceable, and closely interlinked in terms of communication and information between the subsystems involved and the customer (i.e., maximum transparency). Furthermore, a set of fixed rules (including possible repercussions) is required to determine for each actor the scope of interactions, responsibilities, and reactions and with it a reliable role within the transport chain.

The chances to attract more volumes do exist since the price structure in comparison to road transport is competitive and additional advantages could be implemented but must be made visible for customers. To achieve this, intermodal service providers need to do two things:

- A complicated system is to be made more comprehensible and flexible by providing more information on the offered services and giving customers a choice without long-term commitments.
- All service providers involved are to become specialists of their respective subsystem (and the related services) instead of controlling the entire chain as dominating actor. Interfaces just like failures should be managed based on agreed rules by a trusted neutral position or consortium of all actors.

So far, the overall physical infrastructure capacity is to be considered as sufficient for additional volumes – nonetheless there are some problems. This applies to the rail infrastructure (i.e., the track network) in Europe where bottlenecks become increasingly apparent. To mitigate shortcomings both the network operator(s) and the railway companies are required to use their resources more efficiently. The former by a more intelligent track management based on advance traffic control systems such as the *E*uropean *T*rain *C*ontrol *S*ystem (ETCS, see UIC 2019). The latter by improving the utilization of their trains based on more customer-friendly services (ideally) showing all the characteristics and functions discussed in Sect. 23.3.

The role of seaports can be considered as crucial in this context. An improved information flow based on the use of advanced information systems on all levels (i.e., information procurement, storage, and in-/external provision) will enable better use of the existing port infrastructure and terminal superstructure being limited in many cases or not intended to expand. This applies equally to the integration of rail and barge services. Noting that appropriate superstructure for barge processing is completely missing in many seaports. It is recommended to implement such equipment, so that barges have a better chance to compete with the other transport modes, in particular, the long-distance road transport.

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Chapter 24
Importance of Hinterland Transport Network Structures for Seaport Container Terminals: An Update

Joachim R. Daduna and Robert Stahlbock

Abstract In recent decades, the intermodal container transport has emerged more and more as the basis for a globalized economy. This results in appropriate seaport container terminal requirements with terminals serving as transshipment nodes and as an important interface between different transport modes. However, the operational performance in such network nodes is only one fundamental aspect. Especially the capacities of inbound and outbound flows, i.e., the deep-sea and the hinterland transport, play an essential role, in particular because hinterland transport is a typical bottleneck. To solve these problems, different concepts are presented including a dislocation of the terminal structures as well as an increased involvement of rail freight transport. However, some crucial problems and questions should be investigated. Although after the economic crisis in 2009 the international container transport increased again, it is much lower than predicted in previous years. Furthermore, there are some uncertainties that need to be analyzed with regard to future developments.

24.1 Developments in International Container Transport

During the last decades with increasing globalization of economic interdependencies – both in industry and in retail trade with a more and more global oriented division of labor in production processes – logistics has become a key factor for competitiveness of an economy. An essential basis for these developments are profound conceptual and technical improvements of transport logistics resulting

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in reduction of transportation time and costs. Not least because of the increase in offered services in transport markets, the demand for these services raises. That means, the underlying developments induce each other to some extent, leading to a significant acceleration of changes.

An essential point for further technical and structural developments in transport logistics is the increasing containerization while the general cargo has lost its importance. For example, about 80% of the general cargo handled at the North-Range ports Rotterdam, Antwerp, and Bremerhaven were already containerized in 2005, at the port of Hamburg even 96.4% (see, e.g., Notteboom and Rodrigue 2008).

Containerization is based upon a system of appropriate transport modes and corresponding changes in the conceptual design of operational processes. The result of containerization is primarily a significant simplification and acceleration of the handling processes within logistics facilities as well as of the transportation processes among the location of a shipper and the destination of the products. In the foreground are the processes regarding intermodal transportation chains requiring at least one additional handling of containers. The use of standardized load units results in a large reduction of handling effort at the interfaces and thus also in a significant decrease in process time and costs.

With regard to the globalization of trade flows *S*eaport *C*ontainer *T*erminals (SCT) and (*deep*) *sea container transport* play an essential role in a lot of multi-modal transport chains up to now (see, e.g., Bernhofen et al. 2016; Panayides and Song 2008; Rodrigue and Notteboom 2015). In a large number of trade relations, sea transport leads also to a quasi-monopolistic position, because alternative modes are not suitable, based on capacity restrictions and cost considerations (such as air freight transport).

However, not only the seaside linking transport must be considered, but also the necessary port hinterland transport has to be seen as a connection to the industrial and commercial centers in the inland. Currently, these transports within the inter- and transcontinental container flows have significant weaknesses that formed a crucial bottleneck during the last years. Therefore, achieved improvements of internal processes in the SCT by using capable tools for the (internal) planning and control and by using new and more powerful techniques for handling, transport, and storage (see, e.g., Carlo et al. 2014; Dragović et al. 2017; Gharehgozli et al. 2016; Stahlbock and Voß 2008; Steenken et al. 2004) alone cannot provide sustainable solutions of the problems of the global freight transport system.

The worldwide developments in container transport can be essentially described by two key indicators: the evolution of container ship sizes in Fig. 24.1 (see also Jiang et al. 2015) and the increasing container throughput (in million TEU) at the most important SCT (see Table 24.1). However, it is necessary that port infrastructure and technical equipment of container terminals are adapted to the size of the container vessels to be operated and volumes to be handled per call (see, e.g., Meng et al. 2017).

The global economic crisis with its peak in 2009 had a significant impact on the volume of international container transport as can be seen in Fig. 24.2. However, it is also apparent that a re-increase has taken place since 2010, but not as large

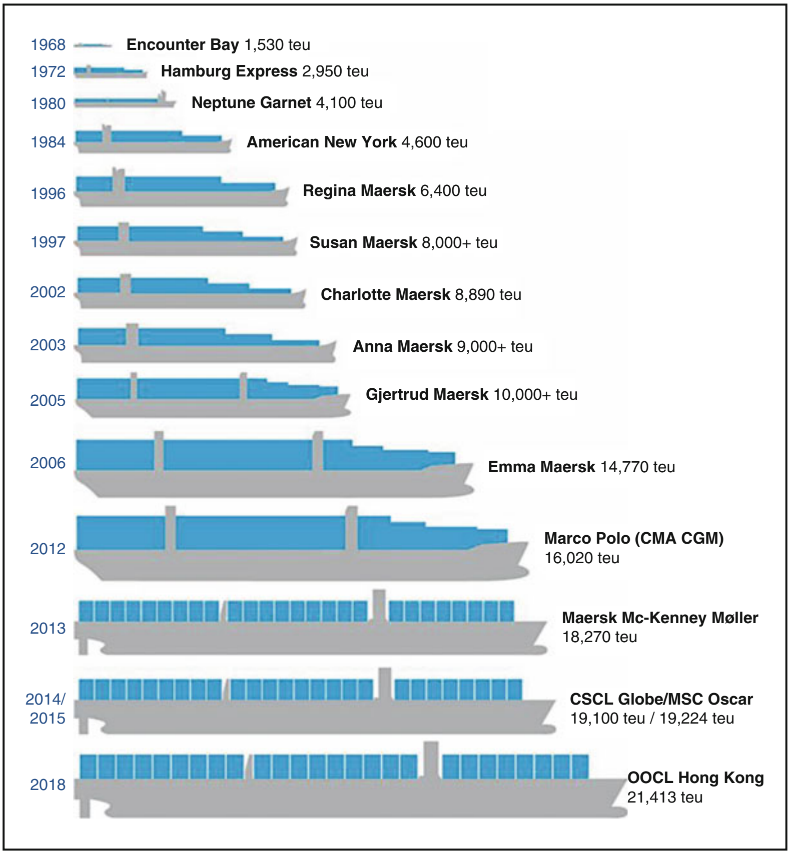

Fig. 24.1 Fifty years of container vessel growth. Based on World Shipping Council (2017)

as predicted some years ago (see, e.g., Heymann 2006). Here, for 2006–2015, an annual increase in container throughput in the SCT of 9% was forecasted. This would result in an increase of 83% for years 2008–2015, but this has never occurred to that extent (see Table 24.1).

It is difficult to estimate whether and to what extent the container transport will grow in future (see, e.g., Halim et al. 2017). The relevant environment is extremely complex and is determined by many influences that cannot be calculated. Thus, e.g., the cost structures in the global division of labor in manufacturing processes can change significantly, in particular with regard to work shares in the low-wage sector. These developments are associated with a spatial adjustment of production site locations and manufacturing structures. Another aspect is the impact of *Additive Manufacturing* (AM) (or 3D printing) on global production and logistics structures (see, e.g., Attaran 2017; Ben-Ner and Siemsen 2017; Jiang et al. 2017; Sasson and Johnson 2016; Weller et al. 2015), which can only roughly estimated

Table 24.1 Evolution of container throughput in the 20 largest container seaports (ranking based on 2016, in Million TEU) Data sources: 1985–2000: Notteboom (2004), 2005: American Association of Port Authorities (AAPA) (2005), 2005+: International Association of Ports and Harbors (IAPH) (2017)

Rank	Port	1985	1990	1995	2000	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016
1	Shanghai, China	0.20	0.46	1.53	5.61	18.10	27.98	25.00	29.00	31.74	32.53	33.62	35.29	36.54	37.13
2	Singapore	1.70	5.09	11.85	17.04	23.20	29.92	25.90	28.43	29.94	31.65	32.60	33.87	30.92	30.90
3	Shenzhen, China	–	0.03	0.37	3.99	16.20	21.41	18.30	22.34	22.57	22.94	23.28	24.03	24.20	23.97
4	Ningbo-Zhoushan, China	–	–	0.16	0.90	5.21	11.23	10.50	13.07	14.72	16.83	17.33	19.45	20.63	21.60
5	Hong Kong	2.29	5.10	12.55	18.10	22.43	24.49	21.00	23.70	24.38	23.12	22.35	22.23	20.07	19.60
6	Busan, South Korea	1.16	2.35	4.50	7.54	11.84	14.35	12.00	14.19	16.18	17.04	17.69	18.65	19.45	19.46
7	Guangzhou Harbor, China	–	0.08	0.51	1.43	4.69	11.00	11.20	12.49	14.42	14.74	15.31	16.16	17.22	18.90
8	Qingdao, China	–	0.14	0.60	2.12	6.31	10.32	10.30	12.01	13.02	14.50	15.52	16.62	17.47	18.00
9	Jebel Ali/Dubai, UAE	–	0.92	2.07	3.06	8.62	10.78	11.10	11.58	13.00	13.30	13.64	15.25	15.60	15.73
10	Los Angeles/Long Beach, USA	–	3.70	5.40	9.48	14.20	14.34	11.82	14.10	14.00	14.12	14.60	15.16	15.35	15.60
11	Tianjin, China	–	0.29	0.70	1.71	4.80	8.50	8.70	10.08	11.59	12.30	13.01	14.05	14.11	14.49
12	Port Klang, Malaysia	–	0.47	1.13	3.21	5.54	7.97	7.30	8.87	9.60	10.00	10.35	10.95	11.89	13.20
13	Rotterdam, Netherlands	2.65	3.67	4.79	6.28	9.30	10.78	9.70	11.15	11.88	11.87	11.62	12.30	12.23	12.40
14	Kaohsiung, Taiwan	1.90	3.49	4.90	7.43	9.47	9.68	8.60	9.18	9.64	9.78	9.94	10.59	10.26	10.46
15	Antwerp, Belgium	1.24	1.55	2.33	4.08	6.48	8.66	7.30	8.47	8.66	8.64	8.59	8.98	9.65	10.04
16	Dalian, China	–	–	–	–	–	–	4.60	5.20	6.40	8.06	9.90	10.00	9.45	10.00
17	Xiamen, China	–	–	–	–	–	–	4.60	5.81	6.47	7.21	8.01	8.57	9.18	9.60
18	Hamburg, Germany	1.16	1.97	2.89	4.25	8.45	9.74	7.01	7.90	9.01	9.06	9.26	9.73	8.82	8.90
19	Tanjung Pelepas, Malaysia	–	–	–	–	–	5.60	6.00	6.50	7.50	7.50	7.60	8.40	9.10	8.28
20	Laem Chabang, Thailand	–	–	–	2.20	3.83	5.13	4.54	5.07	5.73	5.83	6.03	6.52	6.78	7.23

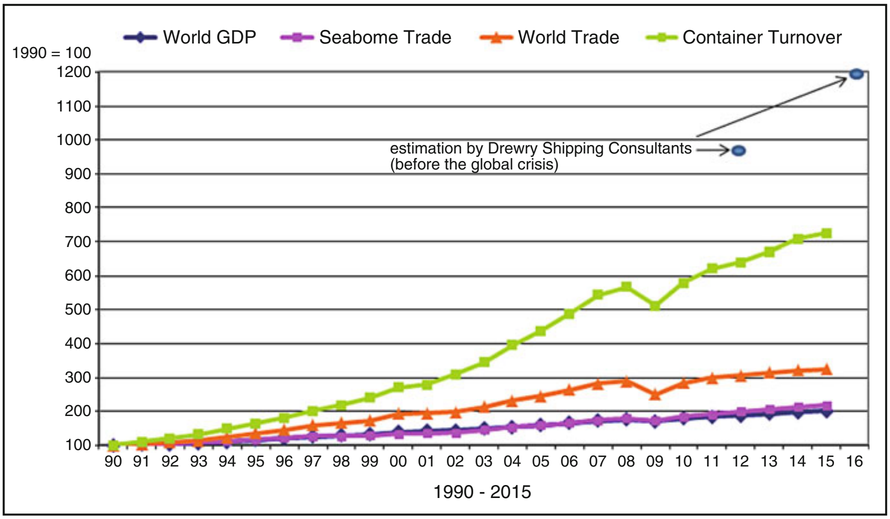

Fig. 24.2 Container turnover, world trade, seaborne trade and world GDP 1990–2015 (based on UNCTAD 2016, p. 2 and p. 18) with a forecast by Drewry Shipping Consultants for the container turnover for 2012 to 2016 before the global crisis 2008/2009

so far. However, these changes will have a considerable influence in the future (see Sect. 24.6).

As a result of such developments, it is likely that growth in container transport may be reduced significantly (see Halim et al. 2017, p. 90). However, measures will still be necessary. With a declining demand for transport and logistics services, competition will drastically increase. That means, the performance of the SCT will be a decisive factor in (international) competition.

A first step towards increasing effectiveness and efficiency in the hinterland processes can be achieved by better cooperation and coordination of the involved parties (see, e.g., Franc and van der Horst 2010; Roso et al. 2009; van der Horst and de Langen 2015). The time required and the cost of such measures are comparatively low; therefore, these can lead to improvements in the short term. However, appropriate measures to qualify and to extend the existing infrastructure must follow to avoid future bottlenecks, which can only be seen in a long-term timeframe. But to undertake such implementations it is often associated with significant problems in the existing (political) environment and the divergent interests of the different stakeholders.

In the following analysis some basic considerations regarding the organizational and technical improvement of processes in the (international) container transport will first be outlined. Then three possible solutions for a reorganization and performance improvement of port hinterland transport will be presented (see Sects. 24.3, 24.4, and 24.5). The objective of this path is to achieve an increase in the SCT handling capacity by acceleration of the inbound/outbound processes from/to the port hinterland and a significant cost reduction.

24.2 Process Design and the Basic Framework

Bases of worldwide organized intermodal container transport are networks with efficient SCT (as central nodes) and their sea- and landside cross-linking through the various transport modes (see, e.g., Liu et al. 2014). Seawards it is the connection between the SCT among them by (deep) sea shipping, while onshore the integration of inland terminals using terrestrial transport modes takes place. To ensure the necessary performance, a cross-network adjustment of the capacities as well as a synchronization of the processes is required. Capacity expansions and accelerations in the processes within the SCT have little or no effect if the external links are not of sufficient performance as well. Especially at the landside increasing bottlenecks were evident in recent years (see, e.g., Merk and Notteboom 2015; Ninnemann 2015).

Over the years, demand developed in a differentiated manner, with different growth rates but also showing significant declines in some cases while at the same time competition pressure was continuously rising. This led to a number of structural and organizational changes in the past, focusing on the field of monitoring and control of (internal) processes in SCT. But more and more the expansion of existing and the construction of new terminals came to the fore. Due to the related investment requirements an increased integration of private sector companies occurs, e.g., applying *Public Private Partnership* (PPP) concepts (see, e.g., Aerts et al. 2014; Panayides et al. 2015; Vining and Boardman 2008). At the same time, there is an internationalization of some of the terminal operators, which expand their market position in this way, as well as an entry of market dominating shipping companies (see, e.g., Lee and Song 2015; Notteboom 2004; Slack 2007). Most of these structural and organizational changes (e.g., to dedicated terminals) have largely seaward effects but on the other hand considerable deficiencies can be seen in the hinterland transport operations of ports. In the following a brief overview of previous and current developments within international container transport operations is provided.

- *Development of seaport container terminals*:
  The enhancements and efficiency improvements in SCT operations (see, e.g., Carlo et al. 2014; Dragović et al. 2017; Gharehgozli et al. 2016; Stahlbock and Voß 2008; Steenken et al. 2004) mainly relate to a shortening of process time (and therewith of laytime in ports) as well as to improvements in cost structures. In the foreground is the use of quantitative methods (as well as an increased use of information technologies) in the context of planning and control processes, the use of new technologies in the handling of in-company operational processes

and capacity-enhancing measures in the field of terminal infrastructure. Within the planning and decision processes a differentiation into three levels arises:

– *Operational level*: Short-term possible improvements in the organization of in-company operational processes on the basis of existing (handling) technologies and the existing infrastructure.
– *Tactical level*: Medium-term involvement of other (improved) technologies into operational processes in the field of transport, handling, and storage.
– *Strategic level*: Long-term oriented investment measures in the development of terminal structures.

In general, these three levels are not clearly separated as they influence each other. Operational planning and control can result in reaching a performance limit due to the used technologies. As a consequence, changes at the tactical level would be necessary. Conversely, measures on this level require adjustments within the operational level. A similar situation is evident in the dependency between the tactical and strategic level. Another important problem is the time needed for implementing the planned measures, as this is often underestimated by insufficient consideration of the legal framework (and also of political influences). In addition, the available technical possibilities and the question of the economic efficiency of the measures must be examined. The measures undertaken in the last decades have led to some significant improvements in efficiency at the operational level, as in the area of sea- and landside process design and yard management (see, e.g., Gharehgozli et al. 2016; Stahlbock and Voß 2008).

- *Development of seaside linking*:
With the increased demand for container transport over the years, a need for larger shipping units is generated (see Fig. 24.1), especially on the routes between East Asia and Europe (see, e.g., Merk et al. 2015, p. 93; Merk et al. 2016), as well as suitable port infrastructure capacities (see, e.g., Meng et al. 2017). Most important here are the trunk connections with accordant volume potentials, which form a necessary basis for the use of large container vessels. A basic condition has been a sufficient improvement of the operational performance within the SCT by the use of more efficient technical suprastructure (see, e.g., Carlo et al. 2014; Wisnicki et al. 2017) as well as the assembly of suitable trunk and feeder networks in order to use system-inherent economies of scale. But depending on different demand structures, the use of smaller vessels may be more economical on certain (even international) routes (see, e.g., Grimstad and Neumann-Larsen 2013). In addition, also regional maritime transport should be considered in this context. The main objectives of these two forms of *Short Sea Shipping* (SSS) (see, e.g., Daduna 2013) are to make more use of sea transport, especially in regional container traffic as well as to reduce the cost-intensive terrestrial hinterland transport.
- *Development of landside linking*:
In this area, there are the largest gaps in the organization of (international) networks in multimodal container transport throughout the past decades. The per-

formance of the transport modes in the hinterland (road and rail traffic, transport via inland waterways) is limited because of various (mode-related) restrictions (e.g., weight and volume capacity). Moreover, the different performance characteristics of the terrestrial transport modes have to be considered (see, e.g., Daduna 2009), which indicate the (usually situational) suitability of the different modes for container transport. The shares of containers being transported via rail, road, or inland waterways (modal split) are shown in Fig. 24.3 (see Pastori 2015, p. 39) for some selected European ports with data from 2013.

It is evident from Fig. 24.3 that the modal split in the hinterland transport of the listed container ports has a wide variance. The container transport by road dominates, while rail transport and transport on inland waterways, with some exceptions, are of comparatively low importance. Since only road transport usually allows a mono-modal link between SCT and customers, the involvement of rail and inland waterway transport requires a pre- and on-carriage, usually

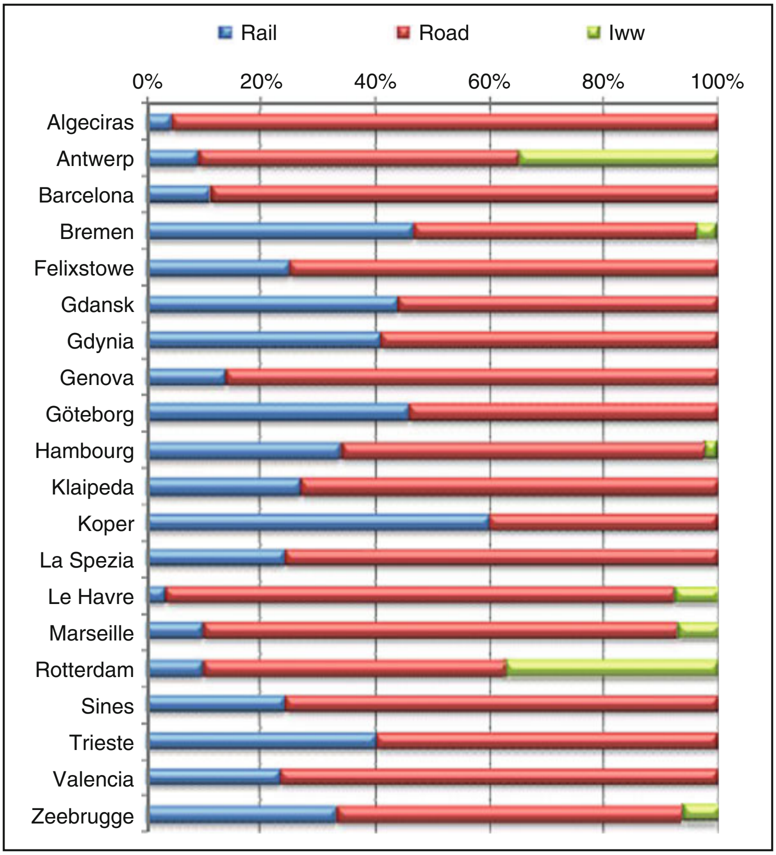

Fig. 24.3 Modal split of selected European container ports (2013)

served by truck. Therefore, a multimodal network has to be designed for installing efficient logistics structures (see, e.g., Bouchery et al. 2015; Daduna et al. 2012).

– *Road freight transport*:
  The low transport volume of trucks from a technical point of view (e.g., vehicle characteristics and specific customer requirements) (see, e.g., Daduna 2009) and the existing capacity bottlenecks within the (main) road networks as well as the partly inadequate road conditions are the fundamental traffic related restrictions. Furthermore, there are discussions about the negative environmental impacts of the road transport. Due to these restrictions, one should assume that this transport mode is not suited to cover an increasing demand for container transport and therefore will lose its importance. However, if the performance characteristics of the terrestrial transport modes are compared, it turns out that only within the road network a mono-modal hinterland transport is possible, especially also due to the high network density. For this reason, the importance of road transport will continue to increase in the future, not only for (mono-modal) direct deliveries, but also in connection with pre- and on-carriage legs within bimodal transport.
– *Rail freight transport*:
  The use of rail freight transport is currently limited. This is due to relative long transportation times and an often missing flexibility, especially regarding the track management. Further difficulties are the partly extensive inefficiencies in the operational processes (e.g., within the shunting yards) as well as the low priority (in many countries) in track allocation for freight transport. Another problem among others is in many cases the lack of (transnational) interoperability within monitoring and control technology, energy supply, and track width. The expansion of network capacities can be a solution, but only in a long-term view, as the planning and implementation of such infrastructure measures would take a longer period of time. In addition, the lack of competition in rail transport, resulting from the quasi-monopoly position of former state-run rail carriers, also has negative effects until today.
– *Transport via inland waterways*:
  The relative low network density, topographical constraints (width and depth of inland waterways), and weather-related influences restrict the use of this transport mode. Due to the political framework in most countries, structural and capacitive adaptations of the infrastructure are only enforceable with severe restrictions or not at all, so that the inland waterway transport can only represent an alternative in the case of appropriate conditions. However, there are several successful examples worldwide: the Amazon River, the Mississippi River, the Rhine River, and the Yangtze River. These are very important segments of the national transport networks, but, however, they can only be effective in a corridor structure (see, e.g., Caris et al. 2012) as normally inland waterways do not allow direct connections between shipper and clients.

Based on the situation outlined above, for long term mainly the rail freight transport (partially in connection with SSS and *River–Sea Shipping* (RSS)) can provide a more sufficient basis for an efficient container hinterland transport over long distances. But from the current capacity and availability as well as the expected measures to qualify and extend the rail transport infrastructure it cannot be expected that, not only in Europe, the importance of rail transport in modal split of SCT hinterland transport will be improved significantly in the next few years.

Taking this situation into account, three measures are considered appearing capable to better meet the long-term volume based requirements for port hinterland transport. The focus is on solutions for a spatial dislocation of SCT structures (Sect. 24.3) and an improved integration of rail freight transport into hinterland operations (Sect. 24.4) as well as SSS based corridor concepts (Sect. 24.5).

24.3 Dislocated Terminal Structures

A first approach to overcome the spatial capacity restrictions in SCT is the incorporation of dislocated terminal structures. There is a large number of examples worldwide that show the advantage of this concept to overcome bottlenecks in SCTs (see, e.g., Beresford et al. 2012; Chen et al. 2016; Do et al. 2011; Li and Jiang 2014; Nguyen and Notteboom 2016; Padilha and Ng 2012). Here nearby satellite terminals are built up, where the basic consideration is to bypass the limitations of available storage capacities and the targeted bundling of container flows (see, e.g., Slack 1999). In connection with SCT, they serve primarily as an intermediate storage for a part of the import containers for further transport to the hinterland as well as for bundling and for an on-demand supply of export containers for shipment by seagoing vessels. An essential problem in this context is the integration of these modified transportation processes as well as the technical systems in the existing structures of an SCT, also regarding the necessary investments and operating costs.

Primarily, possible automation and the required number of additional handling operations should be investigated. Aiming at a sufficiently high level of performance and reasonable costs, shuttle transport based on an automated transport system with its own infrastructure seems to be the most efficient alternative. This can be a rail transport system with *self-propelled (automated) units* or a road-based solution with the use of *Autonomous Vehicles* and *Automated Guided Vehicles* (AGV), also as a partially track-guided system (see Society of Automotive Engineers (SAE) 2014). A number of technical design concepts in this regard are discussed in the literature, e.g., related to Los Angeles Port/Long Beach Port (USA) (see, e.g., James and Gurol 2006; Rose et al. 2008) and Hamburg (Germany). Other concepts can be found at, e.g., Dimitrijevic and Spasovic (2006), Roso (2008), and Rosa and Roscelli (2009). So far, these possible solutions are not implemented, or at least not regarding transport between an SCT and a satellite terminal. However, the technological basis is available but specific adjustments are needed to meet the requirements for a high performance shuttle system.

- *Use of self-propelled units in rail transport*:
  There are a number of existing automated train systems and innovative solutions for self-propelled train units (see, e.g., Gattuso et al. 2017; Nießen et al. 2017; Pfaff et al. 2017; Siegmann and Heidmeier 2005), but they are not or very limited used in rail freight transport. This is mainly due to operational reasons (inadmissibility of mixed transport operations of conventional and automated driven vehicles within the same network) as well as legal restrictions within the admission procedure.

  In case of a closed (in-company) track network, the mentioned legal problems are not given. Due to these framework conditions, for more than 30 years around the world a large number of automated urban rail transit system exist (see, e.g., Wang et al. 2016). In contrast, there are only a few applications in freight traffic, such as the CargoMover (see, e.g., Frederich et al. 2002), with an intelligent sensor system for obstacle and track detection and a control system based on mobile radio.

  Based on these (proven) techniques realizable potentials for autonomous driving can also be seen for rail freight traffic. An example is the concept of the Bremische Hafenbahnen for the Bremerhaven harbor area with developing autonomous driving in shunting operations (see, e.g., Kraemer 2016), which is self-learning and self-steering. The objective is to increase the availability of shunting locomotives while reducing costs. In addition, the technical and organizational feasibility of autonomous rail transport should be demonstrated, also for developing appropriate shuttle systems on this basis.
- *Use of autonomous vehicles and AGVs in road transport*:
  The existing vehicle technology for the road transport enables autonomous driving for individual vehicles (private cars as well as trucks) (see, e.g., Fagnant and Kockelman 2015; Gordon and Lidberg 2015) and in a platooning concept (see, e.g., Bhoopalam et al. 2018; Kamali et al. 2017). The basis for this is, among other things, using electronic equipment developed in the context of *A*utomated *D*river *A*ssistance *S*ystems (ADAS) (see, e.g., Bengler et al. 2014; Kyriakidis et al. 2015) in connection with a satellite-based vehicle tracking (see, e.g., Mansfeld 2010, p. 106; Daduna 2011). As for the rail transport, legal aspects of responsibility and liability in case of accidents (see, e.g., Borges 2016; Gasser 2016) as well as psychological and social issues have been discussed in recent years (see, e.g., Fraedrich and Lenz 2016; Schreurs and Steuwer 2016).

  However, autonomous operating trucks as well as minibuses and taxis have been allowed on public roads since 2015 around the world, but many of them are still in a test mode. This means that the requirements for a shuttle system based on autonomously driving trucks can be realized. In the case that closed network structures are available, such as they are described by Zhang et al. (2006) to connect an SCT and a satellite terminal, the use of an AGV system is possible. With regard to the investment costs for the necessary infrastructure, the use of high speed track-guided systems represents a possibility in this context, which also enables a simplification of flow control.

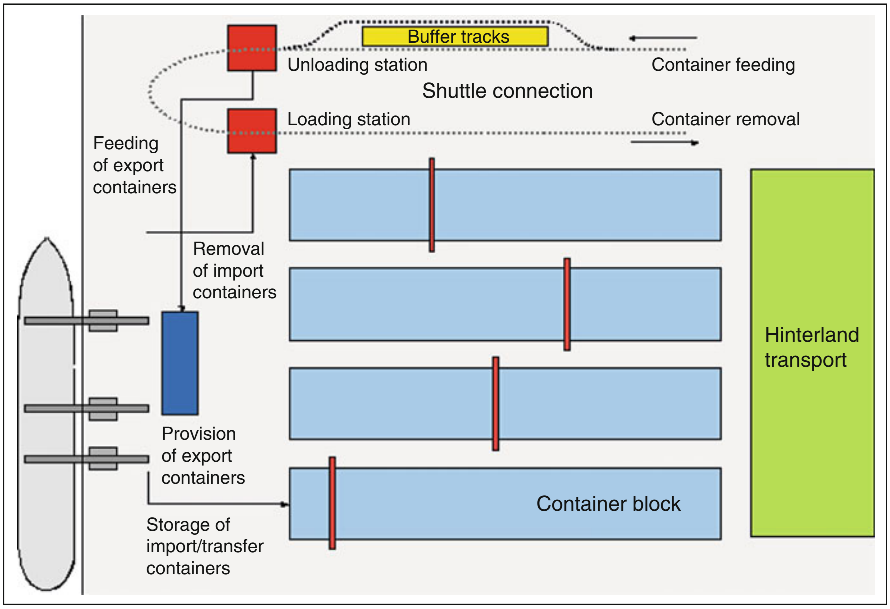

Fig. 24.4 Basic structure of the integration of a shuttle system in an existing SCT to build a connection to a satellite terminal

In the following, the basic structure of the interaction between an SCT and a satellite terminal is outlined. Case-specific (e.g., regional) restrictions would potentially lead to modifications in detail, but without questioning the underlying concept. Figure 24.4 shows the integration of a shuttle system in an existing SCT and the connection with the respective satellite terminal, while Fig. 24.5 depicts the basic layout of a satellite terminal. The operational processes resulting from the shuttle connection to a satellite terminal can be integrated into existing structures, independent of the applied technical approach and of the (necessary) transportation and transshipment operations.

As the availability of sufficient traffic areas for additional transport systems is a critical point, it makes sense to create at least parts of the infrastructure for the shuttle system in an elevated construction. Even if in the future a shared use of the traffic area by manually controlled and autonomous driving vehicles will be permissible, a separation of the traffic on two levels makes sense, since this leads to a more efficient use of the available space in a terminal. Moreover, the landside vehicle use at hinterland interfaces of SCT can be relieved and improved. Here, it often comes to a spatial overlapping of the often dominant hinterland road freight transport (for in- and outbound container flows) with the internal shuttle operations to serve the rail head. With the spatial separation these problems can be overcome, and additional design options are given.

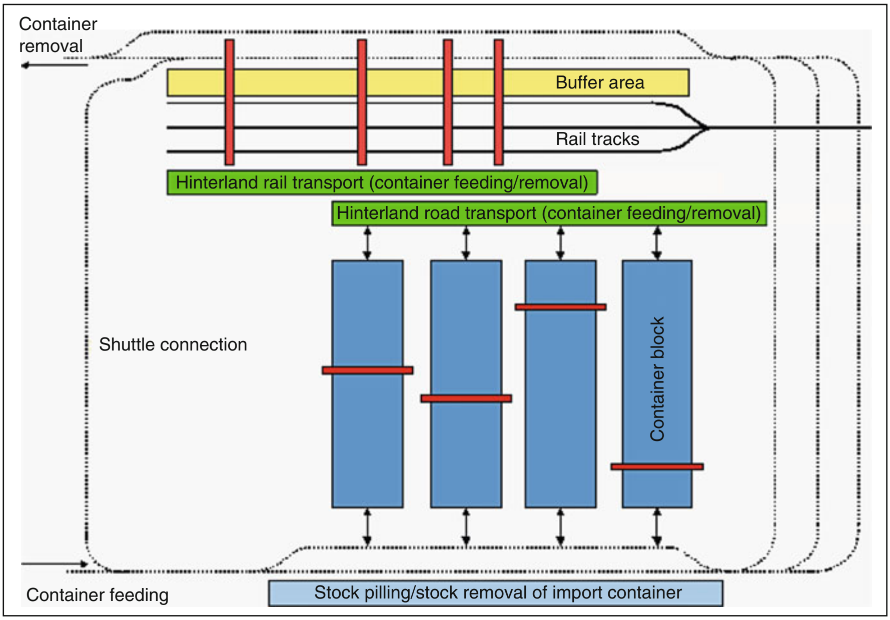

Fig. 24.5 Basic layout of a satellite terminal

As shown in Fig. 24.5, a satellite terminal includes not only additional yard capacities, but it also provides a gateway expansion for hinterland transport. The focus here is on the link to road and rail transport (but also on specific shuttle systems). If appropriate geographic conditions are given, such as an available and sufficiently capable connection to inland waterway networks, this transport mode can be included as well. A specific variant are dedicated terminals which are used exclusively for inland waterway transport with an appropriately adapted infrastructure and handling equipment. These also form the necessary interface between maritime transport and the hinterland transport on inland waterways. These allow a systematic segregation of types of vessels, so that the quay allocation and transshipment operations in the respective terminals can be controlled more efficient (and cheaper as well), e.g., by the use of vessel-specific transshipment techniques.

Associated with the implementation of satellite terminals are investments for the construction of additional facilities and for providing necessary transportation systems. Furthermore, additional operating costs and a reduction of logistic flexibility within the terminal operation might occur. Important factors here are the distance between the SCT and the satellite terminal as well as the container volumes to be handled. A general statement on the advantages of such a decentralized solution is impossible, as, regarding the (additional) costs, the local conditions and existing structures of the SCT must be considered as important restrictions.

24.4 Options to Use Rail Freight Transport

Another way to improve the performance of container throughput in SCTs is an increased use of rail freight operations in port hinterland transport. Two approaches can be considered: the use of *direct connections* to capable inland terminals (dry ports) in the hinterland (see, e.g., Jaržemskis and Vasisliaukas 2007; Roso 2008; Roso and Rosa 2015; Roso et al. 2009) and the integration of hinterland *Megahubs* (see, e.g., Alicke 2002; Limbourg 2007, p. 141) in the organization of continental container flows. The aim is to bypass the storage of a certain amount of containers in the SCT and thereby shift sorting and allocation processes into a hinterland terminal.

- *Direct services to inland container terminals*:
  The basic idea of this concept is the direct shipment of discharged import containers by dedicated block trains considering a presorting for different hinterland destinations. The most important effect is avoidance of intermediate storage in the SCT, which reduces the occurrence of capacity risks. The delivery out of the inland container terminal is mostly done via road transport to the customers that are usually located in the closer surrounding. The concept of connecting an SCT with inland container terminals providing service within their surrounding area is shown in Fig. 24.6.

  But such a solution, however, is only of limited use for an on-time delivery of export containers to be shipped in an SCT. Difficulties are a sufficient level of demand for a scheduled block train and the availability of sufficient yard

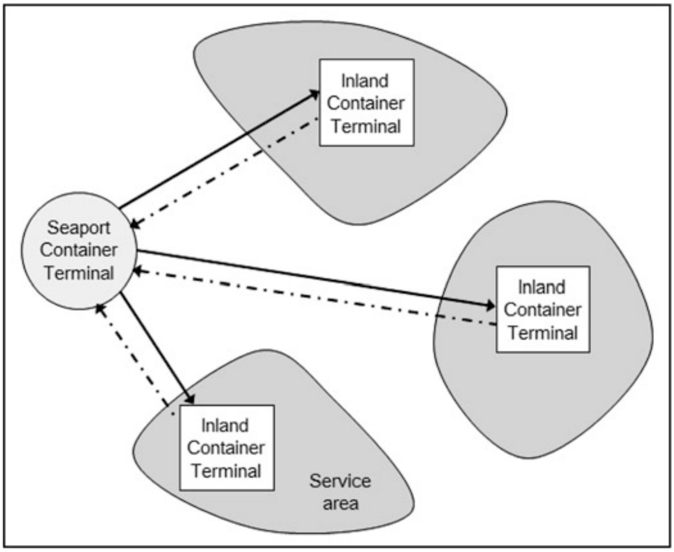

Fig. 24.6 SCT connection to inland container terminals

capacities in inland terminals, to enable a multi-day intermediate buffering of containers. With the time-related requirements for the container supply and the possibility of occurring disturbances in the transport processes in mind, a sufficient time buffer must be considered in advance, so that a (short-term) storage in the SCT is possible.

If an SCT has a sufficiently capable connection to an inland waterway network, an accordant concept can be realized for this transport mode (using, e.g., pushing lighters). But the lower speed of inland waterway vessels must be taken into account.

With the use of pushing units, additional abilities show up, as single pushing lighters can be distributed locally along an inland waterway-route and therefore the transport process can be separated of loading and/or unloading, whereby significant time advantages can be achieved. The supply of an SCT can be organized in an analog way (centralized and decentralized), although a sufficient time buffer in advance is necessary, e.g., resulting from the (relative) low speed. An arrival at the SCT too early does not lead to difficulties, as the pushing lighters can then be used as a (cost-effective) temporary storage system.

- *Incorporation of hinterland Megahubs*:
  A significant simplification of processes can be achieved, if the discharged import containers are directly transported into a hinterland Megahub without sorting (see, e.g., Alicke 2002; Limbourg 2007, p. 141; Boysen et al. 2013). Megahubs, or Thruports (see, e.g., Rodrigue 2008), will form an essential element in the future of containerized rail freight transport. This concept enables a quick removal from the SCT, since the exact assignment of container destinations takes place in the Megahub which is reached first. This simplifies (and speeds up) the processes considerably, as important time advantages can be achieved within suchlike structures in a hub with a direct exchange (transshipment) of load units between several trains (see Fig. 24.7; see also Kreutzberger and Konings 2016). If no direct transfer of some containers is possible within the hub, they can be stored temporarily (up to a certain extent). In addition, Megahubs are serving as an interface to road transport, particularly in consideration of the distribution (or collection) of containers within the (surrounding) area.

  In the opposite direction, which means the supply of export containers to an SCT via Megahubs, an aggregation occurs analog to the processes outlined above, whereas these processes (shown above) are clearly more difficult to organize. A crucial question is whether it is possible to temporarily buffer containers within the different hubs, so as to ensure an exact (real-time) control of the timely delivery of export containers for shipment to the quay wall.

  At the same time, the partially missing interoperability based on technical differences between the applied systems can be resolved, as they exist not only within the European rail network. Simple transfers between networks with, e.g., different track gauges can be simplified and made cheaper by using Megahubs as an interface. An example for such situation is the *Transport Logistics Center* (TLC) at Khorgos at the Eastern border of Kazakhstan as a part of the New Silk Road (see, e.g., Islamjanova et al. 2017; Semak et al. 2017). Here, the

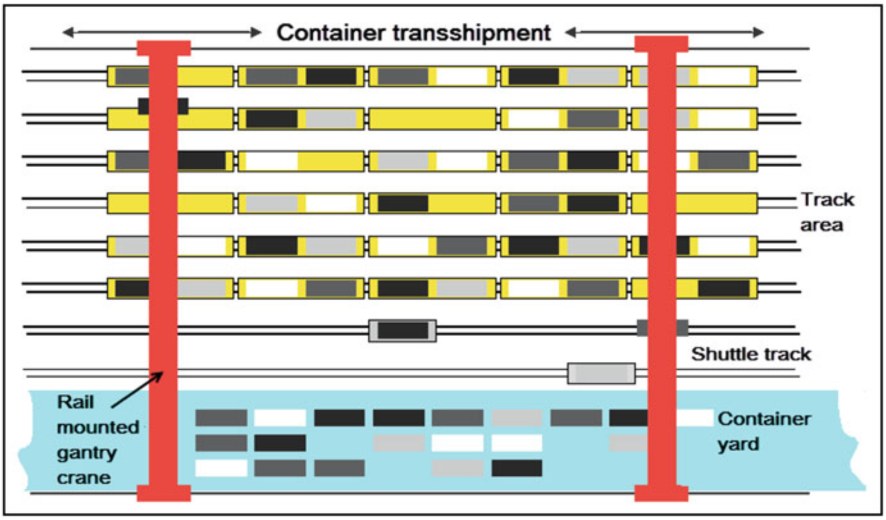

Fig. 24.7 Megahub system concept (basic layout)

transition from standard gauges (China) to wide gauges (Russia) takes place as a quick changeover between the two systems instead of a technically complex gauge change, associated with considerable cost disadvantages.

The realizable potentials of efficiency and service capacities of Megahubs are based on the introduction of integrated hub-structures within a large-scale (international) rail traffic system (see Fig. 24.8). Because of the existing bundling effects (and the associated increase in capacity utilization) as well as the increase of the occurring transshipment operations, the competitive position of rail freight transport can be considerably improved by generating economies of scale. A multi-hub network structure is set up without using point-to-point transport, i.e., instead of a (meshed) network, based on direct connections.

In Limbourg (2007, p. 141) and Limbourg and Jourquin (2009) it is shown that based on adequate structures a net of Megahubs (e.g., within European or Eurasian area) will facilitate the reorganization of rail freight transport. This service improvement within containerized rail transport must be regarded as a necessary condition for changing the modal split (not only) in the seaport hinterland transport shifting container flows from road to rail. Such a concept of network structures requires a sufficient transport volume for being economically successful. This volume currently exists and it can be assumed that it will be also available in a long-term future, based on continuing seaport hinterland container transport as well as the transnational (terrestrial) container transport.

In addition, the introduction of (largely meshed) network structures (see Fig. 24.8) as well as the integration of SCTs in those structures is an essential basis to attain sustainable improvements regarding the efficiency in intermodal container transport. An interesting area here could be, among others, the

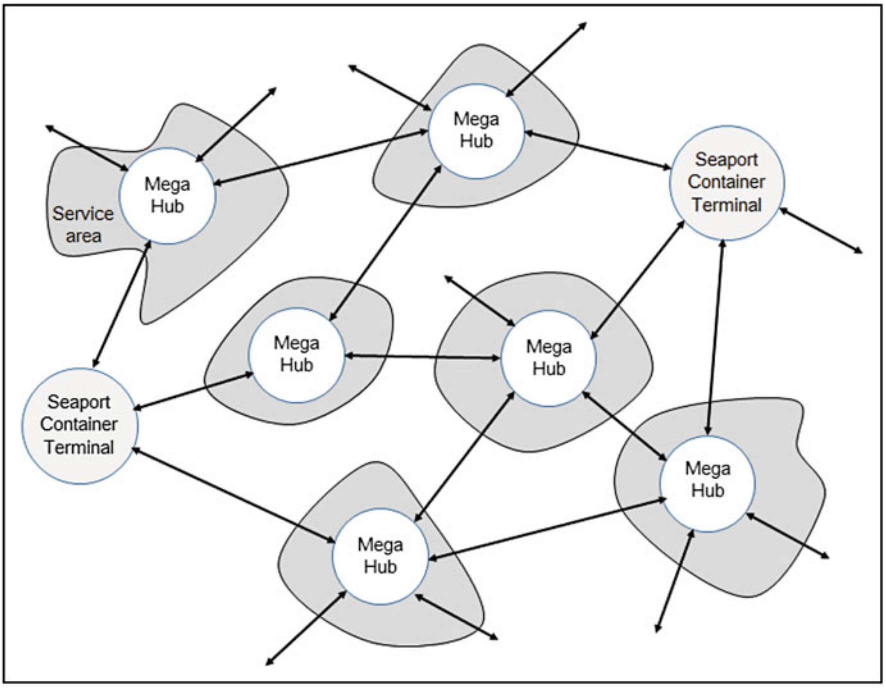

Fig. 24.8 Structural linking of SCT and Megahubs

integration of land bridging transport operation between two SCTs to reduce the transport duration, which may be considered as operationally reasonable (and therefore economically justifiable) within appropriate conditions. This allows improvements in container transport and also reduces the capacity constraints of heavily used SCTs.

A requirement for a comprehensive shift of container flows to rail transport is a fundamental reorientation of transport policy, not only in the *E*uropean *U*nion (EU) but around the world. The currently available network capacities are in no way sufficient to cope with the quantities that should be handled in the future by rail transport. Even if additional potentials can be realized by an improved track management, this is not solving the basic problems.

Due to foreseeable capacity problems, a widespread hinterland network is required, particularly regarding relations among Megahubs to be built or rather existing inland container terminals to be used. A change of the product hierarchy in rail traffic should also be discussed. Compared to (long-distance and high speed) passenger transport, freight transport is often regarded as of secondary importance. A key point here can also be a network design that allows an (extensive) segregation of passenger and freight traffic, thus reducing competition between the different service products. Therefore, the main focus should be on a network expansion taking macroeconomic structures into account. This is an important long-term basis for a sustainable change of modal split in favor of rail freight transport in the port hinterland of the SCT.

24.5 Applying Corridor Concepts

With an integration of SSS (see, e.g., Daduna 2013; Medda and Trujillo 2010; Ng 2009; Paixão Casaca and Marlow 2009; Santos and Soares 2017), and to some extent also with RSS (see, e.g., Charles 2008; Daduna 2013; Radmilović et al. 2011), existing hinterland transport connections of central and heavily frequented SCT can be relieved (in some cases) to a certain extent. The underlying approach is to split parts of the hinterland transport of these SCT by using cost-effective feeder links in the SSS in competition to terrestrial transport modes. To ensure efficient structures, transport corridors can be formed between the North-range ports and the Baltic Sea hinterland (see, e.g., Daduna et al. 2012).

The main objective is to consider possible connections between a hub and the respective destination area as a continuous transport chain in intermodal transport, also from a legal point of view, and not only as a combination of individual services which are provided with the help of different transport modes. In addition, smaller SCT of regional importance should be integrated, which have sufficient technical infrastructure and, in particular, capable hinterland connections. This allows a significant reduction of the share of more expensive terrestrial hinterland transport, also taking the costs of additional sea-to-sea transshipments into account.

In addition to further possibilities for designing hinterland connections, there are other positive effects, both from an economic and an ecological point of view. Thus, an improvement in energy efficiency in the transport operations can be achieved. This is related to reduced emission, resulting from changes in transport mode selection (see, e.g., Aperte and Baird 2013; Morales-Fusco et al. 2012; Tzannatos et al. 2014). Furthermore, there is a relief in particular for road traffic infrastructure (e.g., by reducing traffic density on long distances), and also cost savings in the provision of these can be realized.

The most important operation modes here are point-to-point connections, e.g., specific regional SCTs are served directly, as well as scheduled services where feeder vessels are calling different harbors in a specific area. As these problems are mainly multi-criteria decision-making problems, a corridor analysis (see, e.g., Caris et al. 2012; Daduna et al. 2012) can also be included, taking different objectives into account. Here, a specific SCT can also be assigned to a defined hinterland area (see Fig. 24.9), through which a target-oriented distribution of container flows will be possible.

However, necessary prerequisites still need to be created for the design of corridor concepts. The focus is on the qualification and further development of (intermodal) port hinterland transport networks with regard to capacity expansions of the required infrastructure and a reduction of transport times, whereby public

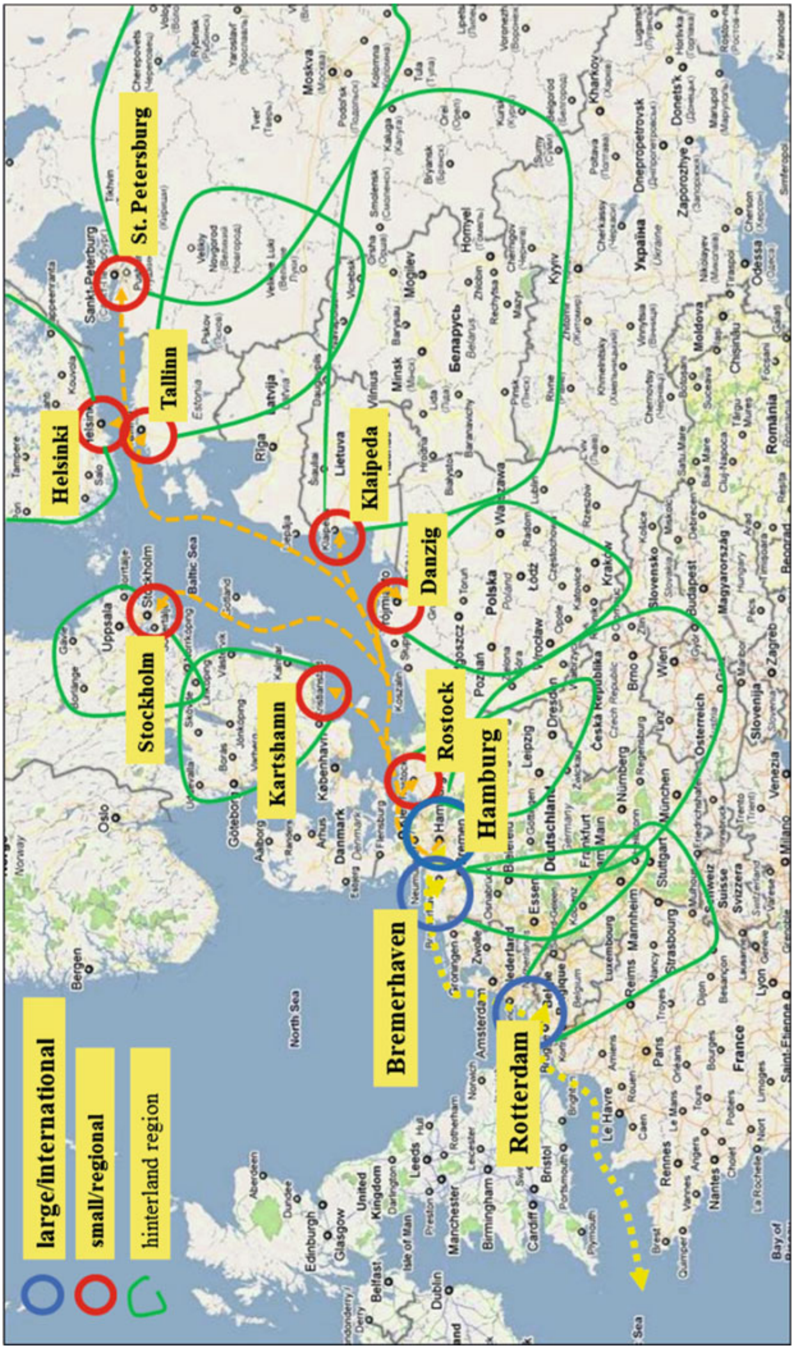

Fig. 24.9 SSS feeder connection between SCT in the South-Eastern area of the North Sea and regional SCT within the Southern and Eastern parts of the Baltic Sea

institutions are needed here. However, this must also include improving the efficiency and effectiveness of the (technical) port equipment. In addition to the infrastructure measurements, a quantitative and qualitative improvement of the offered services by logistics service providers active in this market is required. This refers particularly to sufficient service frequencies and an increase in the transport operations' reliability. To ensure efficient processes, it is also essential to set up an inter-organizational information management to improve the planning and monitoring of transport processes. If the necessary framework conditions are given, in particular by integrating SSS, a clear improvement of the seaport hinterland transport can be achieved.

24.6 Conclusion and Outlook

After the global economic crisis in 2009, there has been a renewed increase in international container transport until now. If these developments continue it will lead to constantly growing requirements on logistics in these transport networks, both in the nodes (the SCT and the hinterland terminals) and in the sea- and land-based cross-linking. Since the existing capacities could not be sufficient for the expected demand in some cases, the question of responsibility for capacity extensions has to be asked and answered. Here, three areas must be differentiated:

- Development of operational structures as well as procurement and provision of necessary transport capacities: Here, the transport service providers are responsible, e.g., the shipping companies.
- Construction, capacity extension, and maintenance of logistic facilities: Here, the owners of the facilities are responsible. Owners may be governmental institutions or private owned companies. In addition, there is also the possibility of applying public–private partnership models.
- Construction, expansion, and maintenance of public traffic infrastructure networks: Usually, governmental institutions are responsible for these tasks, e.g., in the context of providing services of general interest.

Regarding these measurements an important point is not only the technical organization but also the coordination of financial resources. This is an issue in most cases due to the different framework conditions of governmental institutions and private owned companies. In view of the limited financial resources it should be checked whether it can be useful to develop hierarchical network structures with different levels of expansion for the SCT, also in connection with the development of service structures in SSS (see, e.g., Daduna and Hanisch 2015). However, this requires extensive transnational cooperation. Considering the political reality, its realization seems to be very difficult and time-consuming.

It is also questionable whether and to what extent the volume of international container transport will continue to grow in the upcoming years. Although there is still an increase in container throughput in various SCTs, especially in Chinese ports (see Table 24.1), but there are also contrary developments and trends worldwide. In addition, it has been recognized that the exorbitant growth rates predicted a few years ago were influenced by unrealistic expectations. Various factors that will determine future developments are difficult to estimate in terms of their impact. Moreover, a quantification of these effects is only possible to a limited extent. Some trends, however, can be recognized.

Thus, the international container transport will be influenced by the future developments of global economic structures. A key factor here are regionally rising labor costs, which trigger relocation effects to other regions and thus also change the flow of goods. These can be, e.g., relocations from the East Asian region to African or South American regions, where there will be labor cost advantages in the future. In addition, China is undergoing fundamental economic changes. This is how the hitherto prevailing export orientation goes down. The Chinese government does not want to serve only as the extended workbench of the old industrialized economies any longer. The development of the domestic economy is increasingly coming to the fore. As a result of these developments, the dominance of container transport on the East Asian-European route may decline, leading to a structural change in the worldwide container flows.

In connection with the above mentioned increase in labor costs in former low-wage countries and the technological developments that can be subsumed under Industry 4.0, further changes are emerging. As a result, insourcing (or re-shoring) and re-insourcing are becoming more significant, as decentralized manufacturing is proving to be more and more economical and sustainable (see, e.g., Ashby 2016; Wiesmann et al. 2017). Moreover, growing automation combined with an increasing adoption of AM (see, e.g., Bikas et al. 2016; Chen et al. 2017; Jiang et al. 2017; Mohr and Khan 2015; Sasson and Johnson 2016; Weller et al. 2015) allows for a much higher degree of customer proximity in the manufacturing processes, also in connection with an individualization of products.

This does not only apply to industrial manufacturing processes but in particular also to spare parts production (see, e.g., Khajavi et al. 2014; Li et al. 2017; Savastano et al. 2016; Wits et al. 2016), where the use of AM enables a consistent demand orientation. The existing supply chain structures in the industrial and spare parts production are drastically reduced which is connected with a significant reduction in transport and warehousing operations and costs (see, e.g., Ben-Ner and Siemsen 2017). Some even more significant changes can be seen in the consumer goods industry. Here, the previously existing separation between production and retail trade can be widely eliminated. As a result, it comes to a partial de-industrialization (see, e.g., Ben-Ner and Siemsen 2017; Petersen et al. 2017; Attaran 2017, e.g., speaks of micro-manufacturers in this context). An essential step here is the integration of 3D printers in sales facilities in conjunction with an on-demand and customer-specific production. At this point, logistics is essentially reduced to the local provision of printing materials of various kinds. In a final step, the production can also be shifted to the customer location in the sense of a home fabrication (see, e.g., Attaran 2017; Bogers et al. 2016; Petersen et al. 2017; Rayna and Striukova 2016). As a result, the importance of traditional production and retail trade structures as well as the associated logistic processes will decrease significantly especially in the field of consumer goods.

In addition, it is becoming apparent that this production technology can also be considered as a technically and economically feasible transition to mass production in many areas. Thus, it is expected that these outlined developments will prevail comprehensively in the various market segments in the coming years, with the corresponding consequences for the logistic structures.

But there are also other estimations that essentially assume a continuation of the status quo. The problem of such calculation regarding the further developments in worldwide container transport is discussed in Halim et al. (2017). Based on the traditional modeling, a further, sometimes significant increase is reported for 2030 and 2050. This is based on a scenario in which it is assumed that no disruptive changes will occur over the next 20 years that will have a sustainable effect on global flows of goods.

At the same time, however, they also say (see Halim et al. 2017, p. 90) that for discussing future developments considerable uncertainties must be taken into account whose effects cannot be calculated up to now. They therefore find (see Halim et al. 2017, p. 92 "... that the projections [...] should therefore be interpreted with caution. Indeed, there is much uncertainty related to consumption and production patterns, energy production and shipping routes, which make decision making difficult." Essential aspects are here (see Halim et al. 2017, p. 90) "... that fundamental changes are taking place in consumption, production and energy sources. For example, an element of consumption has now become virtual, immaterial and shared. A share of production has become more local, facilitated by innovations such as 3D-printing and tendencies towards a more circular economy. Energy production has also become more localized, focused on renewable energy sources." It follows that the decision on future development of the terminal infrastructure, on technical equipment as well as on expansion and extension of hinterland transport links should take these uncertainties into account, also with regard to possible misallocation of resources.

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