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ORIGINAL ARTICLE

# Container terminal layout design: transition and future

**Amir Gharehgozli**[1] · **Nima Zaerpour**[2] · **Rene de Koster**[3]

## Abstract

Container terminals play an important role in the transportation of containerized goods in global supply chains. The number of containers handled in container terminals has increased astronomically. To accommodate and handle the increasing number of containers entering and leaving container terminals, their layout has seen several changes. New layouts require smaller footprint and must ensure faster, cheaper, and more efficient transfer of containers between the landside and seaside. This paper first reviews the literature on the transition of terminal layout designs from traditional to automated and future container terminals. Second, the relevant research needs to address strategic and tactical layout design problems are listed.

**Keywords** Global supply chain · Maritime transportation · Marine terminal layout design · Next-generation container terminals · Design optimization · Vertical expansion

## 1 Introduction

Container terminals are one of the essential elements of ocean transportation. Nowadays, a large terminal handles millions of containers annually. To increase the efficiency of containerized cargo transportation, closer attention to the layouts and handling systems used to stack containers is key. At terminals, containers are often temporarily stored in stacks, waiting for further transportation either by sea-going vessels or by land-based modes of transportation. In current designs, container terminals typically have a rectangular layout where containers are densely stacked in multiple (usually four) tiers with multiple bays and rows next to each other. However, terminal operators are progressively compelled to design innovative layouts

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✉ Amir Gharehgozli
amir.gharehgozli@csun.edu

[1] College of Business and Economics, California State University, Northridge, CA, USA

[2] College of Business Administration, California State University, San Marcos, CA, USA

[3] Rotterdam School of Management, Erasmus University Rotterdam, Rotterdam, The Netherlands

and develop new handling systems because of three trends: (1) the increase in the number of containers to be handled, (2) scarcity of land, and (3) decreasing cost of technologies and increasing reliability of advanced container handling systems. These trends are discussed in detail below.

According to the World Bank (2018), container throughput has increased from around 224 million twenty-foot equivalent units (TEUs) in 2000 to more than 701 million TEUs in 2016. Transportation of containerized goods has proved to be cheaper, faster, safer, and more efficient. Today, the global fleet consists not only of more containerships but also of larger ones. As carriers exploit economies of scale by increasing vessel size to accommodate larger loads, container terminals must be capable of handling these massive vessels, in the shortest time possible, while offering competitive terminal-handling charges (THCs). Up to now, automation has helped terminals to satisfy such needs. However, continuation of the current trends will eventually require terminals to redesign their layouts in order to keep up with the increased throughput.

As a result of the need to stack and handle an increasing number of containers, land has become scarce at many seaports. To provide terminals with the extra land required, many ports have expanded by land reclamation or using hinterland "dry ports" (see "Container terminal layout design: concepts and status quo" section). Vertical expansion, i.e., storing containers in taller structures, also seems to provide a promising alternative (see "Next-generation container terminals" section).

Designing new layouts for future container terminals seems to be inevitable. However, up to now, terminal operators have been reluctant to put time and effort into such projects. The main reason could be the investment and operational costs required for developing, implementing, and operating new layouts. Furthermore, after spending so much money, it is not clear whether the new layouts could result in the desired performance. Still, the decreasing cost and increasing reliability of advanced container handling systems need to be taken into consideration in development projects. A tradeoff between the costs of current designs (i.e., cost of land) and the costs of new designs (i.e., cost of technology) can help operators to make more informed decisions (see "Future container terminal layout designs: research directions").

A cursory look at the literature shows the massive amount of effort that has been invested by researchers in answering the challenging research questions that container terminals pose [see, for example, Sun and Yin (2017), who have categorized research topics in transportation journals]. A lot of literature reviews have also appeared, summarizing research efforts made in the last decade on container terminals (see, e.g., Gorman et al. 2014; Carlo et al. 2013, 2014a, b; Gharehgozli et al. 2016; Lehnfeld and Knust 2014). However, a closer look at these reviews shows that container terminal layout and system design is not a prevalent research topic. In fact, looking at container terminals also shows that, although automation of handling systems has progressed thanks to technological advancements, the basic terminal layout with seaside, stacking, and landside operations has not fundamentally changed. Bierwirth and Meisel (2010) argue that layout and system design is an important strategic decision that impacts all the other decisions made by container terminal operators (Fig. 1).

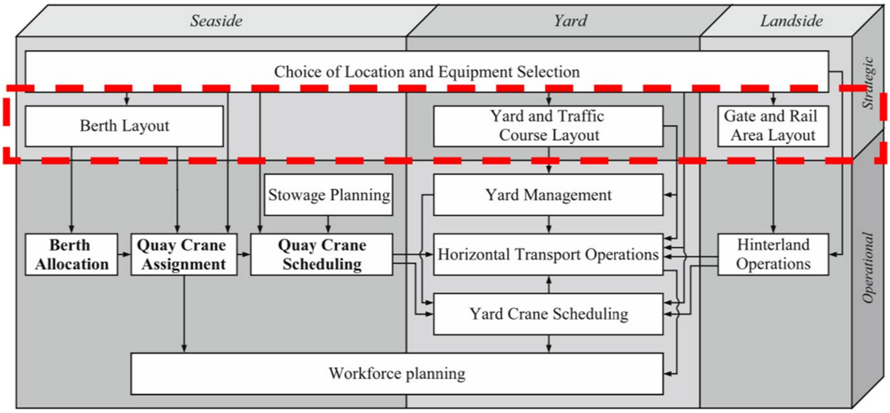


**Fig. 1** Layout design as compared with other decision problems in a container terminal

The contribution of this paper is threefold. First, we highlight the concepts relevant to layout design and system choice and give a comprehensive review of the literature. Second, we discuss potential layouts for next-generation container terminals. Third, we identify strategic, tactical, and operational decision problems pertinent to future layout designs and discuss appropriate solution methodologies for each problem type. Business and academic communities need to start addressing these decision problems in order to make the implementation of such designs feasible.

The remainder of this paper is organized as follows: In "Container terminal layout design: concepts and status quo" section, we discuss typical layout design decision problems currently studied or implemented in container terminals. In "Next-generation container terminals" section, recent innovative layout designs including their pros and cons are discussed. In "Future container terminal layout designs: research directions" section, we discuss new layout design-related research themes, based on our experience, interviews held with container terminal operators, and involvement in some consulting projects. "Conclusions" section concludes the paper.

## 2 Container terminal layout design: concepts and status quo

Containerization is probably the most significant invention of the 20th century in the shipping industry. With no exaggeration, it is the backbone of global trade (Du et al. 2017; Ducruet 2017).

To provide cost-effective and efficient services to containerized cargo transport, terminal operators, shipping companies, and port authorities are investing in new technologies to improve handling infrastructure, operational efficiency, and security (see Fig. 2 for an example of seaside requirements for handling large containerships). According to the United Nations Conference on Trade and Development (UNCTAD 2017), based on data collected across 292 projects between 2000 and 2016, in collaboration with the private sector, ports have invested around US $68.8 billion in

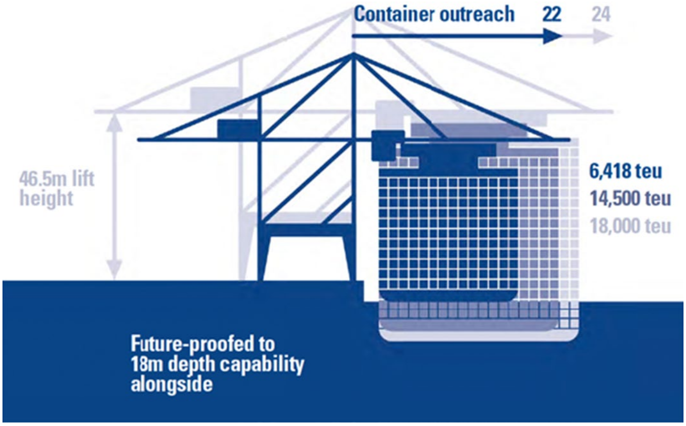


**Fig. 2** Requirements for handling large containerships *Source* Port of Felixstowe 2018

port infrastructure, superstructures, terminals, and channels. However, until now, terminals have invested only marginally in new storage systems and novel layouts that can facilitate the container handling operations of the future. In "Today's container terminal layout" and "Changes in current container terminal layouts" sections, we discuss the current layouts common in container terminals and how these have changed over the past two decades. Future layout designs, which are still mostly at the conceptual level, are discussed in "Next-generation container terminals" section.

## 2.1 Today's container terminal layout

Terminals serve as the main intermediator between seaside and landside operations. At one side of the container terminal there is the sea or quay, where containers are loaded on and off the ships, and at the other side there is the land, where containers are loaded on and off trains, trucks, or barges.

Containers can be moved directly from the seaside to the terminal gates, to be forwarded to their final destinations. However, in most cases, they have to spend time in container stacks at the stacking area. Currently, three main types of seaport terminals can be distinguished, based on the stacking solutions chosen: (1) straddle carriers (SCs) and reach stackers, (2) rail-mounted gantry (RMG) cranes, and (3) rubber-tired gantry (RTG) cranes (Thoresen 2003). The layout of the terminal impacts the stacking solution and the way containers are stacked.

SCs and reach stackers are suitable for manual terminals and cannot achieve the capacity and space utilization requirements for handling the huge number of containers that nowadays have to be handled by large seaport terminals. SCs are more efficient for large operations than reach stackers (i.e., they are faster). They can move between rows of containers and can stack them up to usually four tiers. On the other hand, a reach stacker can stack containers four deep and up to six containers high, but normally the stacking is not more than two deep and three or four high (Vis and Roodbergen 2009; Wiese et al. 2013).

Depending on whether RMG or RTG cranes are used for stacking operations, container terminals organize their container stacks using one of the following two methods: The first method aims to decouple the seaside and landside operations by orienting container stacks perpendicular to the quay, which is more common in export and import terminals (for example, the HHLA Terminal Altenwerder in the Port of Hamburg). In this method, automated stacking cranes (ASCs), which are automated (RMG) cranes, are normally used to stack containers in container blocks (also known as stacks) with multiple tiers, rows, and bays (Carlo et al. 2014a; Gharehgozli et al. 2014b, 2015, 2017a, 2019).

Meanwhile, the second method revolves around streamlining the movement of containers from one ship to another, by orienting containers stacked parallel to the quay; a design more common in transshipment terminals (for example, the Tanjong Pagar Container Terminal in Singapore). In such terminals, RTG cranes are used to stack containers one behind the other. More details regarding the differences between RTG and RMG crane operations can be found in Gupta et al. (2017). Comparative analyses of storage and retrieval equipment in container terminals can be found in Vis and De Koster (2003) and Vis (2006).

A number of researchers have studied the impact of layout and system design on terminal performance. In general, studies on the parallel and perpendicular layouts can be divided into four categories (Lee et al. 2018). Some study the parallel layout with blocks parallel to the quay and one truck lane at each side of the blocks (Alessandri et al. 2008; Petering and Murty 2009; Petering 2009, 2010; 2011; Lee et al. 2011; Woo and Kim 2011, Lee and Kim 2010a, b, 2013; Alcaldea et al. 2015; Woo et al. 2016; Liu et al. 2004). Others study the parallel layout with blocks parallel to the quay and one truck lane at each side of every two blocks (Jiang et al. 2013; Zhen 2014, 2016; Zhen et al. 2016; Kim et al. 2008; Wiese et al. 2010). Finally, with respect to perpendicular layouts, the blocks can be accessed either at the ends or at the sides (Saanen 2004; Kemme 2012; Lee and Kim 2010a, b, 2013; Kim et al. 2008; Wiese et al. 2010; Kemme 2012; Liu et al. 2004).

The academic literature on container terminal layout design has mainly focused on studying the impact of layout variables such as the size of the blocks, the number of blocks, and the type of material handling equipment on the performance of container terminals. Due to the complexity of the problem, simulation is the main tool used in most studies (Nam et al. 2002; Hartmann 2004; Ottjes et al. 2006; Sun et al. 2012). Angeloudis and Bell (2011) and Dragović et al. (2017) give a compressive list of studies that use simulation to model container terminal operations. Queueing theory has also been used in analyzing layout designs (Gupta et al. 2017; Roy et al. 2016; Roy and de Koster 2018; Dhingra et al. 2018). Most of these studies focus on optimizing the current design of container terminals rather than disruptive innovations in container terminal layout design.

To verify the fact that layout design is still a pristine area for academic research, we carried out a comprehensive literature review. In the first step, we identified relevant papers by searching four scientific databases: Science Direct, Taylor & Francis, INFORMS, and Springer. Additionally, Google Scholar was searched using the same terms. To understand the extent of academic research potentially related to our topic, a cursory search of the term "container terminal" was performed. The searches, whose results are presented in Table 1, yielded a total of 30,581 hits from works published between 2000 and 2019. Of those, 5350 were published between 2016 and 2018.

Next, we searched using a variety of keywords to narrow down the scope of each search, thus limiting the results to a greater proportion of pertinent publications. We searched for the term “container terminal” along with “layout design” then “facility design”. The search that included the term “facility design” yielded literature relevant to warehouse planning and design.

The analysis demonstrated that the search using “container terminal” + “layout design” provided the most relevant literature. All publications were read to assess their relevance to the purpose of our paper. Only 21 were found to be germane. Table 1 classifies these papers into three methodology categories: simulation, optimization, and queueing theory.

### 2.2 Changes in current container terminal layouts

Current container terminal layout designs have changed mainly via horizontal expansion in order to create more capacity. Although in most of these designs the initiative has been taken by terminal operators, some projects such as land reclamation have been initiated by port authorities. In this case, the need for more terminal capacity obliged port authorities to take action.

#### 2.2.1 Horizontal expansion by adding or reclaiming land

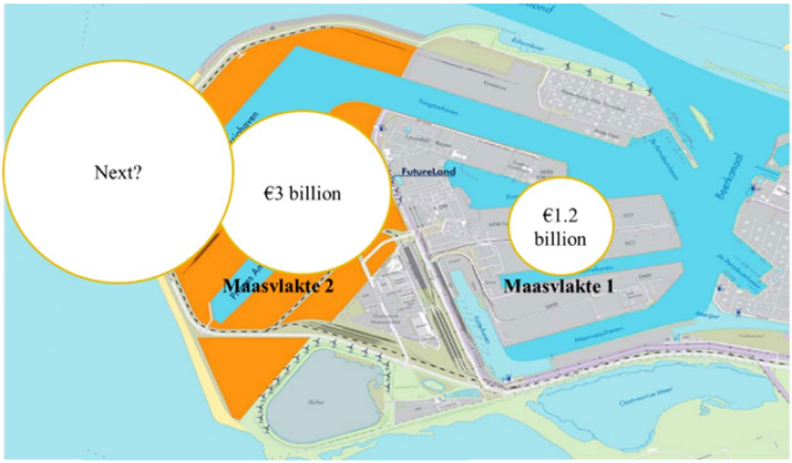
The parallel and perpendicular layouts have experienced only minor changes, although they have expanded “horizontally” to create more capacity (Fan et al. 2012; Jula and Leachman 2011; Leachman and Jula 2011; de Borger and de Bruyne

**Table 1** Classification of literature on layout design by methodology type

| Methodology | 2018 | 2017 | 2016 | 2011–2015 | 2000–2010 |
|---|---|---|---|---|---|
| Simulation | | | | Petering (2011)<br>Woo and Kim (2011)<br>Lee et al. (2011)<br>Kemme (2012)<br>Sun et al. (2012, 2013)<br>Taner et al. (2014)<br>Wiese et al. (2013) | Liu et al. (2004)<br>Ottjes et al. (2006)<br>Petering (2009)<br>Petering and Murty (2009) |
| Optimization | Lee et al. (2018) | | | Wiese et al. (2011)<br>Lee and Kim (2013)<br>Alcaldea et al. (2015) | Lee and Kim (2010b)<br>Wiese et al. (2010) |
| Queueing theory | Roy and de Koster (2018) | Gupta et al. (2017) | | | Alessandri et al. (2008) |

2011; Notteboom 2006). Figure 3 shows two examples of horizontal expansion, providing more land to existing and new terminals: (a) the Port of Rotterdam (Fig. 3a), representing an investment of around €4 billion in the Maasvlakte 1 and 2 projects for land reclamation (Gharehgozli et al. 2017c); (b) the Port of Singapore (Fig. 3b): an investment of US $1.1 billion to construct the Tuas Terminal, with 66 berths and capacity of 65 million TEUs (Li et al. 2016).

Such large expansions imply a need for interterminal container transport (ITT), where multiple container terminals use or share their fleets of vehicles to transfer containers between terminals within the port area (Gharehgozli et al. 2017c; Mishra et al. 2017; Heilig et al. 2017a, b). Heilig and Voß (2017) reviewed all ITT research papers, of which recent ones include those by Hendriks et al. (2012), Lee et al. (2012), He et al. (2013), and Tierney et al. (2014).



**(a)** Land reclamation in the Port of Rotterdam through the Maasvlakte 1 & 2 projects

**(b)** Tuas Terminal in the Port of Singapore (Source: Maritime Singapore Connect, 2018)

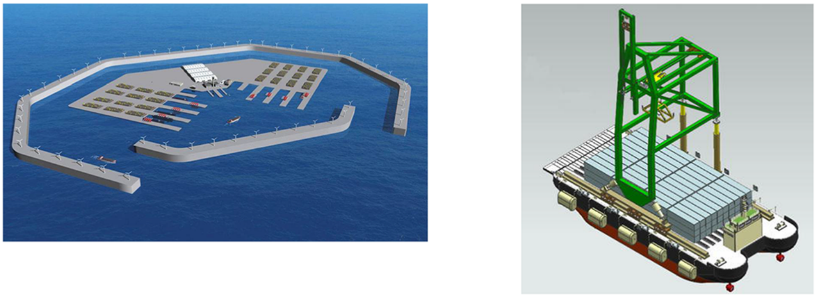
**Fig. 3** Port expansion projects in Europe and Asia

### 2.2.2 Collaboration with hinterland terminals

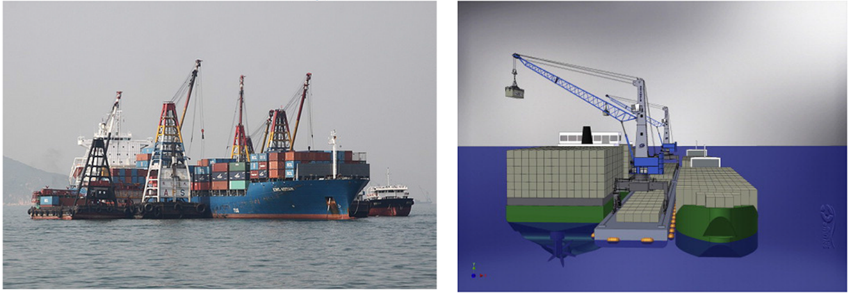
Another solution for horizontal expansion is based on the close collaboration of deep-sea and hinterland terminals (Heaver et al. 2001; Notteboom and Winkelmans 2001; Notteboom 2002; Robinson 2002; Crainic et al. 2015). The main objective of such collaboration is to create extra capacity by utilizing the capacity of dry ports, and to facilitate container transportation between deep-sea ports and hinterland terminals; For example, the opening of the 32-km-long Alameda Corridor between the ports of Los Angeles and Long Beach on the one hand, to intermodal terminals near downtown Los Angeles on the other, eliminated the need to move containers using degraded small railway lines, or trucks, and some 200 street crossings (Roso et al. 2009). In addition to creating extra capacity and reducing congestion, close collaboration of deep-sea and hinterland terminals allows operators to offer part of their value-added activities to the hinterland (see, e.g., Iannone 2012; Veenstra et al. 2012; Zuidwijk et al. 2012; Zuidwijk and Veenstra 2015); For example, European Gateway Services (EGS), a subsidiary of Hutchison Ports—ECT Rotterdam, not only undertakes the movement of containers along a network of inland and deep-sea terminals but also provides additional services such as customs, storage, empty depot, and home delivery. Finally, in line with the idea of dry ports, aiming to improve terminal operations at the seaside, urban intermodal container terminals (IMTs) also exist to facilitate landside operations (Teye et al. 2017a, b). IMTs can be used to create more capacity for landside operations and decrease road traffic around ports. In this regard, most papers study how the location of IMTs can impact port performance (Ghane-Ezabadi and Vergara 2016; Lin et al. 2014a; Zhang et al. 2013; Sorensen et al. 2012; Ishfaq and Sox 2011, 2012).

### 2.2.3 Constructing offshore container terminals

Introducing offshore container terminals is another solution to expand a port. An example of such a concept is the Portunus Project with an estimated investment of US $10 billion (Fig. 4a; Wampler 2010). Another example is the mobile harbor concept, which was studied by Kim and Morrison (2012). A mobile harbor or mobile floating port is a barge with container buffer, onboard quay crane(s), and roll on/roll off capability (Fig. 4b). Storage capacity can vary from 250 to 1200 TEUs. The idea is similar to midstream operations, common in Hong Kong since the 1960s and shown in Fig. 4c, which is the offshore loading and unloading of cargo without going through a container terminal (Fung 2001). According to Lau and Ng (2017), prior to the building of container terminals in Hong Kong, midstream operations were used to load and unload cargo to be shipped to Europe and North America. Kim and Morrison (2012) conclude that such mobile harbors can outperform traditional berth and midstream operations if the annual costs can be reduced by 6% and 45%, respectively. They estimate the annual costs (the sum of the annual depreciation of purchase/construction cost and annual operating costs) for the three systems as US $63.8, US $60.46, and US $37.07 per TEU per year, for the traditional port, mobile harbor, and midstream operations, respectively. A



**(a)** The Portunus Project (source: Mark McDaniel | Lawrence Livermore National Laboratory) **(b)** Mobile harbor (source: Kim and Morrison, 2012)



**(c)** Midstream operation in Hong Kong (source: Wong, 2011) **(d)** Floating Container Storage & Transshipment Terminal (source: Baird and Rother, 2013)

**(e)** Yangshan Port, an expansion to the Port of Shanghai

**Fig. 4** Offshore container terminals

similar idea, shown in Fig. 4d, is the Floating Container Storage & Transshipment Terminal (FCSTT) studied by Baird and Rother (2013). These authors also share the idea that such offshore container terminal operations are more suitable for transshipment operations. Their results show that the FCSTT offers potential for significant capital and operating cost savings, compared with higher-cost landside terminal infrastructure; For example, the investment cost for such a concept is US $50 million, which is one-third of a comparable-capacity, land-based, container terminal. Last but not the least, Fig. 4e shows Yangshan Port, an expansion to the Port of Shanghai based on an investment of US $18 billion for land reclamation and construction of the 31.3-km Donghai Bridge (Marine Insight 2013).

## 2.3 Adding chassis terminals

The Port of Long Beach has opted for horizontal expansion by using a chassis exchange terminal. Dekker et al. (2012) study this innovative layout concept, implemented at the APL terminal at Long Beach. In this terminal, containers are stored on chassis, which can be rapidly moved by terminal trucks. This reduces congestion at the main terminals, as external trucks are handled elsewhere. Since trucks can quickly charge or discharge a chassis, the throughput capacity of the terminal increases substantially. However, Dekker et al. (2012) argue that, as such terminals require a lot of land, cost analysis is necessary to justify their feasibility.

An important factor that needs to be considered in such an analysis is congestion (Chen et al. 2013a, b; Sharif et al. 2011; Gracia et al. 2017). According to Guan and Liu (2009), the commute of an excessive number of trucks in the terminal area can create congestion. However, this may be mitigated by using an appointment system (Ramírez-Nafarrate et al. 2017; Phan and Kim 2015, 2016; Li et al. 2016; Shiri and Huynh 2016; Zehendner and Feillet 2014; Chen and Yang 2010), or time-dependent road pricing (tolls) (Chen et al. 2011a), or gate layout (Minh and Huynh 2014, 2017). Interested readers are referred to Lange et al. (2017), who review and classify current trends in truck arrival systems. On the other hand, in order to ensure chassis availability, an efficient chassis management seems to be indispensable (Ng and Talley 2017; Shiri and Huynh 2017; Le-Griffin et al. 2011; Hartman and Clott 2015).

## 2.4 Moving empty containers to external depots

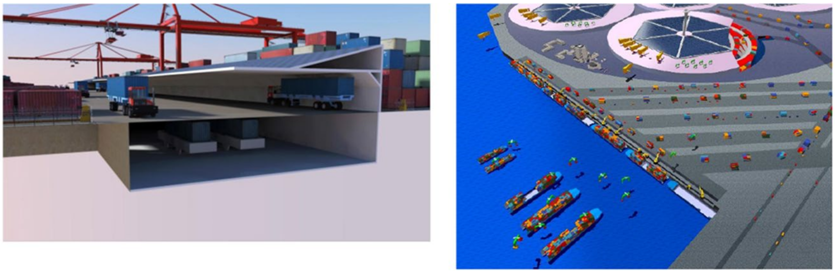
Terminal expansion can also be realized by creating an external depot to store empty containers. In this situation, minimizing the total cost and reducing the mileage involved in repositioning containers are the main objectives (Lei and Church 2011). Boile et al. (2008) and Mittal et al. (2013) suggest that such depots are required not only in areas near a port but also in regions closer to high-volume import and export customer clusters. The above authors call this concept Inland-Depots-for-Empty-Containers (IDEC). Due to the imbalance between exports and imports, determining the capacity of an empty container depot is critical (Epstein et al. 2012). Do Ngoc and Moon (2011) are among the few to study the capacity expansion and space leasing of the empty container depots problem, with the objective of minimizing the total costs. Such costs include capacity expansion, leasing of storage space, inventory holding, container leasing, and positioning costs. The mainstream literature mainly focuses on container repositioning to meet container demand, something rather complex due to the imbalance between incoming and outgoing containers in Eastern and Western countries (Myung 2017; Chen et al. 2016; Long et al. 2012; Zheng et al. 2015, 2016; Moon et al. 2010; Song and Zhang 2010; Meng and Wang 2011; Brouer et al. 2011; Zhang et al. 2014).

## 3 Next-generation container terminals

Efforts by both the maritime industry as well as academic communities to design transformational and breakthrough container terminal layouts have just started. In the Port 2060 project, Kalmar, part of Cargotec, designed an innovative layout for next-generation container terminals. The key features of the design include an underground transportation system, to separate transshipment container movements from vessel operations (Fig. 5a). In Cargotec's futuristic schematic example (Fig. 5b), containers are stacked in underground silos, with solar panels on their roofs (and where large drones unload the vessels). Cargotech envisions round-shaped container stacking structures (silos) in the future container terminal.

In addition, there is an emphasis on autonomous, smart containers and data analytics. Smart containers know their content, trajectory, and destination and can request transport services. Their interior conditions (i.e., temperature and moisture) can be controlled remotely. Last but not least, smart containers could be designed in smaller sizes (as compared with today's standardized 20- or 40-foot containers), which would make them more suitable to be transported via the Hyperloop concept or drones. Such an idea is in line with the concept of the *physical Internet* (PI or $\pi$) (Pan et al. 2017). The PI is a bold paradigm shift that will affect every open global logistics system (Montreuil 2011; Sarraj et al. 2014; Mervis 2014). The PI's main components are standard, smart, and modular containers that can be transported easily through all transportation modes (Lin et al. 2014b) and multimodal transportation networks (Montreuil et al. 2013).

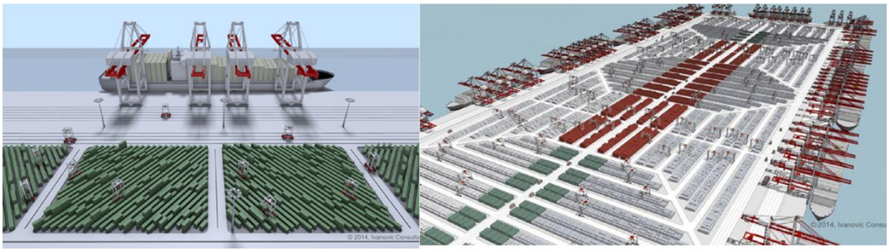
Although Cargotec's design may be far ahead of its time, some of its elements might be implemented sooner. Recently, container terminal designers have started to consider systems prevalent in warehousing (Kim et al. 2012). Some recent studies reveal that designs in which blocks and travel paths are diagonal to the quay, or in which blocks are divided into smaller blocks with I/O points in the middle (Fig. 6a, b), could result in greater flexibility and higher efficiency (Gue 2014; Ivanović 2014). In warehouses, such new layouts have been able to achieve reductions in travel time of up to 20% (Öztürkoğlu et al. 2012; Gue and Meller 2009; Gue et al. 2012).



**(a)** Separation of transhipment traffic from the vessel operation (source: Kho, 2013)

**(b)** Cargotec's Port 2060 design (source: Matinlauri, 2015)

**Fig. 5** Future container terminals by Cargotec Kalmar

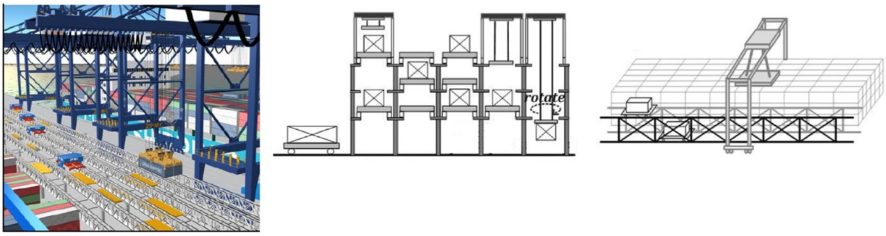


**(a)** Container terminal with straddle carriers **(b)** Container terminal with yard cranes

**Fig. 6** Container terminal designs with blocks diagonal to the quay (Ivanović 2014)

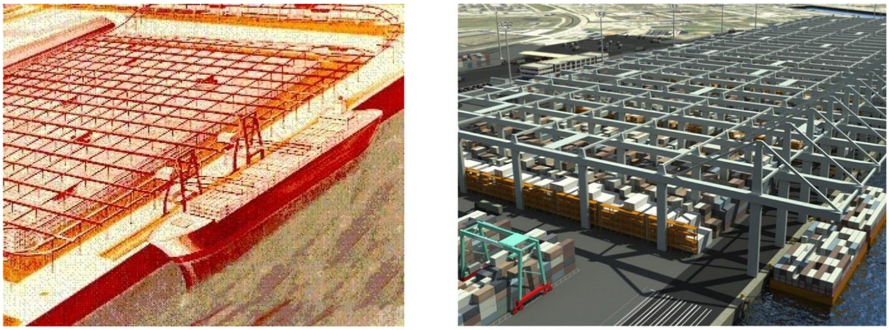
In a different (warehousing-related) design, Zhu et al. (2010) study a system where shuttles are used to transfer containers between the seaside and stacking area, as shown in Fig. 7a. Zhen et al. (2012) and Hu et al. (2013) study the operational aspects of this system. Two extensions, including the triple-storey frame bridges shown in Fig. 7b and the double-storey ground rails shown in Fig. 7c, are also discussed. Recently, Jiang et al. (2018) developed a mixed integer programming model for the frame-bridge-based automated container terminal (without the shuttle system) considering the conflicts and handshakes between frame trolleys. Their findings show that the frame trolleys are the main bottleneck in this design. Terminal operators can shorten the makespan by increasing the number of frame trolleys. However, the performance diminishes because of conflicts. They suggest that containers should be stacked closer to the quay cranes which load or unload them.

Similar to warehousing and manufacturing environments, an overhead grid system has also been considered for container terminals (Fig. 8a). In such a design, containers can be handled using transfer cranes hanging from the overhead grid. The Port of Venice is considering such an overhead system for a new container terminal with estimated capacity of 1.4 million TEUs per year, 1.4 km of quayside, and 90 ha of surface (Fig. 8b; Port of Venice 2018). Recently, Zhou et al. (2017) developed a container allocation strategy for the grid-based system. The performance of different configurations was evaluated by Zhou et al. (2016), using a simulation study.



**(a)** Shuttle system (Source: Zhu et al., 2010) **(b)** Shuttle system with triple-storey frame bridges (Source: Zhen et al., 2012) **(c)** Shuttle system with double-storey ground rail for each stack(Source: Zhen et al., 2012)

**Fig. 7** Container terminal designs with a shuttle system



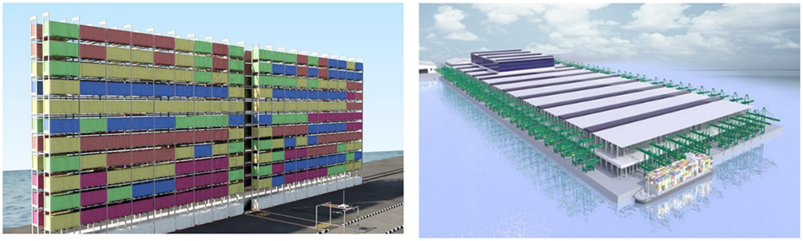
**(a)** The Overhead grid rail system (Source: Kosmatopoulos et al., 2002)

**(b)** The new container terminal of the Port of Venice (Source: Port of Venice, 2018)

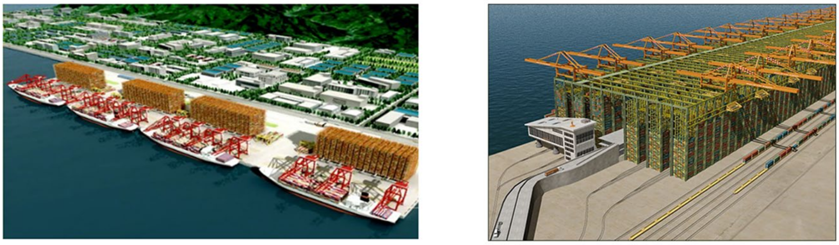
**Fig. 8** Container terminal designs with an overhead grid rail system

Higher and more compact storage systems, which are gaining ground in warehousing, are also being considered to stack containers in the terminals of the future; For example, Fig. 9a shows a system in which containers are stacked in two parallel racks. A lift is used to move containers vertically, while shuttles are used for horizontal movements. This is similar to an automated vehicle-based storage and retrieval (AVS/R) system, commonly used in warehouses (Gharehgozli et al. 2017d). Figure 9b depicts an interesting double-storey container terminal concept, the Automated Next Generation Port, developed for the future needs of Singapore. The design proposes a warehouse with two storage floors, between which containers are transported via a lift. The roof is covered with solar panels and equipped with specially designed triple-hoist quay cranes. Ez-Indus of South Korea has built a prototype of an ultrahigh container warehouse (UCW) system (Fig. 9c). The UCW is a high-rise rack-based automatic system that can significantly save land and space by stacking containers up to 50 tiers high. Containers are delivered to the UCW system, where they are placed on shuttles. The shuttles take containers into the UCW elevator, which takes them to a slot in the rack. Figure 9d–f shows other similar designs to stack containers densely, next to each other, in a high-bay warehouse.

The systems studied until now are rectangular cuboid ones. In warehouse environments, cylindrical structures have been deployed and studied. Zaerpour et al. (2019) are working on a cylindrical container storage system, the next-generation *container tower* system (Fig. 10). Compared with cubic systems, no reshuffling is required in such a cylindrical system. A reshuffle is the removal of a container stacked on top of a desired container. This is a time-consuming and expensive task that occurs as a result of stacking multiple containers on top of each other in container stacks (Gharehgozli et al. 2014a, 2017b; Lin et al. 2015). In a container tower, all containers can be accessed individually by cranes located at the center of the tower. The other advantage of the system compared with cubic systems is the fact that cylindrical shapes are more resistant to wind. By going higher, more containers can be stored and less footprint will be required, making more land available for other container terminal activities.



**(a)** Container racks (Source: VMW systems, 2017) **(b)** Double-storey container port (source: SingaPort, 2013)



**(c)** Ultra-high container ware house system (Source: Ez-Indus, 2017) **(d)** SuperDock (GRID Logistics Inc., 2017)

**(e)** Robotic Container Management System (RCMS) (Rethinking container Management System, 2017) **(f)** Automated Container Transport System (AutoCon) (Source: Germangray's scale modelling, 2017)

**Fig. 9** New-generation container terminals

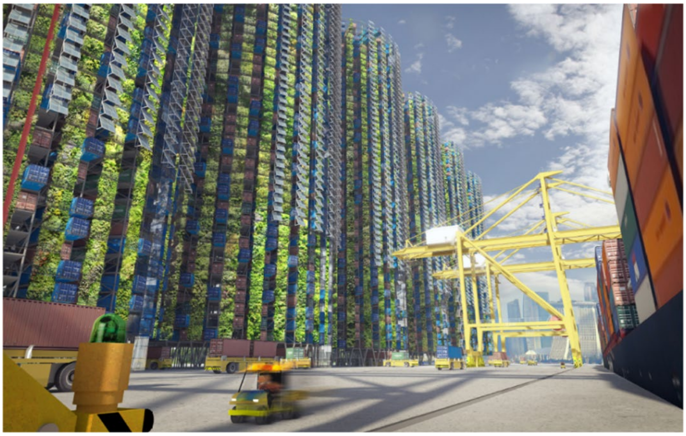


**Fig. 10** A next-generation high-density container tower port Image courtesy of Casanova & Hernandez Architects

Table 2 gives a summary of all the layouts discussed in this section. The layouts are compared based on different design variables such as land footprint, capacity, reshuffling, investment costs, operational costs, and throughput. The table also shows how each layout could potentially impact each design variable, as compared with current rectangular designs. The symbol "↓" signifies a potential decrease, "↑" depicts a potential increase, and "–" represents no potential change. The impacts have been evaluated based on expert opinion. The "Methodology" column in Table 2 shows that, although researchers have started to analyze these layouts using different methodologies, including optimization and queueing networks, many (especially, the vertical designs) are still at the concept stage. Obviously, there is a need for more systematic methods to develop and evaluate future container terminal layout designs. The next section presents suggestions for this.

## 4 Future container terminal layout designs: research directions

The layout of terminals is changing to accommodate the increasing number of containers. Layout design in next-generation container terminals has not been thoroughly studied, and there are still many strategic, tactical, and operational research areas that could result in valuable ideas. Kim et al. (2012) report that, in order to design layouts of next-generation terminals, the following factors need to be taken into consideration: flexibility, cost, environment, technological feasibility, economic feasibility, and resilience. Our paper identifies research questions related to this classification using the following three-step framework: (1) designing a layout for next-generation container terminals, (2) optimizing the configuration and operations of the new layout, and (3) studying the social and environmental impacts of the new layouts (Fig. 11).

The first two steps are at the strategic and tactical decision-making levels, whereas the third step is at the operational level. The modeling approaches that can help decision-makers choose and manage a specific layout include simulation, semi-open and closed queueing networks, and linear and nonlinear programming [i.e., integer programming (IP), and mixed integer programming (MIP)]. In the first two steps, in order to analyze and optimize a layout, simulation and queueing models are more suitable, as they are particularly fit to estimate throughput performance. On the other hand, in the last step, linear programming models are more suitable to determine operations planning and control strategies.

These research topics and modeling approaches have been selected based on our research and experience in the maritime industry. We believe that they could have significant impact and importance, as container terminals are the hubs of global supply chains.

### 4.1 Designing a layout for next-generation container terminals

Different layout designs are discussed throughout this paper. However, there is no consensus regarding which design(s) are appropriate to be implemented in

**Table 2** Future container terminal layout designs

| Layout | Source | Methodology | Design variables | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Figures | Land footprint | Capacity | Reshuffling | Investment costs | Operational costs | Throughput |
| Port 2060 project | | Concept | 5 | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ |
| Diagonal container stacks | Ivanović (2014) | Concept | 6 | – | – | – | – | – | ↑ |
| | Gue (2014) | Concept | | | | | | | |
| Shuttles and frame bridges | Zhu et al. (2010) | Simulation | 7 | – | – | – | ↑ | ↓ | ↑ |
| | Zhen et al. (2012) | Optimization | | | | | | | |
| | Hu et al. (2013) | Queueing | | | | | | | |
| | Jiang et al. (2018) | Optimization | | | | | | | |
| Overhead grid rail system | Port of Venice (2018) | Concept | 8 | ↓ | ↑ | – | ↑ | ↓ | ↑ |
| | Zhou et al. (2017) | Optimization | | | | | | | |
| | Zhou et al. (2016) | Simulation | | | | | | | |
| | Kim et al. (2012) | Concept | | | | | | | |
| Vertical designs | Kim et al. (2012) | Concept | 9 | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ |
| | VMW systems (2017) | Concept | | | | | | | |
| | SingaPort (2013) | Concept | | | | | | | |
| | Ez-Indus (2017) | Concept | | | | | | | |
| | GRID Logistics Inc. (2017) | Concept | | | | | | | |
| | Rethinking Container Management System (2017) | Concept | | | | | | | |
| | Germangray's scale modeling (2017 | Concept | | | | | | | |
| | Zaerpour et al. (2019) | Optimization | 10 | | | | | | |

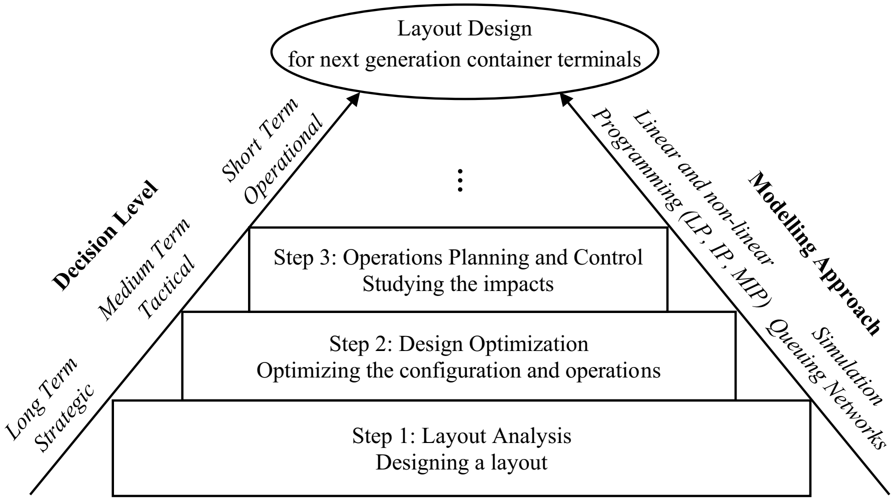


**Fig. 11** Promising research directions on layout design for next-generation container terminals

next-generation container terminals. Nevertheless, in regions with insufficient or expensive land, stacking containers in cubes, racks, or container towers can result in more efficient land utilization, since container terminals will expand vertically rather than horizontally. Therefore, terminal operators may not need high investments to buy, lease, or even reclaim land.

The main question is: which layout design can more effectively and efficiently satisfy the needs of a next-generation container terminal? To answer this question, one needs to study the investment and operational costs associated with those designs that would guarantee sufficient storage and throughput capacity. Investment costs can include items such as:

- Cost of land per square meter, including quay wall and pavement
- Cost of technology per storage location, including:
  - Buildings, and yard infrastructure (cabling)
  - Handling equipment
  - Other technology [Terminal Operating System, hardware, data cabling, radio, handheld computers, International Ship and Port facility Security]

In comparing the investment and operational costs of future and traditional container terminal layouts, two main tradeoffs need to be considered. Regarding investment costs, the high technology costs of future layouts need to be compared with the high footprint costs (e.g., for land reclamation) of traditional layouts. Regarding operational costs, the high costs of depreciation, energy, and maintenance needed for the automation of future layouts must be compared with the high costs of labor in traditional layouts. In such comparisons, the higher revenue of future layouts achieved due to higher efficiency and throughput need to be taken into account.

Model 1 below summarizes the discussion in this section. The objective function shown in Eq. (1) minimizes the total (annualized) investment costs, $C_{\text{capex}}$, and operational costs, $C_{\text{opex}}$, of the new layout over a certain time horizon. Constraint 2 ensures that the expected retrieval time of containers, $E(RT)$, is less than or equal to the maximum allowed time, $T$ (which may be set by the service level or shipping lines). The expected retrieval time depends on multiple factors including the dimensions and stacking policy of the terminal (i.e., shared policy, dedicated policy, single-cycle operations, double-cycle operations, and time windows of transport modes). Similarly, constraint 3 ensures that the expected throughput, $E(TH)$, at least equals the minimum throughput, $TP$ (similar to the maximum allowed retrieval time, the minimum throughput could be set by the service level offered to shipping lines). Constraint 4 guarantees that the storage capacity of the new layout, estimated on the basis of the dimensions of the layout by the function $f(\text{dimensions})$, is more than the total capacity, Cap, required to stack all containers that are forecast to be stacked in the terminal at each point in time. If necessary, other constraints can be added to the model. Dimensions and equipment choices of the new layout are the decision variables of the model.

Solving this problem requires an estimation of its parameters including the expected retrieval time of containers, required total capacity, as well as operational and investment costs, which can be complex. Simulation and queueing models can provide a foundation for estimating such parameters.

$$\text{Model 1}: \min\left(C_{\text{capex}} + C_{\text{opex}}\right), \tag{1}$$

$$\text{subject to}: E(RT) \leq T, \tag{2}$$

$$E(TH) \geq TP, \tag{3}$$

$$f(\text{dimensions}) \geq \text{Cap}. \tag{4}$$

Decision variables: length, width, height, and radius, and specific equipment choices depending on the layout design

In conclusion, here are some examples of research questions that need to be answered with respect to selecting a container terminal layout:

- What are the total investment costs? How much is the total annual operational cost?
- How do the investment and operational costs compare with those associated with traditional container terminal layout designs, including land reclamation?

Addressing these questions needs information about the requirements (i.e., throughput and storage capacity) and configuration of the new layout, and necessitates close attention to operational efficiency. This is discussed in the next section.

### 4.2 Optimizing the configuration and operations of the new layout

Design parameters (i.e., height, width, length, radius, etc.) impact not only the investment and operational costs of the terminal but also the operational efficiency (i.e., throughput, throughput time, storage capacity) of the new designs. Setting the “right” design parameters depends on the accuracy of forecasts regarding capacity and handling requirements. Overestimation or underestimation of these variables can result in parameters which make implementation or operations infeasible. Li et al. (2017) discuss that capacity planning is a critical decision in constructing, expanding, or renovating a container terminal, as also emphasized by Haralambides (2017, 2019). The decisions made are normally discussed in terms of required resources, including the number of quay cranes, yard cranes, and vehicles. Due to the size and complexity of such decisions, the main tools used in most studies consist of queueing theory, simulation, and simulation-based optimization (Taleb-Ibrahimi et al. 1993; Kim and Kim 2002; Chu and Huang 2005; Bassan 2007; Lee et al. 2014). At this stage, a linear programming model can be used to optimize the configuration and operations of a new layout.

Model 2 is an example of such a model. The objective function of Eq. (5) minimizes the expected retrieval time of containers. Depending on the requirements, other objective functions such as expected storage and retrieval times in the case of double cycles, total earliness and tardiness, and total travel time of equipment can also be used in the model. Similar to model 1, constraints 6 and 7 ensure that the maximum retrieval time and the minimum throughput of the system are satisfied. Furthermore, constraint 8 guarantees that the system has enough storage capacity. To model what happens in practice, more constraints can be added. Such constraints may also aim to integrate stacking with the seaside and landside operations. In most cases, obtaining the optimal solution of model 2 can be complex. Therefore, the model may be solved by using heuristics or metaheuristics.

$$\text{Model 2}: \min E(RT), \tag{5}$$

$$\text{subject to}: E(RT) \leq T, \tag{6}$$

$$E(TH) \geq TP, \tag{7}$$

$$f(\text{dimensions}) \geq \text{Cap}. \tag*{((8))}$$

Decision variables: length, width, height, and radius, depending on the layout.

All in all, with respect to the configuration and operations of a new layout, answering the following questions seems to be necessary:

- What is the forecast for the future storage and handling capacities?
- What design parameter values can achieve the storage and handling capacities?
- How do design parameters impact the investment and operational costs?
- What design parameters can result in the same or better operational efficiency and costs as traditional container terminals?

### 4.3 Studying the social and environmental impacts of new layouts

Container shipping is still the most environmentally sustainable mode of transport. However, the industry is now facing new societal and environmental regulations that will force change. The industry transports more than one-third of global trade, and environmentally motivated regulations are likely to become the most important cost element in the coming years, as governments raise the bar on air emissions (BSR 2010).

Until recently, the industry has chosen to take a defensive approach to sustainability: many companies have sought to hide behind claims of the type "sea transportation is naturally sustainable" and similar. However, looking ahead, sustainability performance could become one of the differentiating and value-adding factors in an industry where companies historically have struggled to present a unique value proposition beyond cost competitiveness.

The use of the latest technologies in next-generation terminals can make them relatively "green." Furthermore, there are efforts to take advantage of renewable energy sources such as solar and wind power in new container terminal designs (Fig. 12). Although this can provide terminals with green sources of energy, it can also create new constraints (i.e., intermittent availability of energy or interference with container handling terminal operations) that need to be investigated.

Ports are in the vicinity of many cities. Port expansion can have negative externalities, which affect the well-being of people living in nearby cities (Del Saz-Salazar and García-Menéndez 2016). With the growth in global trade and the expansion of ports, studies on the port–city interface, especially with regard to environmental, social, and spatial planning, need to receive more attention (Hoyle 2000; Hayuth 2007; Wiegmans and Louw 2011). In this regard, the Port-Cities Programme and the

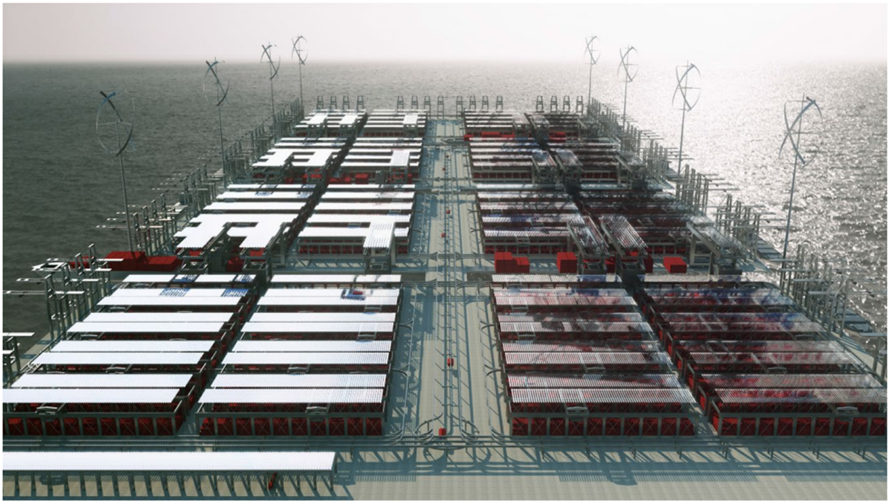


**Fig. 12** Container terminals and renewable sources of energy Image courtesy of Kubota & Bachmann Architects

International Transport (ITT) Forum of the Organisation for Economic Co-operation and Development (OECD) have played an active role in studying the link between ports and cities in multiple research endeavors (ITT 2019; OECD 2014). The main focus of these studies is how ports can regain their role as drivers of urban economic growth and how negative port impacts can be mitigated. Among all the policies and recommendations described in these studies, we maintain that the layout design has a direct impact on the port–city interface, which is one of the most strategic port assets (Daamen and Vries 2013). As an example, container towers can be an answer to the efficient utilization of precious land required for all activities in ports and port cities. Figure 13 shows a conceptual example where the extra land can be used to bring some green areas to the heart of ports or nearby cities.

In conclusion, these are some of the research questions based on the social and environmental impacts of new layouts:

- How environmentally friendly are the new layouts? The question is whether lifting containers to the top levels of vertical container stacking systems (much higher than five tiers, which is common in most terminals) can result in an energy consumption bill that makes the new layouts infeasible, in terms of not only operational but also environmental costs.
- How can the extra space, created as a result of implementing the new higher and denser layouts in next-generation container terminals, be utilized for other terminal activities or even recreational, residential, or business areas for cities in the vicinity of container terminals?

## 5 Conclusions

Handling millions of containers per year while guaranteeing short handling times to shipping lines puts a burden on container terminals. Therefore, terminal operators are looking for technologies and methodologies that can help them improve their efficiency, which, at the same time, should increase their capacity and reduce the social and environmental impacts of their operations. Considering the fact that the layouts of container terminals have not seen major changes in the past few decades, use of innovative layout designs for next-generation terminals

(a) container towers in a port (b) container towers in a port city

**Fig. 13** A hybrid urban solution combining a green container port and city areas Image courtesy of Casanova Hernandez Architects seems to be a promising direction that may achieve these goals. Especially over the past few years, new, innovative layout designs have been proposed. However, research on new layout designs is just beginning. In this paper, we first introduce possible layouts for future container terminals. We then discuss important questions that need to be answered at strategic, tactical, and operational levels so that such new layouts can be realized and implemented.

We find that, to provide the capacity and efficiency required for handling the increasing number of containers, current layouts have grown in size and are being equipped with state-of-the-art container handling systems. Designs for future container terminals particularly focus on vertical expansion, by storing containers in taller structures. Performance, operational and investment costs, as well as social and environmental impacts are the main factors that can be used to choose a layout. We identify the research needs to address strategic and tactical layout design challenges such as the optimal configuration or financial feasibility of a layout, or operational problems including the impact of design variables on the performance of a layout. In addition, our study shows that simulation, and semiopen and closed queueing networks are among the methodologies more suitable for studying strategic questions, whereas linear and nonlinear programming models are apt for operational problems.

The themes discussed in this paper are by no means meant to be an exhaustive list of research opportunities in layout design [see Heragu (2008) for a comprehensive list of all questions that facilities design and planning needs to address].

For example, safety and security may be among the top concerns of terminal operators. Container terminals, by virtue of their location, are severely impacted by disruptive adverse events ranging from long-term changes such as sea-level rise to short-term impacts such as hurricane damage (Gharehgozli et al. 2017e; Mileski et al. 2018; Sharifyazdi et al. 2018). It is interesting to study how new vertically oriented container terminals can withstand such adverse events. Furthermore, compromise of a single container from among all the containers that move through ports has the potential to endanger lives and cost billions of dollars in disrupted trade (Bakshi and Gans 2010; Bakshi et al. 2011; Ruiz-Aguilar et al. 2015a, b). On the other hand, having to inspect each container individually would slow the transport time of modes that use containers to a crawl. Research must be done to develop mechanisms that are able to increase safety and security while minimizing the effect on trade.

Last but not the least, research efforts in layout design should not be limited to container terminals alone. Layout design is a critical factor impacting the performance of all sorts of terminals, including bulk storage terminals, chemical tank storage terminals, cruise terminals, and even terminals for storage of offshore wind farms. In the latter, handling the bulky components of wind turbines creates new constraints for the layout design problem.

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