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ORIGINAL ARTICLE

Performance improvements in container terminals through the bottleneck mitigation cycle

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Abstract

Container terminal capacity is often limited by (in)efficiency bottlenecks. This paper provides the design and proof of concept for the bottleneck mitigation cycle (BMC), consisting of three steps: bottleneck classification, detection and alleviation. While, often, the literature only focuses on alleviation of a single bottleneck and ignores bottleneck detection and interdependencies, this research uses the shifting bottleneck method and thereby considers a variety of possible infrastructural and operational bottlenecks. An empirical approach is adopted to find the cause of the detected bottleneck and to suggest suitable alleviation measures. Application of the BMC to a simulation model of the Fergusson Container Terminal in the Port of Auckland resulted in productivity improvements of 2–6%. To further improve the BMC, future research directions are to improve the empirical approach used for bottleneck alleviation and to apply the BMC in real-time.

Keywords Bottleneck alleviation · Bottleneck classification · Bottleneck detection · Maritime container terminals · Terminal efficiency

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1 Introduction

Over the last decade, container port throughput has grown steadily reaching 816 million Twenty-foot Equivalent Units (TEU) worldwide in 2020 (UNCTAD 2021). Container terminals are nodes in the global transport network where container vessels are (un)loaded and where containers can be temporarily stored. A general schematic overview of the transport chain at a container terminal, as discussed in this paper, is shown in Fig. 1. Import containers arrive by (deep-)sea vessel and are unloaded by quay cranes. Then the containers are brought to the storage yard by transport vehicles, like straddle carriers or autonomous guided vehicles. Containers are retrieved from the storage yard by, for instance, rail-mounted gantry cranes or straddle carriers and are brought to the landside transport mode (truck, train, or inland waterways) that will transport them further into the hinterland. For export containers, the order is reversed as indicated by the bi-directional arrows in Fig. 1.

Due to growing container trade, scarcity of terminal capacity can become a problem for the transport of goods in global supply chains. At the time of writing (2022), no better example of this could be given than port terminal congestion around the world as a result of COVID-19. However, development of port infrastructure is hindered by rising environmental and social concerns. Since the basic design of modern (automated) terminal equipment has remained the same over the last decades, improving terminal productivity has increasingly become a matter of terminal management (Notteboom and Rodrigue 2008). The use of information technology at container terminals enhances the opportunity to implement automated methods, intended to detect and alleviate bottlenecks. There is no universal definition of a bottleneck (Lawrence and Buss 1995; Wang et al. 2005) and depending on the actor and their perspective, the perception of a bottleneck can differ (Wang et al. 2005). We propose the following definition: "the resource or process within a container terminal whose capacity limits the output of the terminal". This definition is left deliberately somewhat vague, as there is a wide variety of bottlenecks possible, and they develop in time and space throughout the container terminal.

As integrated approaches are lacking in practice and literature, this research introduces the *bottleneck mitigation cycle* (BMC) to improve the performance of container terminals. The BMC consists of three steps as schematically shown in Fig. 2. Firstly, a classification of bottlenecks at a terminal is required as input in selecting the most appropriate bottleneck detection method. Secondly, the bottlenecks at

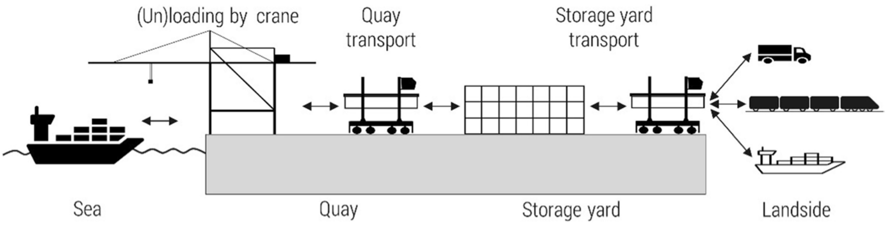

Fig. 1 Schematic representation of a transportation chain at a maritime container terminal

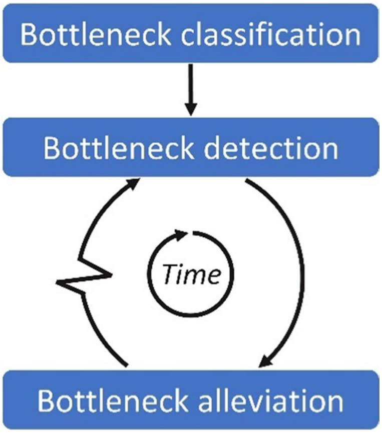

Fig. 2 Bottleneck mitigation cycle

the terminal are detected and ranked. Thirdly, based on the ranking, causes of the most severe bottleneck are identified, and one or multiple alleviation measures are selected and implemented. After a certain delay, depending on the measure implemented, the cycle starts again by detecting bottlenecks, as the bottleneck may have moved to another resource or process.

This paper validates the BMC concept by applying it to an actual, existing, terminal, demonstrating BMC's capability to improve terminal performance. The case study was developed on the Fergusson Container Terminal (FCT) of the Port of Auckland (POAL).

The central contribution of this research is the introduction and application of the BMC. Furthermore, the following contributions are made:

- A classification of bottlenecks at container terminals is proposed which fits the purpose of bottleneck mitigation.
- New definitions of active and inactive states of equipment are formulated, to apply the shifting bottleneck method to container terminals.
- The potential of the BMC to improve the performance of a container terminal is assessed with a simulation model.
- Promising future research directions are formulated to further develop the BMC approach and to improve container terminal efficiency.

The remainder of this paper is organised as follows. In Sect. 2, an overview of the literature is provided on which the approaches of BMC are based. The proposed methodology of the BMC is presented in Sect. 3 and applied to the simulation model of the FCT in Sect. 4. Finally, Sect. 5 presents the main findings of this research together with future research directions towards more efficient terminals.

2 Literature review

This literature review provides the scientific knowledge underpinning the approaches of the three steps of the BMC.

2.1 Classification of bottlenecks at container terminals

Dowd and Leschine (1990) were the first to categorise bottlenecks at container terminals. They distinguish two types of bottlenecks: *physical* and *institutional.* A more recent classification structure is proposed by Veenstra et al. (2008) in which they distinguish three types of bottlenecks: *physical operations*, *information flow* and *administrative processes*. A third classification structure is provided by Ji and Zhou (2010): *resource*, *market* and *statutory* bottlenecks.

Seen from the perspective of bottleneck management, an important common problem of the above classifications is that they make no distinction between bottlenecks due to decisions on the infrastructure of the terminal (long-term) and operational decisions (real-time). Therefore, we propose an alternative classification which encompasses three types of bottlenecks: *infrastructural*, *operational* and *managerial* bottlenecks. Infrastructural bottlenecks have in common that decisions are mostly made on a strategic planning level, e.g., on terminal layout, or the amount and type of terminal equipment. Operational bottlenecks are concerned with real-time planning of operations related to the physical movement of containers across the terminal, e.g., allocation of equipment or interaction between equipment at the terminal. Managerial bottlenecks are related to information sharing and contractual commitments between the terminal operator and external parties. For the remainder of this research, managerial bottlenecks are out of scope.

2.2 Bottleneck detection methods

Due to the sheer complexity and dynamism of a container terminal, a structured approach is required to detect bottlenecks. The following seven potential methods were identified in the literature:

1. Capacity utilization method (Hoshino et al. 2007; Ji and Zhou 2010; Kulak et al. 2013; Ma and Li 2010).
2. Queue length and waiting time method (Kiani Moghadam et al. 2010).
3. Sensitivity analysis method (Boschian et al. 2011; Caballini and Sacone 2015; Demirci 2003; Ha et al. 2007).
4. Average active duration method (Roser et al. 2001).
5. Shifting bottleneck detection method (Roser et al. 2002).
6. Arrow-based method (Kuo et al., 1996).
7. Turning point method (Li et al. 2007).

The literature only reports three simulation-based methods to detect bottlenecks in container terminals (1–3) which have limited capability from a BMC perspective. Therefore, the scope of bottleneck detection methods was expanded to other types of terminals, including manufacturing (4–7). The potential of each detection method is assessed here, based on the following attributes (Van Battum 2021): accuracy of detection of bottlenecks; requirements imposed by the method on the system studied; ability to distinguish between primary (severe), secondary, tertiary and no-bottleneck (Roser et al. 2003); ability to detect momentary and long-term bottlenecks; and difficulty in implementing the method (an overview of this evaluation can be found in Van Battum 2021). Based on the comparison, the shifting bottleneck method explained in detail in Sect. 3.2, seems most appropriate for our purposes, given its high accuracy and ability to detect momentary bottlenecks.

2.3 Bottleneck alleviation methods

There is no straightforward way to determine 'the most suitable or best' alleviation measure in the scientific literature. Furthermore, using the literature to assess the potential of alleviation measures is difficult, since terminals are different and interaction of bottlenecks makes the selection of an effective alleviation measure even more complex. For instance, implementing an alleviation measure on a primary bottleneck may deteriorate terminal performance, as other resources and processes (secondary or tertiary bottlenecks) may be impacted significantly. As a result, often, a trial-and-error approach is adopted.

Therefore, the following commonly applied alleviation measures are identified:

- Increasing the amount of equipment (Caballini and Sacone 2015; Guan and Yang 2010; Kulak et al. 2013; Veenstra et al. 2008).
- Changing the type of equipment (Kulak et al. 2013; Veenstra et al. 2008).
- Changing equipment allocation (Boese et al. 2000; Goodchild and Daganzo 2007; He et al. 2010; Hoshino et al. 2007; Kulak et al. 2013; Ng and Mak 2005; Nguyen and Kim 2009; Speer et al. 2011; Zhen 2016).
- Changing terminal layout (Caballini and Sacone 2015; Guolei et al. 2014; Zhang et al. 2018).
- Changing storage yard stacking strategies (Dekker et al. 2006; Kulak et al. 2013; Park et al. 2010; Said and El-Horbaty 2016; Zhang et al. 2018).

3 Methodology: bottleneck mitigation cycle

In this section, the application of the BMC to a container terminal is described by following its sequential steps including detailed information on the application of the shifting bottleneck method.

3.1 Bottleneck classification

It is important to classify the bottlenecks at a container terminal to effectively select a method to detect them and select appropriate alleviation measures. The distinctive nature of bottlenecks makes it difficult to study all three types of bottlenecks at the same time. Since the information necessary to detect and alleviate infrastructural and operational bottlenecks is directly available, we focus on infrastructural and operational bottlenecks.

3.2 Bottleneck detection: shifting bottleneck method

The core principle of the shifting bottleneck method is that the resource with the current longest uninterrupted active duration is the momentary bottleneck of the system studied (Roser et al. 2002).[1] Due to variability and randomness of terminal operations, bottlenecks develop in time and space across the terminal (Lawrence and Buss 1994). Therefore, it is interesting to analyse terminal operations over a longer period of time and thereby identify the average bottleneck (Roser et al. 2002).

A distinction can be made between *sole* and shifting bottlenecks, defined as follows (Roser et al. 2002):

- *Sole bottleneck* the only bottleneck at a given time, the active duration of the current bottleneck does not overlap with any previous or subsequent bottlenecks.
- *Shifting bottleneck* the bottleneck ‘shifts’ between resources, and therefore the uninterrupted active durations of either the previous or subsequent bottleneck(s) overlap.

Every resource or process in the container terminal studied can become a sole or shifting bottleneck. First, it will always be a shifting bottleneck after which it can become a sole or, again, a shifting bottleneck. To determine the average bottleneck in a long-term analysis, the percentage of time an individual resource or type of resource is a sole or shifting bottleneck is summed over a selected duration.

3.2.1 Determination of the bottleneck state

For infrastructural and operational bottlenecks at a container terminal, two types of resources are distinguished: equipment and location. Examples are the congestion of yard equipment (Hoshino et al. 2007; Saanen 2004; Zhen 2016) and the lack of storage yard capacity (Chen et al. 2013; Gharehgozli et al. 2017; Veenstra et al. 2008), for equipment- and location-related bottlenecks, respectively. This research focuses on equipment-related bottlenecks.

To detect equipment-related bottlenecks at a container terminal, the longest uninterrupted active duration of all equipment needs to be determined. Therefore, all

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[1] An *active duration* is the duration of time a resource spends in the active state (a detailed explanation can be found in Sect. 3.2.1).

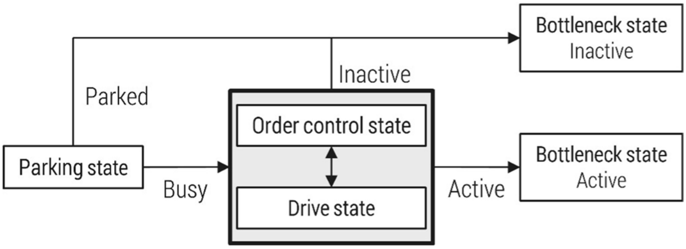

Fig. 3 Determination of the bottleneck state of equipment at a container terminal

equipment at the container terminal studied are assigned a bottleneck state, which is either active or inactive and varies over time. Given the interaction between equipment at a container terminal, assigning a bottleneck state is a complex endeavour. In this research, the bottleneck state is determined by a combination of the following states:

- *Parking state* indicates whether equipment is on its way to a parking location, parked, or neither of the previous two.
- *Order control state* the activity corresponding to a part of the order assigned to the equipment by the terminal operating system.
- *Drive state* while undertaking driving activity.

At every moment in time, all equipment is assigned a parking, order control, and drive state. Order control and drive states can be different for different types of equipment.

To determine whether the bottleneck state is currently *active* or *inactive*, the activities of equipment are divided into mutually exclusive and collectively exhaustive discrete states. However, since the shifting bottleneck method has not yet been applied to container terminals in scientific literature, we propose the following definitions:

- *Active state* when current activities of equipment contribute to terminal performance or when the equipment is waiting on equipment of the same type.
- *Inactive state* when equipment is idle, parked or waiting for the completion of a task performed by equipment of a different type.

Equipment is active when waiting on equipment of the same type, since this represents traffic congestion which is prevalent as a bottleneck across the transport chain of a container terminal (Hoshino et al. 2007; Kiani Moghadam et al. 2010; Kourounioti and Polydoropoulou 2018; Veenstra et al. 2008; Zhang et al. 2018; Zhen 2016).

The procedure of determining the bottleneck state for every single piece of equipment is graphically shown in Fig. 3. Firstly, the operational state of equipment is determined, which can be either “parked” or “busy”. When equipment is parked, the bottleneck state is inactive. Secondly, if equipment is busy, the combination of the order control state and drive state determines the bottleneck state of equipment. When this combination is inactive, the bottleneck state is inactive and vice versa. This procedure of determining the bottleneck state is performed repeatedly according to a specified refreshment interval and thus the bottleneck state can change over time. In the case that there are multiple pieces of equipment with the exact same uninterrupted active duration, there are multiple momentary bottlenecks at the same time.

3.2.2 Determination of shifting and sole bottleneck times

The duration of the time a single piece of equipment i is the sole (D_i^{sole}) or shifting (D_i^{shift}) bottleneck, in seconds, is determined using the following equations:

$$D_i^{\text{sole}} = \int_0^T d_i^{\text{sole}}(t)\mathrm{d}t = \sum_{n=0}^{\mathrm{T/r}} r d_i^{\text{sole}}(nr), \quad \forall i \in I \tag{1}$$

$$D_i^{\text{shift}} = \int_0^T d_i^{\text{shift}}(t)\mathrm{d}t = \sum_{n=0}^{T/r} r d_i^{\text{shift}}(nr), \quad \forall i \in I \tag{2}$$

in which $d_i^{\text{sole}}(t)$ and $d_i^{\text{shifting}}(t)$ represent the function of the sole and shifting bottleneck duration of equipment i over time which can be 0 (not sole nor shifting bottleneck) or 1 (sole or shifting bottleneck), respectively, in seconds; T represents the total duration, in seconds; n represents the refreshment interval in the total duration, dimensionless; r represents the length of the refreshment intervals, in seconds. The set I represents all individual equipment present at the container terminal.

The probability that equipment i of a specific type is either a sole (P_i^{sole} with $i \in I$) or shifting bottleneck (P_i^{shift} with $i \in I$) during the period of time considered, can be calculated using the following equations:

$$P_i^{\text{sole}} = \frac{D_i^{\text{sole}}}{T} \cdot 100, \quad \forall i \in I \tag{3}$$

$$P_i^{\text{shift}} = \frac{D_i^{\text{shift}}}{T} \cdot 100, \quad \forall i \in I \tag{4}$$

Roser et al. (2002) do not provide information on the procedure of aggregating bottlenecks of equipment of the same type. In this research, we propose to sum up the shifting and sole bottleneck durations of equipment of the same type. Using Eqs. (5) and (6), the duration is divided by the total time of simulation to get the average number of individual pieces of equipment being the sole (A_e^{sole} with $e \in E$) or shifting (A_e^{shift} with $e \in E$) bottleneck over the simulated time, respectively. The set E represents all equipment types present at the container terminal. Given the set of equipment types E and the fact that every individual equipment i belongs to an equipment type, this is noted as the vector e_i.

$$A_e^{\text{sole}} = \frac{\sum_{i \in I | e_i = e} D_i^{\text{sole}}}{T}, \quad \forall e \in E \tag{5}$$

$$A_e^{\text{shift}} = \frac{\sum_{i \in I | e_i = e} D_i^{\text{shift}}}{T}, \quad \forall e \in E \tag{6}$$

The primary average bottleneck of the system is defined as the equipment type with the highest sum of the average number of equipment being the sole and shifting bottleneck. The secondary bottleneck has the second highest average number of equipment being the bottleneck, etc.

3.3 Bottleneck alleviation: empirical approach

This section explains how an alleviation measure can be selected corresponding to the bottleneck detected. In this research, the scope is limited to alleviation of average bottlenecks.

3.3.1 Bottleneck shiftiness measure

Lawrence and Buss (1994) introduced the *bottleneck shiftiness measure* to quantify the times a bottleneck changes resource within a specified amount of time. The bottleneck shiftiness measure provides information on whether it is more effective to apply alleviation measures to specific equipment or to all equipment of the same type. The bottleneck shiftiness measure (β) can be calculated using the following equation (Lawrence and Buss 1994):

$$\beta = 1 - \frac{c_v}{\sqrt{N}} = 1 - \frac{\sigma}{\mu\sqrt{N}} \tag{7}$$

here, c_v represents the coefficient of variation of the bottleneck probabilities for the individual equipment (P_i^{sole} and P_i^{shift}), dimensionless; N represents the number of individual equipment of the system studied ($N = |I|$), dimensionless; σ and μ represent the standard deviation and mean of the bottleneck probabilities of all individual equipment (P_i^{sole} and P_i^{shift}) of the system, respectively, percentage. When the bottleneck shiftiness measure is calculated based on types of equipment in the system, the coefficient of variation (c_v), mean (μ), and standard deviation (σ) are based on (P_e^{sole} and P_e^{shift}) and N equals the number of equipment types in the system ($N = |E|$).

The bottleneck shiftiness measure is a scalar ranging from 0 for a unique bottleneck to 1 for the case where all equipment of the system have the same probability to be the bottleneck for the duration of time considered. For each replication of an experiment, the bottleneck shiftiness measure value is calculated which is averaged over the total number of replications of the respective experiment.

3.3.2 Alleviation measures

The shifting bottleneck method does not provide the cause of the bottleneck and since every bottleneck can have a wide range of possible causes, identifying the cause of the bottleneck is not trivial. However, the shifting bottleneck method keeps track of the time spent in each state. States in which the most time is spent are likely causes of the bottleneck because these states have a significant effect on the performance of the equipment.

Based on the identified cause, compiling a list of alleviation measures is easier but still difficult due to interaction of processes at a container terminal and the fact that not one container terminal is the same. Furthermore, applying a measure to alleviate a specific bottleneck may deteriorate the performance of the terminal, since other equipment is significantly hindered by the implemented measure. Therefore, based on the identified bottleneck and the understanding of its likely cause, the experience of field experts can be consulted in a much more informed way in order to determine promising alleviation measures. These alleviation measures are implemented in a simulation model to determine their effect on terminal performance and to select the best alleviation measure given a set of selection criteria.

Once the chosen alleviation measures have been implemented, it is likely that the detected bottleneck will change. Therefore, after a delay dependent on the measure(s) implemented, detection is performed again before a decision is made on the next alleviation measures to be implemented to further improve the performance of the terminal.

4 Case study for proof of concept

To validate the concept of the BMC, the method is applied to a simulation model of the Fergusson Container Terminal situated in the Ports of Auckland, New Zealand. Since the target throughput of this terminal could not be reached with the operations and infrastructure present at the time, insight into the bottlenecks at the terminal was required and therefore the terminal was chosen for this research.

4.1 Overview

An aerial view of the FCT is shown in Fig. 4. At the FCT, there are three different modes of transport: vessel, truck, and train. The terminal has two quays for vessels: Fergusson North (FN) and Fergusson West (FW). Our case study focuses on the maritime side of the terminal and ignores the interchange of rail containers between trains and the stacks.

The three main types of equipment used at the FCT are:

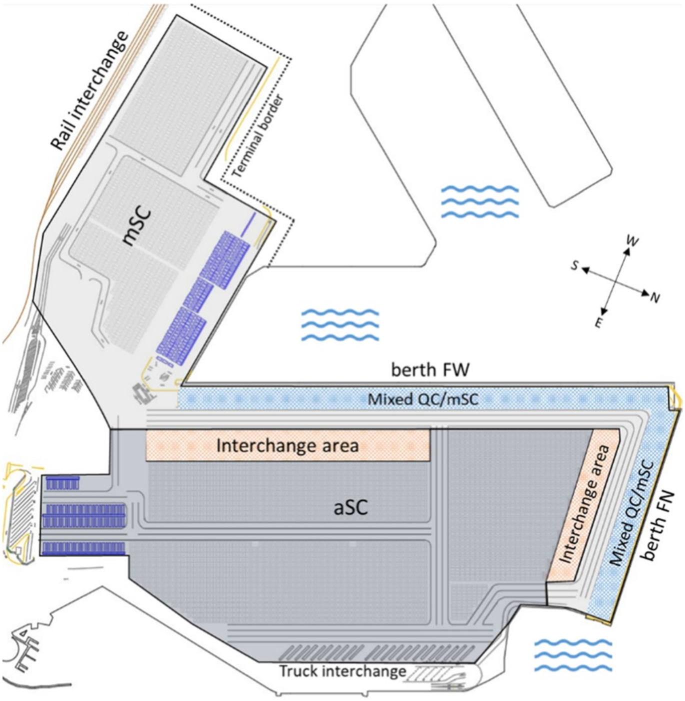

Fig. 4 Operating areas of the different types of equipment present at the Fergusson Container Terminal. *mSC* manned straddle carrier, *aSC* automated straddle carrier, *eQC* quay crane

Table 1 An overview of the terminal settings used in the base scenario of the Fergusson Container Terminal

Simulation model parameter	Quantity
Number of aSCs available	30
Number of mSCs available	24
Number of QCs available	6
Pooling strategy of mSCs	Global
Vessel workload	Unlimited
Truck interchange workload	81 boxes/hour
Initial yard density	74%

- *quay cranes (QC)* interact with *manned straddle carriers* (mSC) through loading and discharging operations.
- *mSCs* transport containers to and from the quay from and to the interchange area or mSC stacks.
- *automated straddle carriers (aSCs)* transport containers to and from the interchange area to and from the (reefer) stack or truck interchange. Trucks are served by aSCs at the truck interchange. A teleoperator takes over control to position import containers on the trucks.

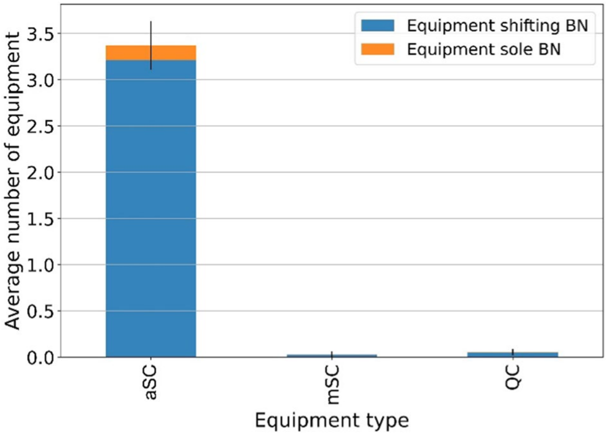

Fig. 5 Results of application of the shifting bottleneck method to the base scenario with a 5-percent significance level. *BN* bottleneck

Interchange areas are used both by mSCs and aSCs to exchange containers. These also form the boundaries between their operating areas.

The simulation model of the FCT was created by TBA Group in collaboration with the FCT based on the simulation package eM-Plant developed by Tecnomatix. This simulation package uses object-oriented discrete-event simulation. The library on which the model is built was validated by Verbraeck et al. (2009), and the model itself was validated by TBA Group together with the FCT based on experiments onsite (Terstegge and De Waal 2019).

In this research, peak-scenario simulations were carried out, in which both waterside and landside workload peaks had to be handled at the same time under dense yard conditions for 8 h. The base scenario settings for a peak simulation were based on the current most efficient configuration for the given layout of the FCT of which an overview is provided in Table 1.

4.2 Bottleneck classification and detection

The definitions of the bottleneck state have been applied to the equipment at the FCT. Overviews of the parking, drive, and order control states of the mSCs, aSCs, and QCs are shown in Tables 5, 6, 7 and 8 in the "Appendix", respectively.

The park, order control, and drive state were updated according to a specified refreshment interval. The value of the interval is a trade-off between simulation speed and accuracy. A refreshment interval of 0.5 s does not significantly decrease the simulation speed and comparison with the average state duration of 196 simulated hours shows that 0.5 s is only 0.50% of the average state duration. Therefore, the refreshment interval length (r) used in (1) and (2) was set to 0.5 s.

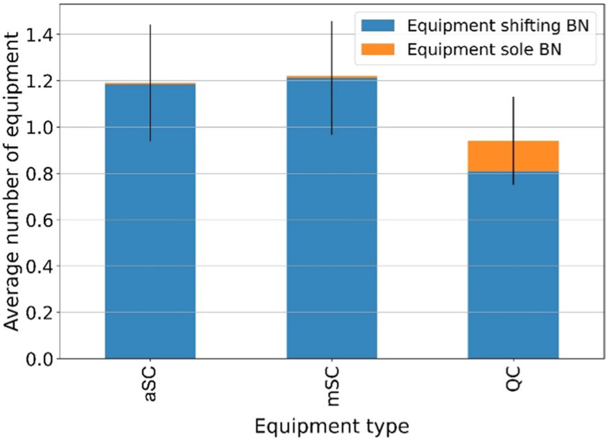

Fig. 6 Results of application of the shifting bottleneck method to base scenario with the drive state "waiting for equipment of the same type" as inactive. *BN* bottleneck

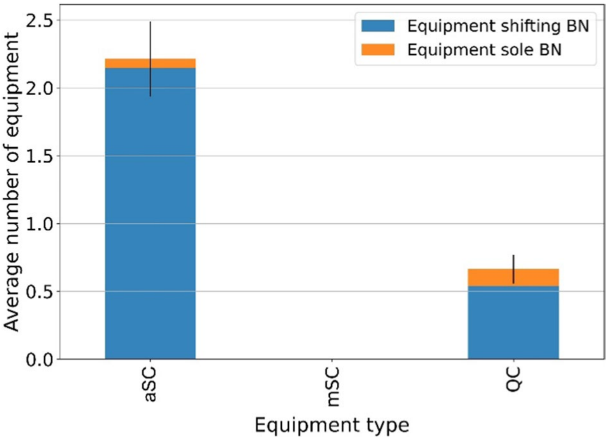

Fig. 7 Results of application of the shifting bottleneck method using 30 aSCs, 24 mSCs, 2 QCs and a truck workload of 81 boxes per hour with a 5-percent significance level. *BN* bottleneck

4.2.1 Verification

A verification of the implementation of the shifting bottleneck method was carried out by varying the definitions of the bottleneck state and parameters of the FCT (terminal parameters).

When changing the definition of "waiting for equipment of the same type" to inactive, the hypothesis is that mSCs and aSCs become the average bottleneck less often, and quay cranes become the average bottleneck more often compared to the base scenario since the active durations of mSCs and aSCs are interrupted

Table 2 Analysis of the average time spent in the order control states of the aSCs in the base scenario with significance level 0.05

Order control state	Average percentage of simulated time spent (%)
Driving empty	37.06 ± 0.66
Driving loaded	31.63 ± 0.57
Grabbing container(s)	14.57 ± 0.24
Dropping container(s)	14.44 ± 0.22
Teleoperator handling	1.37 ± 0.06
Idle equipment	0.91 ± 0.42
Waiting for TOS routing or grounding decision	0.03 ± 0.05

Table 3 Analysis of the average time spent in the drive states of the aSCs in the base scenario with significance level 0.05

Drive state	Average percentage of simulated time spent (%)
Driving	55.45 ± 0.35
Idle driving engine	32.09 ± 0.39
Waiting due to equipment of the same type	12.28 ± 0.55
Waiting due to equipment of another type	0.18 ± 0.01

more often. A comparison of the results of Fig. 5 (base scenario) and Fig. 6 (change in definition) confirms this.

The terminal parameters consist of the number of equipment and the workload. By comparing extreme values of the terminal parameters all results, except for the decreased number of aSCs, match the hypotheses. A possible reason for this is that the aSCs are already the average bottleneck to an extent that it cannot increase any further. In any case, the results are not statistically significantly different. In Fig. 7, an example is shown in which the number of QCs is decreased and the average number of QCs, being the bottleneck, has significantly increased as a result. With these results, the implementation is considered verified.

4.2.2 Validation

Due to the absence of historical data on the bottlenecks of the FCT, the *face validity* technique was used to validate the implementation of the shifting bottleneck method (Sargent 2011; Verbraeck et al. 2009). The results of the base scenario (Fig. 5) indicate that the aSCs are the average bottleneck of the terminal. Over the simulated time, on average 0.16 and 3.21 aSCs were the sole and shifting bottleneck, respectively. This finding is in line with the expectations of field experts (from consulting firms, terminal operators and universities). Therefore, the implemented shifting bottleneck method is considered validated.

4.3 Bottleneck alleviation

The bottleneck shiftiness measure values for individual pieces of equipment and equipment types (mSC, aSC, and QC), at a 5-percent significance level, were 0.63 ± 0.05 and 0.04 ± 0.03, respectively. This means that the aSCs, as equipment type, are the unique bottleneck. A reason for this is the high percentage of shifting bottlenecks for aSCs, which can also be observed in Fig. 5. Based on these results, the alleviation measures should apply to all aSCs, rather than individual aSCs, to efficiently alleviate this bottleneck.

To determine the cause of the detected bottleneck, the time spent in both the order control and drive states of aSCs was analysed. From Table 2, it can be observed that the largest share of simulated time (69%) was spent *driving*. The drive states in Table 3 show that most time was spent driving and not waiting on other equipment (congestion). Field experts confirm that the driving speed of aSCs is relatively slow, compared to other types of equipment. Therefore, slow driving is considered to be the cause that aSCs spend a significant amount of time driving and as a result are the bottleneck.

To reduce the time spent driving, field experts were consulted to determine alleviation measures. From previous experience, it was known that adding aSCs at the FCT does not improve their productivity but increases congestion making it worse. However, the aSCs were still in development and increasing their driving specifications up to 20% was considered viable, resulting in the following alleviation measures.

1. Increase the acceleration and deceleration of aSCs by 20%.
2. Increase the maximum allowed curve speed of aSCs by 20%.
3. Increase the speed on straight sections of aSCs by 20%.

The performance of the FCT is based on maximising throughput for the given layout. Since terminal throughput is a direct consequence of equipment productivity, the productivity of the different types of equipment was used to quantify the performance of the FCT, as shown in Table 4. For both mSC and aSC productivity, reshuffles and housekeeping moves between stacks were excluded.

The measures were implemented in separate scenarios and the results were indexed based on the performance of the base scenario (197 simulated hours); they are presented in Table 4. The results of the implemented alleviation measures 1, 2, and 3 were based on 119, 120, and 160 simulated hours, respectively.

In this case study, an alleviation measure is selected based on the highest productivity improvement. Table 4 shows that increasing the maximum allowed curve speed results in the largest performance improvement of 2 to 6% for the different performance indicators. Therefore, the detected bottleneck is best alleviated by increasing the maximum allowed curve speed of aSCs.

Table 4 Results of the implementation of the different alleviation measures at the FCT indexed based on the performance indicator values of the base scenario (100)

Performance indicator	Units	Base scenario	Increase acceleration and deceleration by 20%	Increase maximum curve speed by 20%	Increase maximum straight speed by 20%
QC productivity	Boxes/hour	100	101.21	104.07	101.26
mSC productivity	Boxes/hour	100	100.92	103.32	100.94
	Moves/hour	100	101.56	103.35	100.33
aSC productivity	Boxes/hour	100	101.19	101.96	100.42
Truck interchange productivity	Boxes/hour	100	98.75	104.05	100.64
Truck handling time	Minutes	100	98.65	94.48	97.62

4.4 Discussion

The next bottleneck mitigation cycle starts again by performing bottleneck detection on the scenario with the increased maximum allowed curve speed (whose results are shown in Fig. 8). From this figure, it can be seen that aSCs are still the bottleneck of the FCT. To further improve the performance of the terminal, alleviation measures should again be applied to alleviate the aSC bottleneck. The BMC is continued until the capacities of the different types of equipment are equal and the whole terminal has the same capacity which makes the whole terminal the bottleneck.

An alternative is to reduce the capacity of the other types of equipment. Although the performance of the terminal will not be improved, the running costs can be

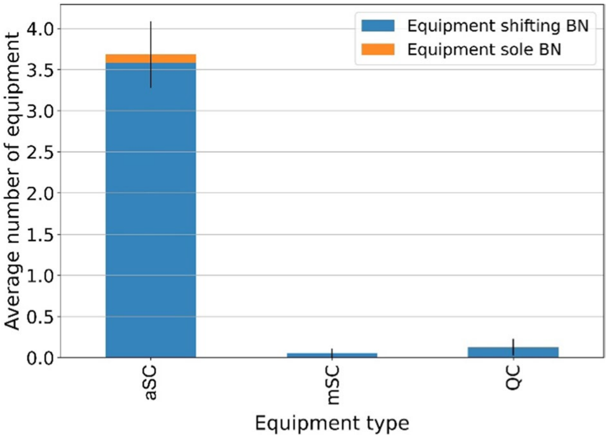

Fig. 8 Result of applying the shifting bottleneck method to the scenario in which the parameters of the base scenario are used and the maximum allowed curve speed is increased by 20%. *BN* bottleneck

reduced by, for instance, reducing the number of mSCs and thereby increasing profitability while maintaining the same performance.

5 Conclusions and future research directions

This research introduced and applied the concept of the *bottleneck mitigation cycle* (BMC) to effectively mitigate bottlenecks at container terminals and thus improve their performance. Such an integrated approach is missing in the literature on container terminals, as most studies focus on a single bottleneck. The proposed BMC consists of three steps: *bottleneck classification, bottleneck detection*, and *bottleneck alleviation*. To provide a proof of concept, the BMC is applied to a simulation model of the Fergusson Container Terminal (FCT), in Auckland, New Zealand.

First, a new structure to classify bottlenecks at container terminals is introduced consisting of *infrastructural*, *operational*, and *managerial* bottlenecks. This classification structure is used to effectively select a bottleneck detection method. The potential of different methods to detect infrastructural and operational bottlenecks at container terminals is evaluated based on a synthesis of various methods available in the literature, including not only container terminals but also other types of terminals and production networks. The shifting bottleneck method is selected because of its high accuracy and ability to detect momentary bottlenecks. However, since this method has not yet been applied to container terminals, new generic definitions for active and inactive states of equipment have been formulated to determine the bottleneck based on the combination of parking, drive, and order control states of every equipment.

Applying the verified and validated shifting bottleneck method to detect equipment-related bottlenecks at the FCT showed that the outcome of the shifting bottleneck method is very sensitive to both the definition of active and inactive states and the refreshment interval. Additionally, it can be concluded that the percentage of shifting bottlenecks is significantly higher than the percentage of sole bottlenecks at the FCT. The automated straddle carriers are identified as the current bottleneck at the FCT. To complete the BMC, an empirical approach is used to determine suitable measures to alleviate the detected bottleneck. Based on the value of the bottleneck shiftiness measure, there is chosen to apply the alleviation measures to all automated straddle carriers. As a result, a performance improvement, ranging from 2 to 6% of the performance indicators, is obtained. It is therefore concluded that the BMC has the potential to improve the performance of the FCT significantly. Since the simulation model of the FCT can be considered a relevant end-to-end environment, it can be concluded that, with the performance improvement achieved, a proof of concept of the BMC is given in this environment.

Terminal operators could benefit considerably from improved terminal performance by including the BMC as part of their terminal operating system.

Additionally, especially for quiet (off-peak) hours, the BMC can potentially also be used to reduce the costs of the terminal while maintaining the same performance.

The next step in the development of BMC is to apply it to an actual operational environment. This can be an emulated environment in which a virtual container terminal, in combination with the real control system, is used, as explained by Boer and Saanen (2012). Once the concept of the BMC has been verified and validated by emulation, the final steps to bring it to practice would be to successfully operate it at a real container terminal and to provide all necessary software support and documentation.

Many research directions can be recommended to improve the application of the BMC to container terminals. A limitation of the current application of the shifting bottleneck method is that it detects which equipment type is the bottleneck but not all causes can be directly identified based on the time spent in each state. Future research could focus on expanding the shifting bottleneck method to be able to also determine the cause of the bottleneck detected. It would also be interesting to investigate the possibilities of increasing the agility of the terminal to cope with variations in arrival patterns of containers by, for instance, distinguishing between specific flows of containers across the terminal, like deep-sea to truck. Distinguishing between flow-specific bottlenecks potentially allows one to temporarily increase the performance of the terminal with respect to specific flows of containers. Application of the BMC in real-time can potentially improve the agility of a container terminal as well. Moreover, given the dynamism of bottlenecks both in space and time, applying the BMC in real-time can possibly improve the performance of container terminals even more compared to the longer time horizon considered in this research. To apply the BMC in real-time, a more efficient bottleneck alleviation approach is required. Additionally, the BMC could be improved by also considering location-related bottlenecks, especially critical ones, such as the layout of the storage yard (Dekker et al. 2006), or transfer points at quay cranes (Boese et al. 2000). Furthermore, research on interactions between bottlenecks should be included, as this could significantly improve the effect and selection of suitable alleviation measures to improve the performance of the terminal. Lastly, future research could consider including managerial bottlenecks in the application of the BMC. To be able to detect and alleviate these bottlenecks, other relevant parties of the supply chain should be included, like shipping lines and public entities.

Appendix

See Tables 5, 6, 7 and 8.

Table 5 An overview of the park states of mSCs and aSCs

#	Equipment	Parking state	Bottleneck state
1	aSC, mSC	Parked	Inactive
2	aSC, mSC	Busy	Depends on the combination of the order control and drive state

Table 6 An overview of the drive states of mSCs and aSCs

#	Equipment	Drive state
1	aSC, mSC	Driving
2	aSC, mSC	Idle driving engine
3	aSC, mSC	Waiting due to equipment of the same type
4	aSC, mSC	Waiting due to equipment of another type

Table 7 An overview of the order control states of mSCs and aSCs

#	Equipment	Order Control state	Bottleneck state
1	aSC, mSC	Driving empty	Active (1,4), Inactive (3)
2	aSC, mSC	Driving loaded	Active (1,4), Inactive (3)
3	aSC, mSC	Dropping container(s)	Active (all)
4	aSC, mSC	Grabbing container(s)	Active (all)
5	aSC, mSC	Idle equipment	Inactive (all)
6	mSC	Waiting for free transfer point at QC	Inactive (all)
7	aSC	Teleoperator handling	Active (all)
8	aSC, mSC	Waiting for TOS routing or grounding decision	Inactive (all)

The combination with the drive states (see Table 6) determines whether the order control state is defined as active or inactive

Table 8 An overview of the order control states of QCs

#	Equipment	Order control state	Bottleneck state
1	QC	Bay change	Active
2	QC	Dropping container(s)	Active
3	QC	Grabbing container(s)	Active
4	QC	Idle equipment	Inactive
5	QC	Moving trolley with(out) container(s)	Active
6	QC	Tandemswitch	Active
7	QC	Twistlock handling	Active
8	QC	Waiting due to equipment of another type	Inactive

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References

Boer, C.A., and Y.A. Saanen. 2012. Improving container terminal efficiency through emulation. *Journal of Simulation* 6 (4): 267–278. https://doi.org/10.1057/jos.2012.10.

Boese, J., T. Reiners, D. Steenken, and S. Voss. 2000. *Vehicle dispatching at seaport container terminals using evolutionary algorithms.* Paper presented at the Proceedings of the Hawaii International Conference on System Sciences.

Boschian, V., M. Dotoli, M.P. Fanti, G. Iacobellis, and W. Ukovich. 2011. A metamodeling approach to the management of intermodal transportation networks. *IEEE Transactions on Automation Science and Engineering* 8 (3): 457–469.

Caballini, C., and S. Sacone. 2015. Modeling and simulation of the rail port cycle. *IEEE Systems Journal* 9 (1): 273–282. https://doi.org/10.1109/JSYST.2014.2298073.

Chen, G., K. Govindan, and Z. Yang. 2013. Managing truck arrivals with time windows to alleviate gate congestion at container terminals. *International Journal of Production Economics* 141 (1): 179–188. https://doi.org/10.1016/j.ijpe.2012.03.033.

Dekker, R., P. Voogd, and E. Van Asperen. 2006. Advanced methods for container stacking. *Or Spectrum* 28 (4): 563–586. https://doi.org/10.1007/s00291-006-0038-3.

Demirci, E. 2003. Simulation modelling and analysis of a port investment. *Simulation* 79 (2): 94–105. https://doi.org/10.1177/0037549703254523.

Dowd, T.J., and T.M. Leschine. 1990. Container terminal productivity: A perspective. *Maritime Policy and Management* 17 (2): 107–112. https://doi.org/10.1080/03088839000000060.

Gharehgozli, A.H., F.G. Vernooij, and N. Zaerpour. 2017. A simulation study of the performance of twin automated stacking cranes at a seaport container terminal. *European Journal of Operational Research* 261 (1): 108–128. https://doi.org/10.1016/j.ejor.2017.01.037.

Goodchild, A.V., and C.F. Daganzo. 2007. Crane double cycling in container ports: Planning methods and evaluation. *Transportation Research Part B: Methodological* 41 (8): 875–891. https://doi.org/10.1016/j.trb.2007.02.006.

Guan, Y., and K.H. Yang. 2010. Analysis of berth allocation and inspection operations in a container terminal. *Maritime Economics and Logistics* 12 (4): 347–369. https://doi.org/10.1057/mel.2010.12.

Guolei, T., G. Zijian, Y. Xuhui, S. Xiangqun, and D. Pengcheng. 2014. SPAC to improve port performance for seaports with very long one-way entrance channels. *Journal of Waterway, Port, Coastal and Ocean Engineering* 140 (4): e0000248. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000248.

Ha, B.H., E.J. Park, and C.H. Lee. 2007. *A microscopic simulation model for container terminal with 3D real-time visualization and its applications.* Paper presented at the International Conference on Intelligent Manufacturing and Logistics Systems (IML 2007).

He, J., D. Chang, W. Mi, and W. Yan. 2010. A hybrid parallel genetic algorithm for yard crane scheduling. *Transportation Research Part E: Logistics and Transportation Review* 46 (1): 136–155. https://doi.org/10.1016/j.tre.2009.07.002.

Hoshino, S., J. Ota, A. Shinozaki, and H. Hashimoto. 2007. Improved design methodology for an existing automated transportation system with automated guided vehicles in a seaport container terminal. *Advanced Robotics* 21 (3–4): 371–394. https://doi.org/10.1163/156855307780132009.

Ji, S., and R. Zhou. 2010. *Simulation and bottleneck analysis of container port handling resources based on bounding theory.* Paper presented at the 2010 International Conference on Logistics Systems and Intelligent Management, ICLSIM 2010.

Kiani Moghadam, M., J. Sayareh, and A. Nooramin. 2010. A simulation framework for optimising truck congestions in marine terminals. *Journal of Maritime Research* 7: 55–70.

Kourounioti, I., and A. Polydoropoulou. 2018. Application of aggregate container terminal data for the development of time-of-day models predicting truck arrivals. *European Journal of Transport and Infrastructure Research* 18 (1): 76–90. https://doi.org/10.18757/ejtir.2018.18.1.3220.

Kulak, O., O. Polat, R. Gujjula, and H.O. Günther. 2013. Strategies for improving a long-established terminal's performance: A simulation study of a Turkish container terminal. *Flexible Services and Manufacturing Journal* 25 (4): 503–527. https://doi.org/10.1007/s10696-011-9128-x.

Kuo, C.T., J.T. Lim, and S.M. Meerkov. 1996. Bottlenecks in serial production lines: A system-theoretic approach. *Mathematical Problems in Engineering* 2 (3): 233–276. https://doi.org/10.1155/S1024123X96000348.

Lawrence, S.R., and A.H. Buss. 1994. Shifting production bottlenecks: Causes, cures and conundrums. *Production and Operations Management* 3 (1): 21–37. https://doi.org/10.1111/j.1937-5956.1994.tb00107.x.

Lawrence, S.R., and A.H. Buss. 1995. Economic analysis of production bottlenecks. *Mathematical Problems in Engineering* 1 (4): 341–363. https://doi.org/10.1155/S1024123X95000202.

Li, L., Q. Chang, J. Ni, G. Xiao, and S. Biller. 2007. *Bottleneck detection of manufacturing systems using data driven method.* Paper presented at the ISAM 2007—IEEE International Symposium on Assembly and Manufacturing.

Ma, H., and Y. Li. 2010. *Research on multi-agent container terminal logistics operation scheduling system based on TOC.* Paper presented at the 2010 The 2nd International Conference on Computer and Automation Engineering, ICCAE 2010.

Ng, W.C., and K.L. Mak. 2005. Yard crane scheduling in port container terminals. *Applied Mathematical Modelling* 29 (3): 263–276. https://doi.org/10.1016/j.apm.2004.09.009.

Nguyen, V.D., and K.H. Kim. 2009. A dispatching method for automated lifting vehicles in automated port container terminals. *Computers and Industrial Engineering* 56 (3): 1002–1020. https://doi.org/10.1016/j.cie.2008.09.009.

Notteboom, T., and J.P. Rodrigue. 2008. Containerisation, box logistics and global supply chains: The integration of ports and liner shipping networks. *Maritime Economics and Logistics* 10 (1–2): 152–174. https://doi.org/10.1057/palgrave.mel.9100196.

Park, T., M. Sohn, and K.R. Ryu. 2010. *Optimizing stacking policies using an MOEA for an automated container terminal.* Paper presented at the 40th International Conference on Computers and Industrial Engineering: Soft Computing Techniques for Advanced Manufacturing and Service Systems, CIE40 2010.

Roser, C., M. Nakano, and M. Tanaka. 2001. *A practical bottleneck detection method.* Paper presented at the Winter Simulation Conference Proceedings.

Roser, C., M. Nakano, and M. Tanaka. 2002. *Shifting bottleneck detection.* Paper presented at the Winter Simulation Conference Proceedings.

Roser, C., M. Nakano, and M. Tanaka. 2003. *Comparison of bottleneck detection methods for AGV systems.* Paper presented at the Winter Simulation Conference Proceedings.

Saanen, Y.A. 2004. An approach for designing robotized marine container terminals.

Said, G.A.E.N.A., and E.S.M. El-Horbaty. 2016. *An intelligent optimization approach for storage space allocation at seaports: A case study.* Paper presented at the 2015 IEEE 7th International Conference on Intelligent Computing and Information Systems, ICICIS 2015.

Sargent, R.G. 2011. *Verification and validation of simulation models.* Paper presented at the Proceedings—Winter Simulation Conference.

Speer, U., G. John, and K. Fischer. 2011 Scheduling yard cranes considering crane interference. In *Vol. 6971 LNCS. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics,* 321–340).

Terstegge, M.J., and A. De Waal. 2019. *TEAMS Performance Lab Test POAL.* Internal documents. TBA Group.

UNCTAD. 2021. *Review of maritime transport*. Retrieved from

Van Battum, C.H.H. 2021. *Performance improvement of maritime container terminals through the bottleneck mitigation cycle.* (Master of Science). Delft University of Technology, Delft. https://repository.tudelft.nl/islandora/object/uuid%3Ac530e578-7c76-4f44-93b7-44834b5714b3.

Veenstra, A., J. Hintsa, and G. Zomer. 2008. *Global container supply chain compendium*.

Verbraeck, A., M.D. Seck, and M. Fumarola. 2009. *Validation Simulation Models Maasvlakte 2*. TU Delft.

Wang, Y., Q. Zhao, and D. Zheng. 2005. Bottlenecks in production networks: An overview. *Journal of Systems Science and Systems Engineering* 14 (3): 347–363. https://doi.org/10.1007/s11518-006-0198-3.

Zhang, C., Z. Liu, and Y. Chen. 2018. *Simulation analysis of multi-stage gate operation in container terminals.* Paper presented at the Proceedings of the 30th Chinese Control and Decision Conference, CCDC 2018.

Zhen, L. 2016. Modeling of yard congestion and optimization of yard template in container ports. *Transportation Research Part b: Methodological* 90: 83–104. https://doi.org/10.1016/j.trb.2016.04.011.