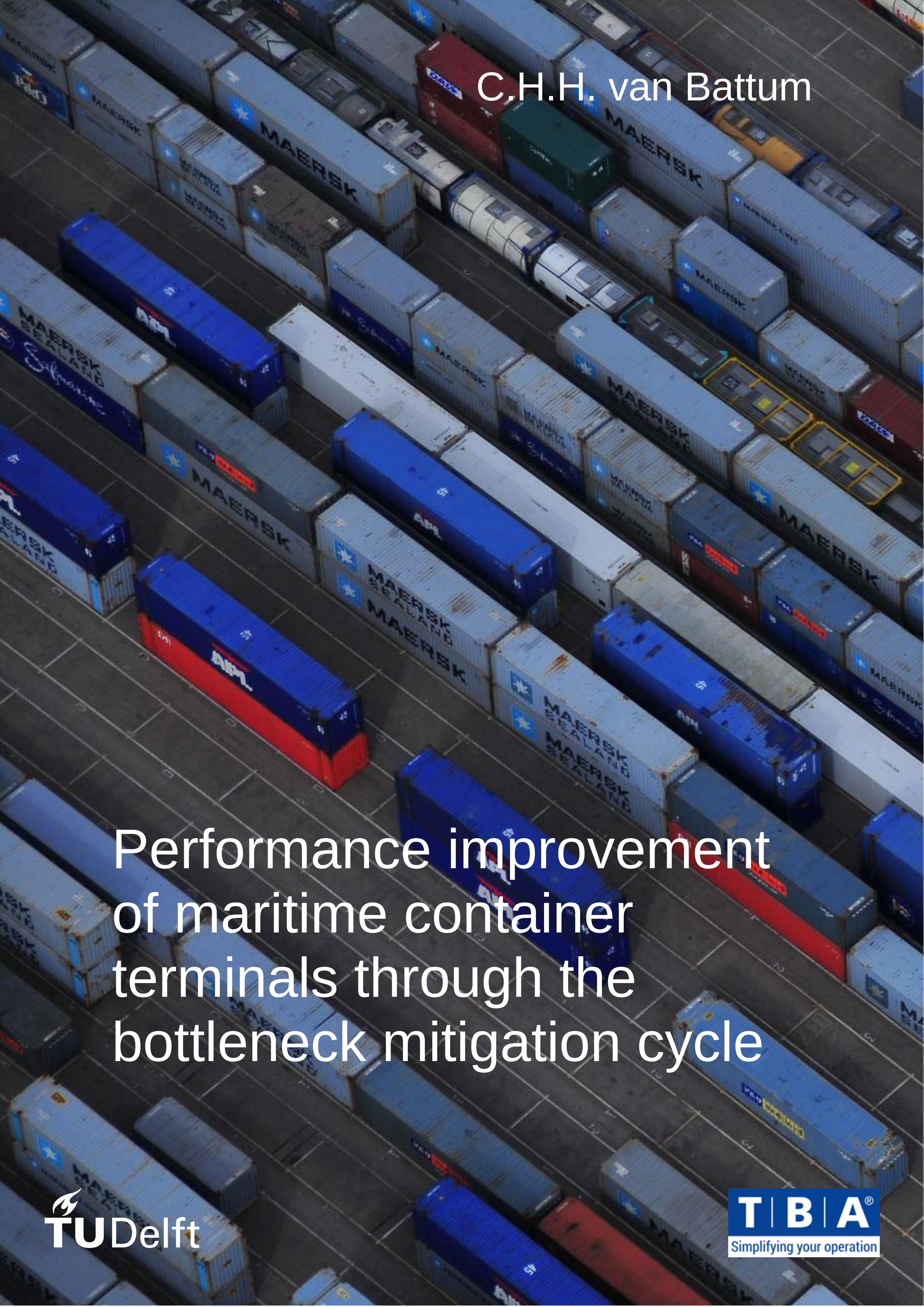

C.H.H. van Battum

# Performance improvement of maritime container terminals through the bottleneck mitigation cycle

# Performance improvement of maritime container terminals through the bottleneck mitigation cycle

By

Coen Herman Hans van Battum

## Master Thesis

in partial fulfilment of the requirements for the double degree of

**Master of Science in Mechanical Engineering**
at the Department Maritime and Transport Technology of Faculty Mechanical, Maritime and Materials Engineering of Delft University of Technology

&

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# Preface

This thesis takes you on a journey through the fascinating and challenging world of bottlenecks at maritime container terminals. Along this journey, there will be three stops: bottleneck classification, bottleneck detection, and bottleneck alleviation. This research has been performed to complete my double degree combining the studies Transport Engineering and Logistics at Mechanical Engineering and Transport and Planning at Civil Engineering.

The topic of bottlenecks at maritime container terminals is located on the intersecting plane of Mechanical Engineering and Civil Engineering. At container terminals, logistic activities of multiple modes of transportation are connected requiring coordination of equipment to efficiently facilitate the exchange of containers. From a Mechanical Engineering perspective, this research is particularly interesting because all three themes of Transport Engineering and Logistics come together at a container terminal: large-scale mechanical systems design, operations and maintenance, and multi-machine coordination and logistics, with the focus of this thesis on the latter theme. From a Civil Engineering perspective, maritime container terminals are an interesting topic of research because their role is critical in global supply chains for the transport of freight. Sustainable and reliable transport systems are paramount for our society, and therefore research into the mitigation of bottlenecks is of the utmost importance.

First of all, I would like to thank Arjen and Lóri for their interesting discussions through which this research topic has been established. During my research, I have learnt more than I could ever have expected for which I would like to express my profound gratitude to my daily supervisors: Erwin, Bart, and Bilge. Your dedication to keep on answering my questions, having animated discussions, and providing me with invaluable feedback, really helped me to develop my research skills and sparked my interest for conducting research in general. Learning from you how to write a structured and concise academic report and scientific paper was one of the most educational moments in my studies at the TU Delft.

Furthermore, I am genuinely grateful for the opportunities TBA Group has offered me. I would also like to take this opportunity to thank my colleagues of the design department at TBA Group which created a very inspiring environment for me to work in. A special thanks to my roommates for their motivating jokes about interns. In the end, I don’t think I ticked all the boxes for a typical intern, but at least we have had a lot of fun along the way.

Last but not least, I would like to thank family and friends for their unconditional support and motivating me throughout the course of this research and my studies at the TU Delft. Additionally, I would like to sincerely thank them for helping me to dot the i’s and cross the t’s of this thesis.

*Coen van Battum*
*Delft, January 2021*

# Abstract

Scarcity of maritime container terminal (MCT) capacity can become a problem for global supply chains. Bottlenecks limit the capacity of these terminals and should therefore be detected and alleviated. However, there is no structured approach available in literature to mitigate the effects of bottlenecks at MCTs. Therefore, this research introduces a holistic approach called the bottleneck mitigation cycle (BMC) which consists of three steps: bottleneck classification, bottleneck detection, and bottleneck alleviation. This research provides a proof of concept of the BMC. Scientific value is added by proposing a contemporary and comprehensive classification structure of bottlenecks at MCTs which consists of infrastructural, operational, and managerial bottlenecks. Infrastructural and operational bottlenecks are the focus of this research. Furthermore, while literature often only focuses on alleviation of a single bottleneck and skips bottleneck detection, this research uses the shifting bottleneck method and thereby considers a variety of possible infrastructural and operational bottlenecks. The shifting bottleneck method originates in production networks and is adapted such that it can be applied to detect both momentary and average bottlenecks at MCTs. 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 results in productivity improvements of 2-6%. Due to its generic formulation, the BMC is potentially successful in improving performance of MCTs in general which could be confirmed by future research. To make the BMC even more effective and efficient, future research directions are to improve the empirical approach used for bottleneck alleviation and to apply the BMC in real-time.

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# List of Abbreviations

| | |
|---|---|
| AGV | Autonomous Guided Vehicle |
| autoSC | automated Straddle Carrier |
| BMC | Bottleneck Mitigation Cycle |
| BN | Bottleneck |
| EDI | Electronic Data Interface |
| FCT | Fergusson Container Terminal |
| FN | Fergusson North |
| FW | Fergusson West |
| ITU | Intermodal Transport Unit |
| IWW | Inland Waterways |
| MCT | Maritime Container Terminal |
| mSC | manned Straddle Carrier |
| POAL | Ports of Auckland |
| QC | Quay Crane |
| RMG | Rail-Mounted Gantry crane |
| RTG | Rubber-Tyred Gantry crane |
| SC | Straddle Carrier |
| TEU | Twenty-foot Equivalent Unit |
| TGS | Twenty-foot Ground Slots |
| TOS | Terminal Operating System |
| TRL | Technology Readiness Level |

# List of Symbols

**Greek symbols**

| | | |
|---|---|---|
| $\alpha$ | Significance level of a two-tailed confidence interval | [-] |
| $\beta$ | Bottleneck shiftiness measure | [-] |
| $\mu$ | Mean of the bottleneck probabilities of all individual equipment | [-] |
| $\sigma$ | Standard deviation of the bottleneck probabilities of all individual equipment | [%] |

**Latin Symbols**

| | | |
|---|---|---|
| $c_v$ | Coefficient of variation of the bottleneck probabilities for individual equipment | [-] |
| $D_i^{shifting}$ | Duration of time individual equipment $i$ is the shifting bottleneck | [s] |
| $D_i^{sole}$ | Duration of time individual equipment $i$ is the sole bottleneck | [s] |
| $d_i^{shifting}(t)$ | Function of the shifting bottleneck duration of individual equipment $i$ over time | [s] |
| $d_i^{sole}(t)$ | Function of the sole bottleneck duration of individual equipment $i$ over time | [s] |
| $E$ | Set of all equipment types $e$ present at the container terminal studied | [-] |
| $e_i$ | Vector which connects the individual equipment $i$ to its equipment type $e$ | [-] |
| $H_{stack}$ | Maximum stacking height of the stack in the yard | [container] |
| $I$ | Set of all individual equipment $i$ present at the container terminal studied | [-] |
| $n$ | Number of subintervals | [-] |
| $N$ | Number of equipment in the system studied | [-] |
| $P_e^{shifting}$ | Percentage of time a type of equipment is a shifting bottleneck | [%] |
| $P_e^{sole}$ | Percentage of time a type of equipment is a sole bottleneck | [%] |
| $P_i^{shifting}$ | Probability that an individual equipment $i$ is the shifting bottleneck | [%] |
| $P_i^{sole}$ | Probability that an individual equipment $i$ is the sole bottleneck | [%] |
| $r$ | Refreshment interval of the shifting bottleneck method | [s] |
| $T$ | Total simulation duration | [s] |
| $TEU_{yard}$ | Total number containers stored in the yard | [TEU] |
| $TGS_{stack}$ | The number of Twenty-foot Ground Slots for each stack at a container terminal | [TGS] |

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# 1 Introduction

This section explains the purpose and approach of this research. Firstly, Section 1.1 introduces maritime container terminals and provides background knowledge. The problem addressed in this research is presented in Section 1.2. Based on this problem, the research objective is formulated, and a concise overview of the research approach is provided in Section 1.3. The relevance of this research and the research gaps addressed are explained in Section 1.4. Lastly, the outline of the remainder of this report is provided in Section 1.5.

## 1.1 Research context

Over the past two decades, containerised trade has annually grown by 5.8 percent on average (UNCTAD, 2019). The key to its success are its standardised dimensions, which facilitate easy and fast handling of freight as well as convenient transshipment between different modes of transport (Gharehgozli, Roy, & De Koster, 2016). Goods are not transported faster along the different modes, but the velocity of transshipment has increased tremendously (Maloni & Jackson, 2005; Notteboom & Rodrigue, 2008).

Transshipment has become the driving force behind the growth in container port throughput (Notteboom & Rodrigue, 2008) which has grown steadily over the course of the last decade, reaching 793 million Twenty-foot Equivalent Units (TEU) worldwide in 2018 (UNCTAD, 2019). Therefore, Maritime Container Terminals (MCTs) are crucial in globe-spanning supply chains (Gharehgozli et al., 2016).

MCTs, sometimes referred to as container terminals, are nodes in the transport network where container vessels are (un)loaded, but also where containers can be temporarily stored. A schematic overview of a transport chain at an MCT is shown in Figure 1.1. Import containers arrive by (deep-)sea vessel and are unloaded by quay cranes (as in Figure 1.1), mobile harbour cranes, or on-board cranes. Then the containers are picked up at the quay and brought to the storage yard by transport vehicles, like straddle carriers (as in the figure) or Autonomous Guided Vehicles (AGVs). Containers are retrieved from the storage yard either by for instance Rail-Mounted Gantry cranes (RMGs), Rubber-Tyred Gantry cranes (RTGs), or by the transport equipment itself (in the case of straddle carriers) and are brought to the landside transport mode (truck, train, or inland waterways) that will transport the containers further into the hinterland. For export containers, the order is reversed as indicated by the bi-directional arrows.

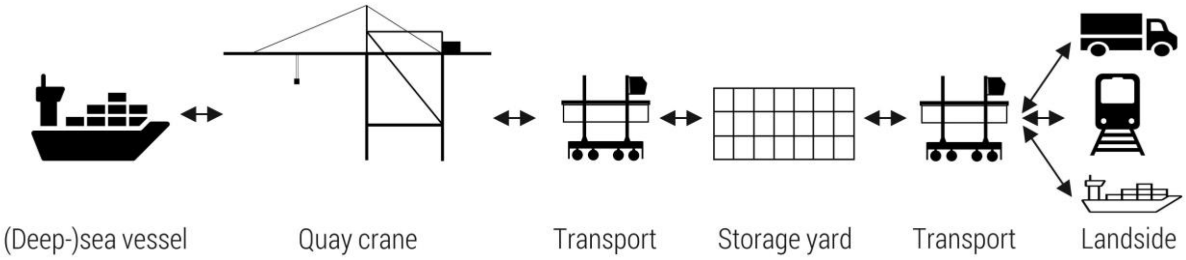


*Figure 1.1: Schematic representation of a transportation chain at a maritime container terminal.*

## 1.2 Problem statement

Due to growing container trade, scarcity of terminal capacity can become a problem for the transport of goods in global supply chains. However, development of port infrastructure is hindered by rising environmental and social concerns. There have not been significant improvements in the basic design of equipment. As a result, improving terminal productivity has increasingly become a matter of terminal management (Notteboom & Rodrigue, 2008).

The use of information technology at MCTs creates the opportunity to implement (automated) methods to detect and alleviate the factor(s) limiting performance, also known as *bottlenecks*. In this research, the terms "*alleviate*" and "*alleviation*" are used because bottlenecks cannot be prevented; at any given point in time there is always a process that is the bottleneck.

At MCTs, bottlenecks come in all shapes and sizes ranging from the layout of the terminal or amount of equipment to contractual commitments. To avoid ambiguity and confusion, it is important to have a clear definition of a bottleneck as there is no universal definition (Lawrence & Buss, 1995; Wang, Zhao, & Zheng, 2005). Depending on the actor and its perspective, the bottleneck can be different within the same system (Wang et al., 2005). In this research, bottlenecks within the terminal are considered from the terminal operator's point of view and the following definition is used: "*the resource or process within a maritime container terminal of which the capacity limits the output of the terminal".* This definition is deliberately somewhat loose as there is a wide variety of bottlenecks possible, and they move in time and space throughout an MCT.

In literature, research regarding bottlenecks at MCTs is still at an early stage. Scientific studies often primarily focus on a single bottleneck at MCTs without showing how it is detected and how its severity measures against other bottlenecks detected. Consequently, there is no information on the selection criteria to alleviate a particular bottleneck which is important because every terminal is unique in its goals and characteristics.

Goldratt (1990) provides a general approach to identify the system's constraints (bottlenecks) and to alleviate these by applying the Theory of Constraints. However, an important limitation of this approach is that it does not explain how the bottlenecks can be detected and alleviated. Since an MCT is a particularly complex system, this information is critical. Consequently, an integrated approach showing how to mitigate the effect(s) of bottlenecks on the performance of MCTs is lacking.

## 1.3 Research objective

As it is observed that integrated approaches are lacking in practice and literature, this research introduces the *bottleneck mitigation cycle* (BMC) to improve the performance of MCTs. The BMC is a holistic approach to mitigate the effects of bottlenecks in MCTs. The BMC consists of three steps as schematically shown in Figure 1.2. Firstly, a classification of bottlenecks at a terminal is required as input to select the most appropriate bottleneck detection method. Secondly, the bottlenecks at the terminal studied can be detected and ranked. Thirdly, causes of the most stringent bottleneck are identified, and one or multiple alleviation measures are selected and implemented. After a certain delay in time, which depends on the measure implemented, the cycle starts again by detecting bottlenecks as the bottleneck may have moved to another resource or process.

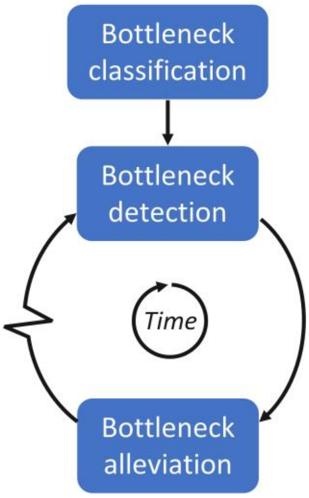


*Figure 1.2: The bottleneck mitigation cycle.*

This research aims to provide a proof of concept of the application of the BMC to enhance the performance of an MCT. To provide a proof of concept, a case study has been performed at the Fergusson Container Terminal (FCT) in the Ports of Auckland (POAL) which is also used to answer the following main research question:

*"How to apply the concept of the bottleneck mitigation cycle to improve the performance of a maritime container terminal?"*

A rigid definition of performance of an MCT is not provided, for every container terminal is unique given its different characteristics, like equipment and layout. In this research, the performance of the FCT is defined as the annual throughput of the terminal in TEU. The target throughput of the FCT cannot be reached with the given terminal infrastructure and equipment which makes the FCT particularly interesting to apply the concept of the BMC to.

## 1.4 Relevance of the research

To assess the incremental contributions made in this research as part of the larger innovation roadmap regarding the development of the concept of the BMC, the measurement system of the Technology Readiness Level (TRL) is adopted and the definitions from NASA Earth Science Division (2007) are used. An overview of this measurement system is provided in Figure 1.3 (NASA, 2012). It starts at level 1 (ideas underpinning the technology) and increases until level 9 (successful operation of the final product).

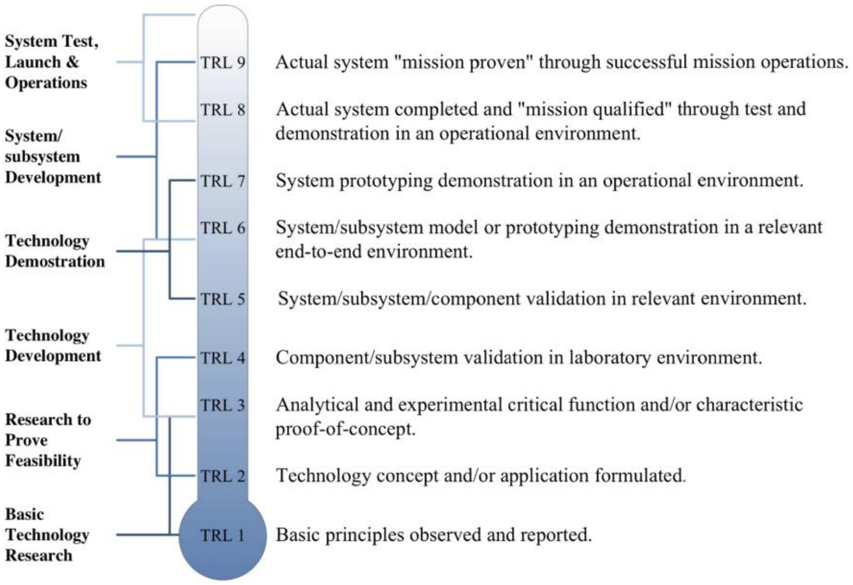


*Figure 1.3: An overview of the Technology Readiness Levels (TRL) (NASA, 2012).*

To address the problem of bottlenecks at MCTs, this research starts at TRL 1 by borrowing basic ingredients for the BMC available in current scientific literature. The introduction of the concept of the BMC increases the maturity of the BMC to TRL 2.

The central contribution of this research is the introduction and application of the BMC, which is a holistic approach to improve MCT performance. Furthermore, the following contributions are made:

- This research considers all three steps of the BMC to improve the performance of an MCT, instead of only considering a single step which is currently done in scientific literature.
- A contemporary and comprehensive classification of bottlenecks at MCTs is proposed to give a structured overview of bottlenecks at MCTs currently identified in scientific literature.
- The potential of different bottleneck detection methods for MCTs is analysed based on a synthesis of various methods available in literature including not only maritime container terminals but also other types of terminals and production networks.
- To apply the shifting bottleneck method to MCTs, new definitions of active and inactive states of equipment are formulated. These definitions have been successfully verified and used to detect both momentary and average bottlenecks using a simulation model of the FCT.
- The potential of the BMC is shown by applying the shifting bottleneck method to detect bottlenecks, to determine the cause of a detected bottleneck, and to select suitable measures to alleviate the detected bottlenecks in a simulation model of the FCT.
- Research gaps and promising future research directions towards increasing the TRL of the BMC and more efficient MCTs are formulated.

Successful application of the BMC increases terminal performance and capacity while using the same infrastructure. From an economic perspective, investments for terminal operators could be saved. From an environmental perspective, exploiting current infrastructure and resources as efficiently as possible is a more sustainable way of terminal development. Moreover, using the same terminal infrastructure prevents environmental and social concerns from local stakeholders associated with terminal infrastructure expansion.

## 1.5 Outline

In Section 2, a literature review is conducted to provide a synthesis of the state-of-the-art knowledge on bottleneck detection and alleviation at maritime container terminals with a holistic view to improve its performance. Section 3 uses the acquired insights from the literature review to develop the approach of applying the devised BMC to an MCT. In Section 4, this approach is used to apply the BMC to the FCT as a case study. Lastly, Section 5 presents the main findings of this research together with possible future research directions towards more efficient terminals.

# 2 Literature review: performance improvement of maritime container terminals

The objectives of this literature review are to provide a synthesis of the state-of-the-art knowledge on improving the performance of maritime container terminals (MCTs) by detecting and alleviating their bottlenecks.

Scopus and Google Scholar have been used with the main search terms “bottleneck”, “container”, and “terminal” in different combinations to find the publications. Furthermore, backwards snowballing was successfully adopted to find a significant number of additional publications. Since, to the best of the author’s knowledge, there is no comparable preceding literature review, there is no time frame imposed on the search results. These search results have been systematically examined and as a result 53 relevant publications were used in this review consisting of journal articles (30), conference proceedings (16), books (3), dissertations (2), and serials (2).

The results of this literature review are structured based on the BMC (see Figure 2.1) which is explained in Section 1.3. Section 2.1 compares currently available bottleneck classification structures and proposes a contemporary and comprehensive classification structure. This structure is used to categorise the bottlenecks at MCTs currently identified in scientific literature. In Section 2.2, the potential of bottleneck detection methods applied to (maritime) container terminals and other fields of research is compared. Alleviation measures are categorised based on the type of bottleneck in Section 2.3.

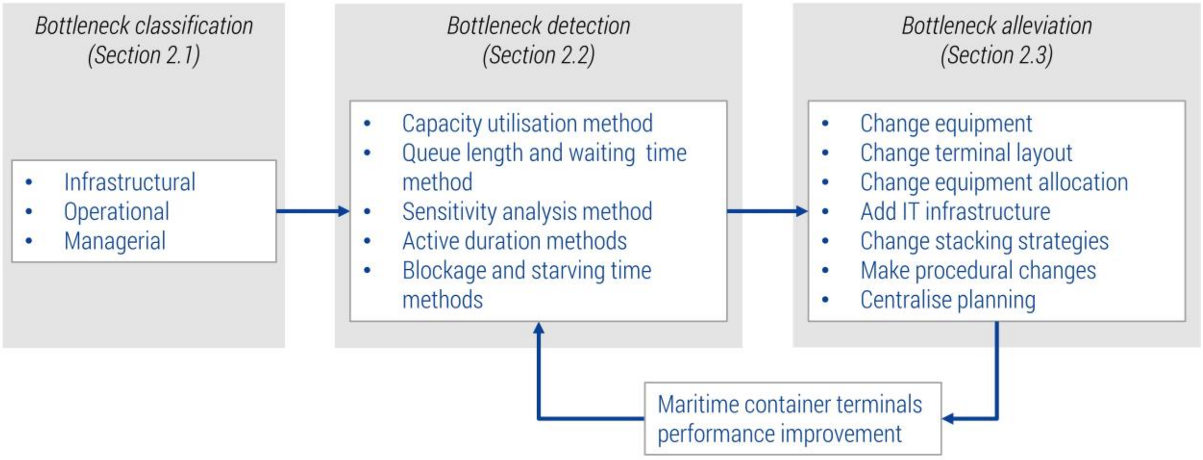


*Figure 2.1: The bottleneck mitigation cycle including approaches found in literature.*

## 2.1 State-of-the-art bottleneck classification at container terminals

It is important to classify the bottlenecks present at an MCT to effectively select a method to detect bottlenecks and select corresponding alleviation measures. In literature, only a few attempts have been made to create a classification structure for the types of bottlenecks present at a container terminal. The classifications of bottlenecks found are presented along with a proposed contemporary classification.

### 2.1.1 Classification of bottlenecks at container terminals

To the best of the author's knowledge, Dowd and Leschine (1990) were the first to categorise bottlenecks or limiting factors to productivity of a container terminal, as they call it. They distinguish two types of limiting factors: *physical* and *institutional limiting factors*. Physical limiting factors comprise the layout, area and shape of the terminal as well as vessel characteristics and the number and type of equipment used at the terminal. The definition of institutional limiting factors (e.g. customs and union work rules) is broader in the sense that they may also be imposed on the terminal operator by another actor in the containerization system. An advantage of this structure is that it distinguishes between physical and non-physical processes.

A more recent classification structure is proposed by Veenstra, Hintsa, and Zomer (2008) in which they distinguish three types of bottlenecks: *physical operations* (including loading/unloading facilities), *information flow* and *administrative processes* (including customs procedures, security scanning and port requirements). Information flow bottlenecks could relate to information exchange between equipment within the terminal, but also to information exchange between the terminal operator and external parties. Next to that, it is not clear what the difference between information flow and administrative processes is. Lastly, a category in which bottlenecks caused by actor relations is missing.

A third classification structure is provided by Ji and Zhou (2010): *resource*, *market* and *statutory* bottlenecks. Resource bottlenecks refer to the production capacity of equipment. There is no description of market and statutory bottlenecks provided. In this structure, it is not clear how the market can become a bottleneck of the terminal. In addition, relations between actors could be included in the statutory bottlenecks, but this is not clear.

An important common problem of the structures found in literature is that definitions and examples are remarkably limited, and that there is no distinction between bottlenecks due to decisions in infrastructure of the terminal (long-term) and operational decisions (real-time). Therefore, a classification structure is devised encompassing three types of bottlenecks: *infrastructural*, *operational* and *managerial* bottlenecks, as shown in Table 2.1. Detailed explanations of these types are provided in the following sections.

*Table 2.1: Summary of four bottleneck classification structures for an MCT from literature including the proposed classification.*

| **Bottleneck classification by Dowd and Leschine (1990)** | **Bottleneck classification by Veenstra et al. (2008)** | **Bottleneck classification by Ji and Zhou (2010)** | **Proposed bottleneck classification** |
|---|---|---|---|
| • Physical<br>• Institutional | • Physical operation<br>• Information flow<br>• Administrative processes | • Resource<br>• Market<br>• Statutory | • Infrastructural<br>• Operational<br>• Managerial |

### 2.1.2 Bottlenecks at maritime container terminals

The bottlenecks at MCTs are categorised based on our proposed classification (infrastructural, operational, and managerial) and the process or the resource where they occur in the transport chain of containers within a general MCT. This transport chain is an elaboration of the handling steps as described by Figure 1.1.

#### Infrastructural bottlenecks

Based on scientific literature, the identified infrastructural bottlenecks at MCTs are shown in Table 2.2. Infrastructural bottlenecks include the terminal layout and size, the amount and type of terminal equipment, waterway access to the terminal, vessel dimensions, IT infrastructure, and personnel. Infrastructural bottlenecks have in common that decisions are mostly made on a strategic planning level and therefore decided upon in the design of the terminal.

*Table 2.2: Infrastructural bottlenecks identified in scientific literature categorised based on the location or transport process of occurrence within a general transport chain of an MCT. *IWW: Inland Waterways.* (Boese, Reiners, Steenken, & Voss, 2000; Caballini & Sacone, 2015; Carlo, Vis, & Roodbergen, 2015; Dekker, Voogd, & Van Asperen, 2006; Dowd & Leschine, 1990; Guolei, Zijian, Xuhui, Xiangqun, & Pengcheng, 2014; Ha, Park, & Lee, 2007; He, Chang, Mi, & Yan, 2010; Ji & Zhou, 2010; Kourounioti & Polydoropoulou, 2018; Kulak, Polat, Gujjula, & Günther, 2013; W. Li, Wu, Petering, Goh, & Souza, 2009; Mulder & Dekker, 2017; Nguyen & Kim, 2009; Stahlbock & Voß, 2008; McCartney et al., as cited in Tang et al., 2016; Van Es, 2019; Wan, Yuen, & Zhang, 2014).

| **Locations (L) / Transport (T)** | **Sea: entrance channels, port (L)** | **(Un)loading of vessels by crane (T)** | **Quay: berth, cranes, apron (L)** | **Transport from the crane to the storage yard (T)** | **Storage yard (L)** | **Storage yard transport: stacking, yard transport, land-side transport (T)** | **Landside: road, IWW*, rail (L)** |
|---|---|---|---|---|---|---|---|
| **Infrastructural bottlenecks** | Coastal entrance channel traffic | Number of quay cranes | Quay crane transfer point capacity | Coupled transport operations | Layout of the storage yard | Amount of yard equipment | Number of sidings (rail) |
| | Draft restrictions of access ways | Technical specifications of quay cranes | | Amount of transport equipment | | Technical specifications of yard equipment | Road infra-structure around the port (road) |
| | Access restrictions due to the tide | Lack of skilled operators | | | | | Insufficient resources (road) |

## Operational bottlenecks

Based on scientific literature, the identified operational bottlenecks at MCTs are shown in Table 2.3. Operational bottlenecks are concerned with short-term and real-time planning. Operational bottlenecks include physical movement of containers across the terminal, interaction between equipment at the terminal, information flows, and short-term planning within the control of the terminal operator related to the physical movement of containers.

*Table 2.3: Operational bottlenecks identified in scientific literature categorised based on the location or transport process of occurrence within a general transport chain of an MCT. *IWW: Inland Waterways.* (Carlo et al., 2015; Dekker et al., 2006; Goodchild & Daganzo, 2007; Guan & Yang, 2010; Hoshino, Ota, Shinozaki, & Hashimoto, 2007; Kiani Moghadam, Sayareh, & Nooramin, 2010; Kourounioti & Polydoropoulou, 2018; Kulak et al., 2013; Mulder & Dekker, 2017; Ng & Mak, 2005; Nguyen & Kim, 2009; Park, Sohn, & Ryu, 2010; Said & El-Horbaty, 2016; Tang et al., 2016; Van Es, 2019; Veenstra et al., 2008; Zhang, Liu, Wan, Murty, & Linn, 2003; Zhang, Liu, & Chen, 2018; Zhen, 2016).

| **Locations (L) / Transport (T)** | **Sea: entrance channels, port (L)** | **(Un)loading of vessels by crane (T)** | **Quay: berth, cranes, apron (L)** | **Transport from the crane to the storage yard (T)** | **Storage yard (L)** | **Storage yard transport: stacking, yard transport, land-side transport (T)** | **Landside: road, IWW*, rail (L)** |
|---|---|---|---|---|---|---|---|
| **Operational bottlenecks** | | Equipment breakdowns | Security operations | Equipment breakdowns | Re-shuffles | Equipment breakdowns | Congestion of trucks at the gate (road) |
| | | Complex stowage planning | | Traffic congestion of yard equipment | | Traffic congestion of yard equipment | Congestion of trucks at the weighbridges (road) |
| | | Complexity of tasks of quay cranes | | Vessel berth deviation from planning | | Workload imbalance of yard equipment | Long stay of containers at the terminal (road, rail, IWW) |
| | | Interference of quay cranes | | | | Interference of yard equipment | |

## Managerial bottlenecks

Based on scientific literature, the identified managerial bottlenecks at MCTs are shown in Table 2.4. Managerial bottlenecks include rules and regulations imposed by external institutions on the terminal (operator), actor relations (including information sharing), and contractual agreements between the terminal operator and external parties.

*Table 2.4: Managerial bottlenecks identified in scientific literature categorised based on the location or transport process of occurrence within a general transport chain of an MCT terminal. *IWW: Inland Waterways.* (Caballini & Sacone, 2015; Carlo et al., 2015; Dowd & Leschine, 1990; Menger, 2016; Van Es, 2019; Veenstra et al., 2008).

| **Locations (L) / Transport (T)** | **Seaside: entrance channels, port (L)** | **(Un)loading of vessels by crane (T)** | **Quay: berth, cranes, apron (L)** | **Transport from the crane to the storage yard (T)** | **Storage yard (L)** | **Storage yard transport: stacking, yard transport, land-side transport (T)** | **Landside: road, IWW*, rail (L)** |
|---|---|---|---|---|---|---|---|
| **Managerial bottlenecks** | | Safety rules | | | | | Priority of deep-sea vessels (IWW) |
| | | | | | | | No contractual relation-ship with terminal operator (rail, IWW) |
| | | | | | | | No information sharing between terminals (IWW) |
| | | | | | | | Lacking information exchange between terminal and landside parties (road, rail, IWW) |
| | | | | | | | Lacking digitalization in customs procedures (road, rail, IWW) |
| | | | | | | | Schedule unreliability of deep-sea vessels (IWW) |
| | Union work rules | | | | | | |

## 2.2 State-of-the-art bottleneck detection methods

Due to the sheer complexity and dynamism of an MCT, a structured approach is required to detect the bottlenecks present. These detection methods can be separated into two groups: analytical and simulation-based methods (Leporis & Králová, 2010; L. Li, Chang, & Ni, 2009). With the aim of applying one of these methods to the complex dynamic structure of an MCT, analytical methods are unsuitable due to their computational complexity (Caballini & Sacone, 2015). Analytical methods become intractable when the complexity of the system increases (L. Li et al., 2009). Therefore, analytical methods are outside the scope of this review.

To the best of the author's knowledge, only three methods to detect bottlenecks are used in MCTs (1-3). Due to the limited number of bottleneck detection methods applied to MCTs, the scope of bottleneck detection methods is expanded to other types of terminals as well as manufacturing (4-7). The following seven methods have been identified:

1. Capacity utilization method
2. Queue length and waiting time method
3. Sensitivity analysis method
4. Activity duration methods: Average active duration method
5. Activity duration methods: Shifting bottleneck detection method
6. Blockage and starvation time methods: Arrow-based method
7. Blockage and starvation time methods: Turning point method

### 2.2.1 Bottleneck detection methods for container terminals and production networks

In the following subsections, detailed explanations of the bottleneck detection methods are given. The advantages and limitations of each method are highlighted. Lastly, the potential of these methods is discussed regarding the application specifically to an MCT. The potential of the detection methods is assessed based on the following attributes:

- Accuracy of detection of bottlenecks
- Requirements imposed by the method on the system studied
- Ability to distinguish between primary, secondary, tertiary and non-bottlenecks
- Difficulty of implementation of the method
- Ability to detect momentary and long-term bottlenecks

First of all, the accuracy of the method in detecting bottlenecks is important. Besides, in case the system does not meet the requirements imposed by the detection method, the method may produce faulty results or even become unusable. Next to that, it is important for a method to be able to distinguish between primary, secondary, tertiary and non-bottlenecks. Especially when the primary bottleneck cannot (easily) be alleviated, knowledge about the secondary and possibly tertiary bottleneck is valuable. Additionally, the idle time of the primary bottleneck can be reduced by improving the secondary bottleneck (C. Roser, M. Nakano, & M. Tanaka, 2002). In assessing the potential of a method, the difficulty of implementation should be taken into account as well. Furthermore, in case that real-time control of operations is pursued, the method should be able to detect both momentary and long-term bottlenecks.

#### 1. Capacity utilisation method

The capacity utilization method identifies the equipment or location with the highest utilisation rate as the bottleneck. It is adopted by Hoshino et al. (2007); Ji and Zhou (2010); Kulak et al. (2013); Ma and Li (2010). Hoshino et al. (2007) studied a cyclic closed queuing network of AGVs in an MCT. By studying the occupancy rate of the nodes by the AGVs, congestion of AGVs at the drop-off area of containers was identified as the bottleneck since it had the largest occupancy rate. Ji and Zhou (2010) and Ma and Li (2010) analysed the utilisation rate of equipment of the terminal with the current demand. Ji and Zhou (2010) used a simplified terminal in their simulation considering the transport chain from the sea to the storage yard and found that the number of quay cranes is the bottleneck. In contrast, Kulak et al. (2013) use a two-step approach in which first the maximum throughput of the terminal is determined by shortening the arrival interval of vessels. The average utilisation rate of the equipment is analysed using the demand corresponding to the maximum throughput. Dotoli, Epicoco, Falagario, and Cavone (2016) developed a timed Petri Nets model to evaluate the performance of an inland rail-road terminal. By analysing the occupation of the storage yard area and the access roads to the yard, both the storage yard capacity and congestion on the access roads to the storage yard were detected as bottlenecks. Wiercx, van Kalmthout, and Wiegmans (2019) made a model of an inland waterway (IWW) terminal to support decision making by IWW operators. The capacity utilisation method is adopted in the form of an equation to determine whether the handling capacity or the stacking capacity (on the quay and in the yard) is the bottleneck. A roll-on roll-off terminal is analysed by Keceli, Aksoy, and Aydogdu (2013) using the capacity utilisation method. Using the current demand, the utilisation rate of the five different terminal areas is analysed. The utilisation rate of the waiting area for export trailers is the highest and is therefore identified as the bottleneck. An overview of studies in literature using the capacity utilisation method is given in Table 2.5.

The main advantage of the capacity utilisation is its inherent simplicity (Möller, Froese, & Vakilzadian, 2011; Roser, Nakano, & Tanaka, 2001, 2003; Wang et al., 2005) which makes it easy to implement and automate (Roser et al., 2001, 2003; Wang et al., 2005). However, problems arise when multiple resources have a similar utilisation rate causing uncertainty in which resource is the bottleneck due to errors arising from random variation of the data (Roser et al., 2001; C. Roser et al., 2002; Christoph Roser, Masaru Nakano, & Minoru Tanaka, 2002; Wang et al., 2005). Furthermore, the method only provides insight into the primary bottleneck and does not provide information about the secondary, tertiary or non-bottlenecks (Roser & Nakano, 2015; Christoph Roser et al., 2002; Roser et al., 2003). Lastly, this method is based on average utilisation rates and thus not able to find momentary bottlenecks (Roser, Lorentzen, & Deuse, 2015; C. Roser et al., 2002).

Especially when there is not much time available for implementation, the capacity utilisation method might be useful as it still is relatively accurate. Moreover, this method does not impose any system requirements to work correctly. However, as an MCT is very complex and interaction between bottlenecks is important to consider, it is important to be able to determine which resources are secondary, tertiary or non-bottlenecks, which this method is not able to. Furthermore, this method cannot be used for real-time bottleneck detection limiting its use to steer operations.

*Table 2.5: An overview of literature in which the capacity utilization method is applied to terminals. *ITU: Intermodal Transport Unit, **Twenty-foot Equivalent Unit*

| Paper | Application | Terminal sections in case study | Performance indicators | Bottleneck(s) detected |
|---|---|---|---|---|
| Hoshino et al. (2007) | Maritime container terminal | Sea - storage yard | • Occupancy rate yard locations [%] | • Congestion of AGVs in transport from crane to yard |
| Ji and Zhou (2010) | Maritime container terminal | Sea - storage yard | • Utilization rate equipment [%] | • Number of quay cranes |
| Ma and Li (2010) | Maritime container terminal | n/a | • Utilization rate equipment [%] | n/a |
| Keceli et al. (2013) | Roll-on roll-off terminal | n/a | • Utilization rate locations [%] | • Waiting area for export trailers |
| Kulak et al. (2013) | Maritime container terminal | Sea - landside | • Throughput [containers/year]<br>• Utilization rate equipment [%] | • Slow yard equipment operations<br>• Coupled transport operations |
| Dotoli et al. (2016) | Inland container terminal | n/a | • Occupation of the storage yard area [ITU]*<br>• Occupation of the access roads to the yard storage area [veh/h]<br>• Average throughput of the terminal [ITU/h] | • Storage yard capacity<br>• Congestion on the access roads to the storage yard |
| Wiercx et al. (2019) | Inland container terminal | n/a | • Terminal throughput [TEU/year]<br>• Handling capacity [TEU]**<br>• Stacking capacity [TEU] | • Handling capacity of the terminal<br>• Storage capacity of the terminal |

### 2. Queue length and waiting time method

The queue length and waiting time method concentrates on finding the resource with the longest queues or waiting time which is then identified as the bottleneck. It is applied by Kiani Moghadam et al. (2010) to improve the truck turnaround times at an MCT. By analysing the maximum and average queue length and waiting time of containers transported by trucks at the three weighbridges (located at the entrance gate, yard, exit gate), bottlenecks are identified at all three locations.

Advantages of the method are that it simply determines the momentary bottleneck by comparing the waiting times or queue length at a particular time (C. Roser et al., 2002), and is also able to detect long-term bottlenecks. Additionally, this method is easy to implement (Roser et al., 2003). Important limitations of the queue length and waiting time method are that every resource should have a buffer (C. Roser et al., 2002; Wang et al., 2005; Yan, An, & Shi, 2010), and that it cannot accurately detect bottlenecks for systems with buffers of limited size (Roser et al., 2003; Wang et al., 2005; Yan et al., 2010). Next to that, the queue length can only be used to detect the bottleneck in a linear system with one type of part. When different types of products have different processing times, a resource with a short processing time may form a longer queue than another resource with only few products and a long processing time (Roser et al., 2003; Wang et al., 2005). Therefore, it is recommended to use the waiting time over the queue length (Roser et al., 2003). If the demand exceeds the capacity of the system in the long term, queues are filled permanently and the method does not work (C. Roser et al., 2002; Roser et al., 2003). Furthermore, if waiting times or queue lengths are similar, the method cannot determine the unique bottleneck limiting its accuracy (Wang et al., 2005). Lastly, the method is only able to point out the primary bottleneck without providing insight into secondary, tertiary or non-bottlenecks (Roser et al., 2003). This method can be characterised by its easy implementation and ability to detect both momentary and long-term bottlenecks. However, this method does not provide any insight into secondary, tertiary or non-bottlenecks.

Despite its easy implementation and ability to detect both momentary and long-term bottlenecks, this method imposes several requirements on the system which are not fulfilled by an MCT. Moreover, this method does not provide any insight into secondary, tertiary or non-bottlenecks.

### 3. Sensitivity analysis method

The main idea of the sensitivity analysis method is to find the variable(s) of the model which affect the key performance indicator(s) the most. The variable with the largest sensitivity is the primary bottleneck of the modelled system. Ha et al. (2007) and Caballini and Sacone (2015) used the sensitivity analysis method in combination with a simulation model to detect bottleneck(s). Ha et al. (2007) varied the number of yard tractors, the speed of yard cranes and the number of stack blocks in the storage yard to determine the effect on the berth productivity. The number of yard tractors and the speed of yard cranes independently contributed to the berth productivity and were therefore identified as the bottlenecks. Caballini and Sacone (2015) took this method one step further by using the methodology of Design of Experiments to reduce the number of simulations to be run. Organisational delays, the number of sidings and the number of tracks in the external shunting yard are identified as the bottlenecks. Demirci (2003) built a simulation model of a multi-purpose terminal. In his simulation, the current demand and demand at full capacity of the terminal (by decreasing the number of arriving of ships) are considered. The largest increase was found in the queue length and the ship turnaround times indicating that the loading and unloading operations (the service time of the ship) are the bottleneck. Boschian, Dotoli, Fanti, Iacobellis, and Ukovich (2011) created a model of an intermodal transport chain consisting of both a maritime and an inland container terminal. The utilisation of resources was only used to study the effect of changes in the system on the utilisation of other resources in the network. In their case study, the number of forwarders at both the maritime and inland container terminal are identified as the bottleneck. Table 2.6 provides an overview of the application of bottleneck detection methods to terminals in literature.

The sensitivity analysis method, also known as experimental (Roser et al., 2003) or scenario-based method (Lemessi, Rehbein, Rehn, & Schulze, 2012) in literature, is characterised by its ability to pinpoint bottlenecks in complex systems. Next to that, this method is able to distinguish primary, secondary, tertiary, and non-bottlenecks (Roser & Nakano, 2015; Roser et al., 2003). However, the development time of such detailed simulations is long and thereby impedes wide application of this method (L. Li et al., 2009). Assumptions have to be made as the real system has to be translated into a simulation which could lead to potential problems regarding the quality of the data required (Roser et al., 2015). Another crucial step of this method is the design scenarios. When the scenarios are not correctly defined, it is impossible to detect the bottlenecks of the system. All model items possibly constraining the system should be carefully identified upfront (Lemessi et al., 2012). Another limitation of this method is misinterpretation of the simulation results (L. Li et al., 2009) by for instance making erroneous comparisons between scenarios where multiple variables are varied to a different extent (Lemessi et al., 2012). The sensitivity analysis method finds long-term bottlenecks (L. Li et al., 2009), but it is not clear whether it can also detect momentary bottlenecks.

When accuracy is the main priority of bottleneck detection, it is expected the sensitivity analysis method is eligible as it can accurately detect primary, secondary, tertiary and non-bottlenecks. Successful application of this method has been shown in both container terminals and manufacturing. However, to ensure this accuracy, the system has to be accurately modelled using the right assumptions and scenarios which can be difficult and time-consuming. Furthermore, a simulation model has a long development time. Even more importantly, as the simulation model gets larger, simulation runs take longer and therefore using this model might become infeasible considering a limited amount of time.

*Table 2.6: An overview of literature in which the sensitivity analysis method is applied to terminals.*

| Paper | Application | Terminal sections in case study | Performance indicators | Bottleneck(s) detected |
|---|---|---|---|---|
| Ha et al. (2007) | Maritime container terminal | Sea - landside | • Berth productivity [number of containers handled per quay crane] | • Number of yard trucks<br>• Speed of yard cranes |
| Caballini and Sacone (2015) | Maritime container terminal | Storage yard - landside | • Average dwell time containers [day]<br>• Cycle time of containers [day]<br>• Number of trains left (import) [-]<br>• Number of trains arrived (export) [-] | • Number of sidings<br>• Number of tracks in the external shunting yard<br>• Maritime agency, customs and freight forwarder delays |
| Demirci (2003) | Multi-purpose terminal | n/a | • Average ship waiting time [hour]<br>• Average ship turnaround time [hour]<br>• Average and maximum queue length at quay [ship]<br>• Quay utilization ratio [%] | • Number of quay cranes<br>• Number of transport vehicles assigned to each quay crane |
| Boschian et al. (2011) | Intermodal transport chain including inland and maritime container terminal | n/a | • Throughput of the network [containers/month]<br>• Total lead time of containers [hours]<br>• Utilization rate of resources [%] | • Number of forwarders in both the inland terminal and maritime terminal |

### 4. Average active duration method

Roser et al. (2001) proposed the average active duration method in which the bottleneck is the resource with the longest uninterrupted active period. The first step is to define two states in which a resource is either *active* or *inactive* and assign the activities of the resources to one of these categories. For an AGV system, the inactive state might for instance be defined by the time it is waiting or moving to a waiting area, in all other cases the system would be active. This method is different from the utilisation method in the sense that not the percentage of time but the duration of uninterrupted activity of a resource is measured.

The average active duration method has the advantage that the structure of the system is not required, only the log file of the simulation containing the change of active duration of the resources over time (Roser et al., 2001; Sengupta, Das, & VanTil, 2008). The method can be implemented independently of the system structure because the active period is measured for each resource separately (Leporis & Králová, 2010; Roser et al., 2001; C. Roser et al., 2002). Moreover, the method detects bottlenecks reliably and accurately (Roser et al., 2001) and provides insight into secondary, tertiary and non-bottlenecks (C. Roser et al., 2002). Due to its simplicity, the method is easy to use and implement (Roser et al., 2001). On the other hand, the data required for the average active duration method is extensive. Consequently this method is only useful when this data is available

(Roser & Nakano, 2015). Additionally, in the case that there are multiple bottlenecks with approximately the same severity, only one bottleneck is marked which does not necessarily have to be the correct one (Leporis & Králová, 2010). With this method, long-term bottlenecks are detected.

The average active duration method is characterised by its easy implementation while being able to provide relatively accurate insight into secondary, tertiary, and non-bottlenecks. Moreover, the only requirement imposed on the system studied is that extensive data is required. However, this method only provides insight into long-term bottlenecks. Furthermore, the fact that this method is not yet applied to container terminals might make it difficult to estimate its potential as a significant amount of work may be needed to successfully do so.

### 5. Shifting bottleneck method

The successor of the average active duration method is the shifting bottleneck method proposed by C. Roser et al. (2002) which works based on the same principles and uses the same data as the active duration method. The difference is that the shifting bottleneck detection method not only determines the uninterrupted longest period, but also distinguishes between sole and shifting bottlenecks. A shifting bottleneck occurs when the two longest uninterrupted active durations of either the previous or subsequent bottleneck or the current bottleneck overlap at a given time, i.e. the bottleneck shifts between two resources. During this time of shifting, both resources are noted as a shifting bottleneck. In contrast to a shifting bottleneck, a sole bottleneck is the only bottleneck at a given time and does not overlap with previous or subsequent bottlenecks. This method is therefore able to detect momentary bottlenecks. To detect long-term bottlenecks, the percentage of time the bottlenecks are the shifting or sole bottleneck are determined and added for all resources.

Advantages of the shifting bottleneck method are that bottlenecks can be detected accurately (Wang et al., 2005) and reliably (C. Roser et al., 2002; Yan et al., 2010). Furthermore, the method is able to distinguish between primary, secondary and tertiary bottlenecks (Lima, Chwif, & Barreto, 2008; C. Roser et al., 2002; Roser et al., 2003), and the method can distinguish between momentary and long-term bottlenecks (C. Roser et al., 2002; Yan et al., 2010). Besides, just like for the average active duration method, the structure of the system is not required (C. Roser et al., 2002; Roser et al., 2003). The shifting bottleneck method requires an extensive amount of data (Roser & Nakano, 2015) and is more difficult to implement than the average active duration method (Möller et al., 2011; Roser et al., 2003).

The shifting bottleneck detection method is an extension of the average active duration method resulting in an improved accuracy. In addition to the average active duration method, this method is able to detect momentary bottlenecks. However, the increased complexity of this method might make it even more difficult to apply this method to an MCT.

### 6. Arrow-based method

Kuo, Lim, and Meerkov (1996) presented the arrow-based method which is based on the principle that a bottleneck machine blocks upstream and starves downstream machines. A machine is starved if it has to wait due to an empty upstream process or buffer and blocked if it has to wait due to a full downstream process or buffer. An arrow is drawn in the direction of downstream machine if the blockage time of the current machine is larger than the starvation time of the adjacent downstream machine. An arrow is drawn in the direction of the upstream machine if the blockage time of the current machine is smaller than the starvation time of the adjacent downstream machine. The machine without emanating arrows is the bottleneck.

An advantage of the arrow-based method is that it is able to detect multiple bottlenecks (Kuo et al., 1996). In the case that there are multiple machines without emanating arrows and thus multiple bottlenecks, the primary bottleneck is the machine with the largest severity. The severity is defined as the sum of the absolute value of the starvation time of the downstream machine minus the blockage time of the bottleneck machine and the absolute value of the starvation time of the current machine minus the blockage time of the upstream machine (Biller, Li, Marin, Meerkov, & Zhang, 2008). Unfortunately, the method only works for open serial production lines and therefore its application is limited (Kuo et al., 1996). The method for instance does not work for serial production lines with a rework (Biller et al., 2008). Next to that, the arrow-based method does not always identify the bottlenecks accurately and sometimes misses secondary or tertiary bottlenecks (Roser & Nakano, 2015). Nonetheless, the method is able to detect momentary and long-term bottlenecks (Kuo et al., 1996).

Since the arrow-based method is able to rank bottlenecks, a distinction can be made between primary, secondary and non-bottlenecks. However, the accuracy of this method is low. Additionally, it imposes strict requirements on the system which may make it very difficult to apply this method to an MCT. This method focuses on equipment (machines in manufacturing) as a bottleneck, and when locations should also be considered it could be difficult to apply this method to an MCT.

### 7. Turning point method

The turning point method, developed by L. Li et al. (2009), detects a bottleneck by finding the turning point. The turning point is defined as the machine where the sum of the percentage of time the machine is blocked and starved is smaller than the two adjacent machines, and the trend that the percentage of time of blockage is higher than starvation changes to a higher percentage of time of starvation than blockage when analysing a production line. In case there is no turning point found and the percentage of time of starvation is higher than blockage for all machines, the first machine is the bottleneck. Else, if the percentage of time of blockage is higher than starvation for all machines, the last machine is the bottleneck.

The turning point method has the advantage that it can detect multiple bottlenecks within a system (L. Li et al., 2009; Roser & Nakano, 2015). In the case that multiple bottlenecks are found, these can be ranked (L. Li et al., 2009). Additionally, the turning point method can be applied on both a local and global view of the system increasing the accuracy compared to the arrow-based method (L. Li et al., 2009) but at the same time increasing the complexity of the calculation (Roser & Nakano, 2015). Moreover, the method can be used to detect both momentary and long-term bottlenecks (L. Li et al., 2009). However, the method is not always able to detect all bottlenecks correctly, does not always detect primary or secondary bottlenecks, and the calculation which machine is the bottleneck is more complex than the arrow-based method (Roser & Nakano, 2015).

The turning point method detects momentary and long-term bottlenecks. Next to that, the accuracy of the turning point method is somewhat improved compared to the arrow-based method. However, the accuracy is still expected to be lower than the other methods. The more complex calculations, compared to the arrow-based method, make it more difficult to apply this method to an MCT. Despite that this method imposes less strict requirements on the system to which it is applied, the application of this method to the considered terminal is expected to be difficult as this method is particularly focussed on equipment bottlenecks.

### 2.2.2 Comparison and evaluation of bottleneck detection methods

To find a suitable method to apply to the FCT, the detection methods found in literature have been compared using the attributes as introduced in Section 2.1.1. Based on the overview in Table 2.7 and the explanation of the potential of the methods as provided in Section 2.1.2, it is expected that the two active duration methods (average active duration and shifting bottleneck method) are the most promising to be applied to an MCT, for long-term and momentary bottlenecks respectively (shaded and bold borders in Table 2.7). However, both active duration methods are not yet applied to MCTs.

*Table 2.7: A comparison of bottleneck detection methods applied to container terminals and manufacturing, the methods with the highest expected potential for an MCT are marked with bold borders.*

| Method | Accuracy | System require-ments | Insight into primary (P), secondary (S), tertiary (T), non-bottlenecks (N) | Implementation | Time horizon of detection | Applied to |
|---|---|---|---|---|---|---|
| Capacity utilisation method | Moderate | Low | P, N | Easy | Long-term | • Container terminals<br>• Manufacturing |
| Queue length and waiting time method | Low | High | P, N | Easy | • Momentary<br>• Long-term | • Container terminals<br>• Manufacturing |
| Sensitivity analysis method | High | High | P, S, T, N | Very difficult | Long-term bottlenecks | • Container terminals<br>• Manufacturing |
| Average active duration method | Moderate | Low | P, S, T, N | Easy | Long-term bottlenecks | Manufacturing |
| Shifting bottleneck method | High | Low | P, S, T, N | Difficult | • Momentary<br>• Long-term | Manufacturing |
| Arrow-based method | Low | Very high | P, S, T, N | Unknown | • Momentary<br>• Long-term | Manufacturing |
| Turning point method | Low | Moderate | P, S, T, N | Unknown | • Momentary<br>• Long-term | Manufacturing |

## 2.3 State-of-the-art bottleneck alleviation measures

After selecting a bottleneck detection method and detecting the bottlenecks, possible measures to alleviate the bottlenecks have to be identified and selected to improve MCT performance. Given different terminal characteristics (each is unique), there is no straightforward way to determine ‘the most suitable or best’ alleviation measure. Using scientific literature to quantitatively assess the potential of a bottleneck alleviation measure is difficult. Reasons for this are that the assumptions in terminal models are different, and information about the detection of (other) bottlenecks including their severity is missing. Both these aspects influence the effectiveness of the alleviation measure. With this knowledge, there is opted for an overview of possible bottleneck alleviation measures, see Table 2.8, of which some have already been successfully applied to MCTs. Table 2.8 shows that the same alleviation measures can be used to alleviate other types of bottlenecks, and thus possibly alleviating multiple bottlenecks of different types at the same time.

*Table 2.8: Bottleneck alleviation measures categorised based on the type of bottleneck and the type of alleviation measure.*

| | **Infrastructural alleviation measures** | **Operational alleviation measures** | **Managerial alleviation measures** |
|---|---|---|---|
| **Infrastructural bottlenecks** | • Change the type or amount of equipment<br>• Change the terminal layout | • Change equipment allocation<br>• Change storage yard stacking strategies | Not found |
| **Operational bottlenecks** | • Change the amount of equipment<br>• Change the terminal layout | • Change equipment allocation<br>• Change storage yard space allocation and stacking strategies<br>• Make procedural changes | Not found |
| **Managerial bottlenecks** | • Change the type or amount of equipment<br>• Change the terminal layout<br>• Add IT infrastructure | Not found | • Centralise planning of terminal operators and landside parties |

### 2.3.1 Infrastructural alleviation measures

#### Change the type or amount of equipment

Changes in the type or amount of equipment are implemented across the terminal. At the quay, Veenstra et al. (2008) and Van Es (2019) suggested to improve the barge handling capacity by creating a separate handling area with dedicated and additional cranes, additional operators, and use of tandem spreaders. Guan and Yang (2010) explained that to speed up container security inspection operations at the quay, the number of inspection machines could be increased. Kulak et al. (2013) replaced yard trucks by straddle carriers to decouple transport operations at the terminal to reduce waiting times, and they doubled the number of yard cranes to increase the total yard crane capacity. In contrast to increasing the amount of equipment, Hoshino et al. (2007) proposed to reduce the number of AGVs to reduce congestion in the yard. At the landside, Caballini and Sacone (2015) proposed measures to improve rail transport at the landside of the terminal by increasing the number of handling equipment at the tracks (rail cranes, reach stackers, or trailers). To reduce long queues and waiting times of trucks at the gate of the terminal, Kiani Moghadam et al. (2010) added extra weighbridges to weigh the container and the trucks.

#### Change the terminal layout

Changes in the layout of the terminal are mainly suggested at the landside. Caballini and Sacone (2015) proposed to electrify the rail tracks to avoid shunting operations, to reduce the number of crossings of railway tracks, and extend the track length of sidings at the terminal to further improve the transport by train. To reduce congestion for trucks, Zhang et al. (2018) changed the layout of the of the gate by implementing a multi-stage gate. In this multi-stage gate, trucks are categorised based on attributes of the goods within the container at the manually operated front gate before being assigned to a certain lane of the automatic second gate stage reducing the congestion at the gate. In case long one-way traffic channels are used to get to the terminal by vessels, Guolei et al. (2014) proposed to create temporary mooring locations approximately halfway the channel.

#### Add IT infrastructure

Additional IT Infrastructure is required to alleviate managerial bottlenecks. Veenstra et al. (2008) also proposed the implementation of an Electronic Data Interface (EDI) to transmit data between ports. With the adoption of the EDI customs clearance procedures can be digitalized, significantly increasing the speed of customs procedures. However, this measure will only work if all ports adopt the EDI. Additionally, Veenstra et al. (2008) proposed an electronic channel to share information about the state of containers between the terminal and landside parties.

### 2.3.2 Operational alleviation measures

#### Change equipment allocation

Changing equipment allocation is applied by Boese et al. (2000); Kulak et al. (2013); Nguyen and Kim (2009) by changing the dispatching strategy of transport vehicles travelling between the storage yard stack and the berths. Boese et al. (2000) implemented straddle carrier pooling instead of static assignment of straddle carriers to a quay crane. Kulak et al. (2013) and Nguyen and Kim (2009) did the same for yard trucks and automatic lifting vehicles, respectively. Zhen (2016) focused on scheduling yard trucks considering congestion and minimising the total expected travel time of containers across the yard. Hoshino et al. (2007) increased the number of possible routes with different lengths to be used by AGVs to prevent congestion. At the quay, Goodchild and Daganzo (2007) implemented a dual cycling strategy for quay cranes. This means that when a quay crane unloads a container from a vessel, it loads a container onto the vessel on the way back to the vessel, or vice versa. Improved allocation of yard cranes is adopted as a measure by He et al. (2010); W. Li et al. (2009); Ng and Mak (2005); Speer, John, and Fischer (2011). To reduce yard truck waiting times and to increase the throughput of the terminal, Ng and Mak (2005) devised a Mixed Integer Linear Programming model to schedule yard crane operations more efficiently. In addition, W. Li et al. (2009) and Speer et al. (2011) both improved scheduling of yard crane operations by considering crane interference as alleviation measure. He et al. (2010) also proposed a scheduling model for yard cranes using the rolling-horizon technique to minimise travelling times of yard cranes between blocks and the total delayed workloads. At the landside, Kourounioti and Polydoropoulou (2018) proposed a pick-up time-of-day model to predict the retrieval of import containers by trucks to use resources, like equipment and their operators, more efficiently by improved allocation.

#### Change storage yard space allocation and stacking strategies

Dekker et al. (2006); Kulak et al. (2013); Park et al. (2010) use storage yard stacking strategies to alleviate infrastructural bottlenecks. Dekker et al. (2006) implemented category stacking instead of random stacking. In contrast to random stacking, using category stacking means creating piles of containers of the same categories in the storage yard. Dekker et al. (2006) proposed another alleviation measure: improved scoring parameters to determine the stacking locations of containers in the storage yard. Kulak et al. (2013) assigned specific parts of the storage yard to stack containers on to specific berths in order to reduce transport times between storage yard and berths. Park et al. (2010) proposed an algorithm to improve the stacking strategy by focusing on incoming containers and temporary movement of containers within the storage yard. The storage space allocation problem is addressed by Said and El-Horbaty (2016) and Zhang et al. (2018) in a similar manner. Both minimise the total transport distance between the vessel berthing location, and the location where the containers are stacked in the yard.

#### Make procedural changes

To alleviate bottlenecks at the gate, Kiani Moghadam et al. (2010) implemented two procedural changes: drivers do not get off their vehicles while weighing the truck and container(s), and weighing of empty chassis is directed to specific weighbridges.

### 2.3.3 Managerial alleviation measures

Managerial alleviation measures focus on centralised planning of terminal operators and landside parties. Caballini and Sacone (2015) focused on synchronisation and coordination between terminal operators on rail operators to create a detailed schedule of operations to prevent fragmented and suboptimal decision making. Van Es (2019) focused on centralised planning with both terminal and barge operators to, for instance, prevent the assignment of a single barge operator to the same time slot at two different terminals. Another measure suggested by him is to introduce pricing of time slots for barges to spread barge handling demand at the terminal over the day.

## 2.4 Conclusion literature review

When it comes to bottleneck classification, only a few attempts have been made to create a structure for the types of bottlenecks present at a container terminal. A bottleneck classification is important to effectively select an appropriate bottleneck detection method and suitable alleviation measures. Furthermore, the classification of bottlenecks shows that bottlenecks and their causes are difficult to distinguish. This highlights the need for a careful definition of bottlenecks to select an appropriate bottleneck detection method. However, in scientific literature, definitions and examples of each type of bottleneck do not exist at this moment. In this research, a classification structure is proposed that encompasses three types of bottlenecks: *infrastructural*, *operational,* and *managerial* bottlenecks. Infrastructural bottlenecks occur throughout the transport chain. Among operational bottlenecks, interference or congestion of equipment is prevalent across the transport chain. Managerial bottlenecks are mainly found at the landside. Finally, bottlenecks are dynamic; they vary across time and space. This means that regular re-evaluations are needed in order to understand this dynamism.

Bottleneck detection methods in MCT literature are limited based on this review. Therefore, the scope of literature considered is broadened. In addition to container terminals, other terminal detection methods (roll-on roll-off, multi-purpose, and inland container terminals), manufacturing, and production networks are included. As a result, the following seven methods have been identified:

1. Capacity utilization method
2. Queue length and waiting time method
3. Sensitivity analysis method
4. Average active duration method
5. Shifting bottleneck detection method
6. Arrow-based method
7. Turning point method

The potential of each detection method is assessed based on the following attributes: accuracy of detection of bottlenecks, requirements imposed by the method on the system studied, ability to distinguish between primary, secondary, tertiary and non-bottlenecks, ability to detect momentary and long-term bottlenecks, and difficulty of implementation of the method. The 'average active duration method' and 'shifting bottleneck method' are the most promising for integrated bottleneck detection at MCTs. The average active duration method is characterised by its easy implementation, and providing relatively accurate insight into secondary, tertiary, and non-bottlenecks. Despite extensive data requirements, it only provides insight into long-term bottlenecks and the method has not yet been applied to container terminals. In contrast, the shifting bottleneck method is able to detect momentary bottlenecks. The increased complexity of this method makes it at the same time challenging and labour-intensive but in the end potentially successful as well.

A common aspect of the bottleneck detection methods found is that all use a simulation-based approach to detect bottlenecks. In these simulations, different indicators are used to quantify the performance of the terminal. Based on the papers found, there is no commonly accepted approach to quantify the performance of a terminal. A possible reason for this could be that not one container terminal is the same.

The investigation of literature regarding bottleneck alleviation showed that there is no straightforward way to determine 'the most suitable or best' alleviation measure and often a trial-and-error approach is adopted. Furthermore, the same measure might be used to alleviate bottlenecks of a different type. Using literature to quantitatively assess the potential of a bottleneck alleviation measure applied to MCTs is difficult. Reasons for this are that the assumptions in terminal models are different, and information about the detection of (other) bottlenecks including their severity is missing. Both these aspects influence the effectiveness of the alleviation measure.

# 3 Proposed methodology: Bottleneck Mitigation Cycle

This section describes the application of the Bottleneck Mitigation Cycle (BMC) to a container terminal. An overview of the steps taken in the BMC together with the structure of this section is provided in Figure 3.1. In this figure, the arrows indicate the actions that need to be taken to get the results shown in the boxes.

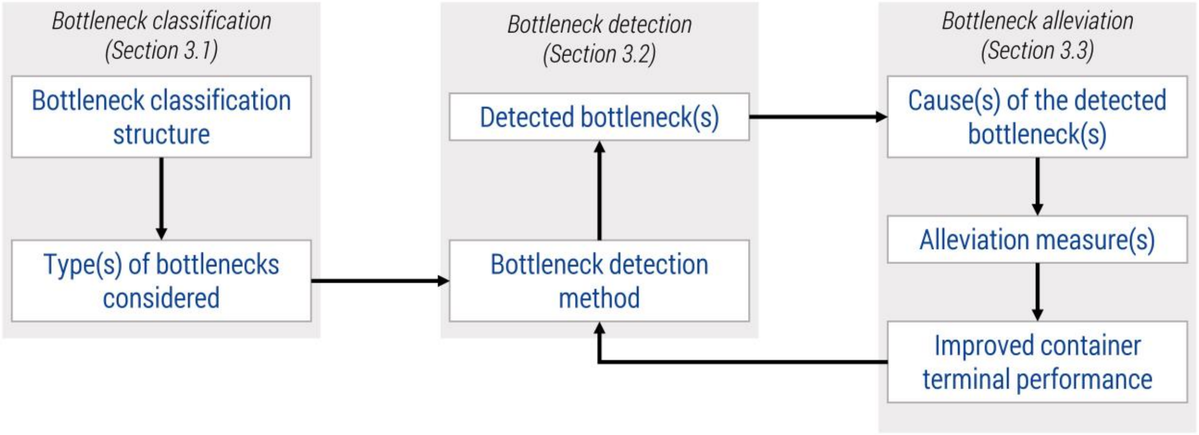


*Figure 3.1: An overview of the steps taken in the bottleneck mitigation cycle.*

## 3.1 Bottleneck classification

In Section 2.1, a classification structure of bottlenecks is proposed at MCTs which consists of three types of bottlenecks:

- Infrastructural bottlenecks
- Operational bottlenecks
- Managerial bottlenecks

Infrastructural and operational bottlenecks are within control of the terminal operator and can therefore be directly influenced. On the other hand, managerial bottlenecks are often imposed by external institutions through actor relations and contractual agreements. The dependence on other parties may result in unavailability of information to detect and alleviate bottlenecks and may even be a bottleneck itself (Menger, 2016).

Due to the distinctive nature of bottlenecks, different approaches are required which makes it difficult to study all three types at the same time. Since infrastructural and operational bottlenecks are within control of the terminal operator, the information necessary to detect and alleviate these types of bottlenecks is directly available. Therefore, managerial bottlenecks are considered outside the scope of this research.

## 3.2 Bottleneck detection: shifting bottleneck detection method

Based on the potential of different bottleneck detection methods as discussed in Section 2.2, the shifting bottleneck method is adopted to detect bottlenecks at an MCT. For this research, the shifting bottleneck method is considered superior to the active average duration method given its higher expected accuracy and ability to detect bottlenecks in real-time. With real-time detection, bottlenecks can be detected as they arise allowing for implementation of alleviation measures in real-time. This potentially results in increased terminal performance compared to long-term analysis and increases the agility or responsiveness of the terminal.

### 3.2.1 Main principle of the 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 (C. Roser et al., 2002). To illustrate this somewhat counterintuitive line of reasoning, first an analogy with filling a swimming pool is drawn as shown in Figure 3.2. Water is transported from its source through a network consisting of four pipelines with different diameters to fill the swimming pool. Figure 3.2 shows that pipeline 3 currently constrains the filling rate of the swimming pool and can therefore be identified as the momentary bottleneck of the system. Since pipeline 3 is constantly "active", it has the longest uninterrupted active duration and therefore is the momentary bottleneck of this swimming pool system.

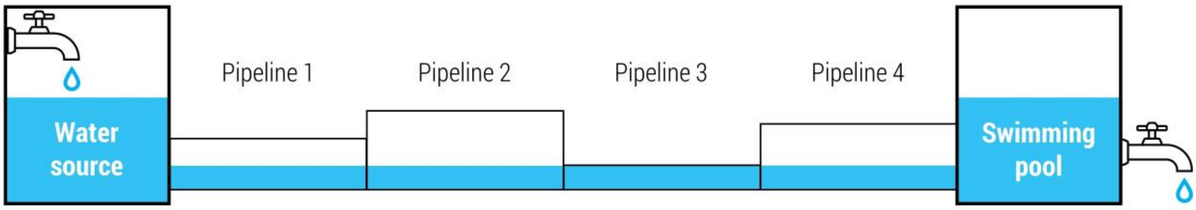


*Figure 3.2: Snapshot of a simplified schematic representation of filling a swimming pool through a pipeline network from a water source.*

The analogy of the swimming pool can then be drawn with a container terminal as shown in Figure 3.3. At a container terminal, the source of containers is represented by an entering mode of transportation, the pipeline network by a series of equipment types, and the swimming pool by the exiting mode of transportation. For the case of a container terminal, the pipelines representing the equipment type can be split into multiple smaller parallel pipelines which represent individual equipment through which a share of the water or containers flows. The amount of containers flowing through the different equipment types is constant, while the share of the flow of containers through the individual equipment varies. Although the flow of containers through the pipelines can vary in time, there is a pipeline that restricts the flow of water or containers as it is used to its maximum capacity. At this moment in Figure 3.3, pipe 2 of equipment type A is active (as it is completely filled) and thus is the momentary bottleneck of the system.

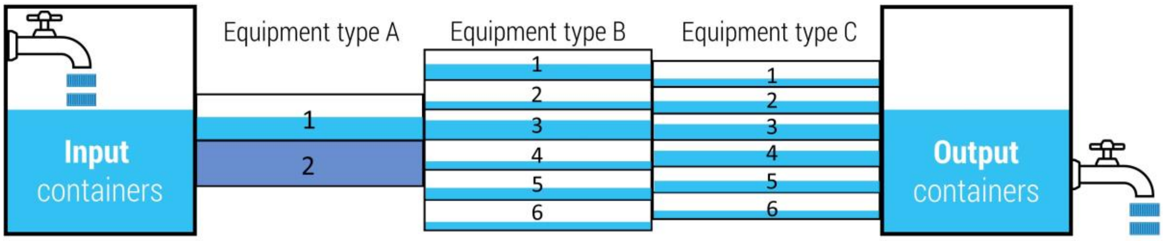


*Figure 3.3: An analogy between a swimming pool and a container terminal to identify the bottleneck based on the active status.*

Since Figure 3.3 shows a snapshot in time, a moment later the flow of containers can be different possibly resulting in the interruption of the longest active duration of one of the pipelines. When the system is analysed over a longer period of time, afterwards a distinction can be made between *sole* and *shifting* bottlenecks which can be defined as follows (C. 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. Shifting bottlenecks are the result of variability and randomness of the system (Lawrence & Buss, 1994).

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. The resource with the largest sum of sole and shifting bottleneck is identified as the primary bottleneck.

### 3.2.2 Shifting bottleneck detection at a container terminal

The shifting bottleneck method, based on the active duration of resources, is devised by C. Roser et al. (2002) to detect bottlenecks in production systems. In a way, a container terminal can also be seen as a production system as depicted in Figure 3.4. In both a production system and a container terminal, the sequential stages of the product are separated by machines or equipment of different types while the product is different. In a production system, a chair is created from wood and nails for example, while at a container terminal a container is discharged from a vessel and put on a truck to be transported to the hinterland.

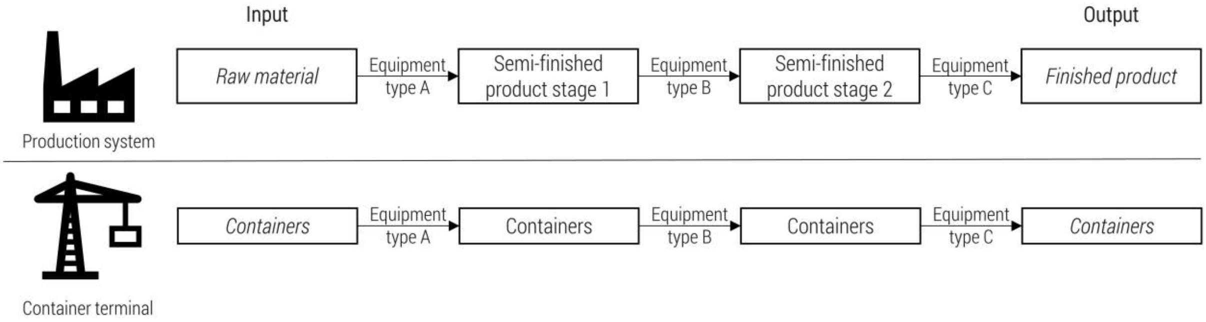


*Figure 3.4: A comparison between the flow of goods for a production system and a container terminal.*

Profound differences between production systems and container terminals make it complex to apply the shifting bottleneck method to an MCT. Based on discussions with field experts, an overview of important differences between characteristics of these systems is presented in Table 3.1. While production systems add value by transforming a raw material into a finished product, at container terminals containers are transshipped and transported between different transportation modes, and the product (containers) is not altered but only temporarily stored. Next to that, the size and the number of transportation modes served at a production system is in general relatively small compared to an MCT. Moreover, while a large buffer of material is often present as inventory in production systems, there is no inventory at MCTs as both the input and output are the same: containers. For instance, a chair production system can have a large inventory of wood and nails to keep machines busy, whereas at a container terminal the input equals the output and there is only a limited inventory of empty containers (which usually stay for a longer time at the terminal) available. Furthermore, in a production system a limited number of production lines is often set up in series, while at an MCT all individual equipment of the same type can be seen as production lines operating in parallel. Additionally, the equipment types at an MCT often can perform different tasks or have several functions, machines in a production system are dedicated to a specific task making them significantly less flexible in deployment. Since at an MCT the number of equipment of the same type can exceed 100 pieces (especially for horizontal transport across the terminal), there is significantly more interaction between equipment (of different types) than at a production facility which makes operations at an MCT particularly complex.

*Table 3.1: A comparison between important characteristics for production systems and maritime container terminals based on discussions with field experts. *IWW: Inland Waterways.*

| | Production system | Maritime container terminal |
|---|---|---|
| **Added value** | Transforming raw material into finished products | Transshipment and transport of containers between different modes of transport including temporary storage |
| **Size of the facility** | Small | Large |
| **Number of transportation modes served (rail/road/IWW*/sea)** | 1-2 | 2-4 |
| **Inventory** | Very large | Very limited |
| **Equipment setup** | Mostly in series | Mostly in parallel |
| **Flexibility in equipment deployment** | Low | High |
| **Interaction between equipment** | Low | High |

### Terminal operating system

To apply the shifting bottleneck method successfully, detailed real-time information and control of operations and resources across the terminal is required. In production systems these data are monitored and stored in so-called Manufacturing Execution Systems or Enterprise Resource Planning systems. At container terminals, such a system is referred to as the Terminal Operating System (TOS). Without a well-functioning TOS the costs of operations increase and the performance of the terminal decreases (Boer & Saanen, 2012); terminal operations may even come to a complete stop (Kim, Won, Lim, & Takahashi, 2004).

A schematic representation of the control structure of a TOS is shown in Figure 3.5 in which the bi-directional arrows indicate communication between the components. The corresponding relevant part of the TOS for the shifting bottleneck method in this research is also indicated. Although the exact functionalities of a TOS depend on the vendor and the equipment used at the terminal, their general functions are the same (Boer & Saanen, 2012). A TOS contains the following components and corresponding functionalities based on Boer and Saanen (2012); Günther and Kim (2006); Kim et al. (2004) and field experts:

- *Equipment planning* consists of:
    - Equipment managers to communicate current orders to equipment, create routes for individual equipment considering traffic (of other types of equipment), and control the equipment (driving). Equipment managers are present for each type of equipment at the terminal.
    - The transfer point manager to regulate the availability of locations for container exchange between equipment.
- *Vessel management* consists of stowage planning and berth scheduling.
- *Yard management* assigns grounding locations to containers destined for the yard.
- *Rail management* regulates the entrance of rail wagons onto the terminal. It also keeps track of the required container(s) for each wagon, the need for twistlock application or removal, and schedules when which part of each train is handled.
- *Gate management* regulates the entrance and exit of trucks onto and from the terminal.
- *Administration* saves information for invoices and information on container status (required customs inspections, dangerous cargo contents, maintenance or required repairs).

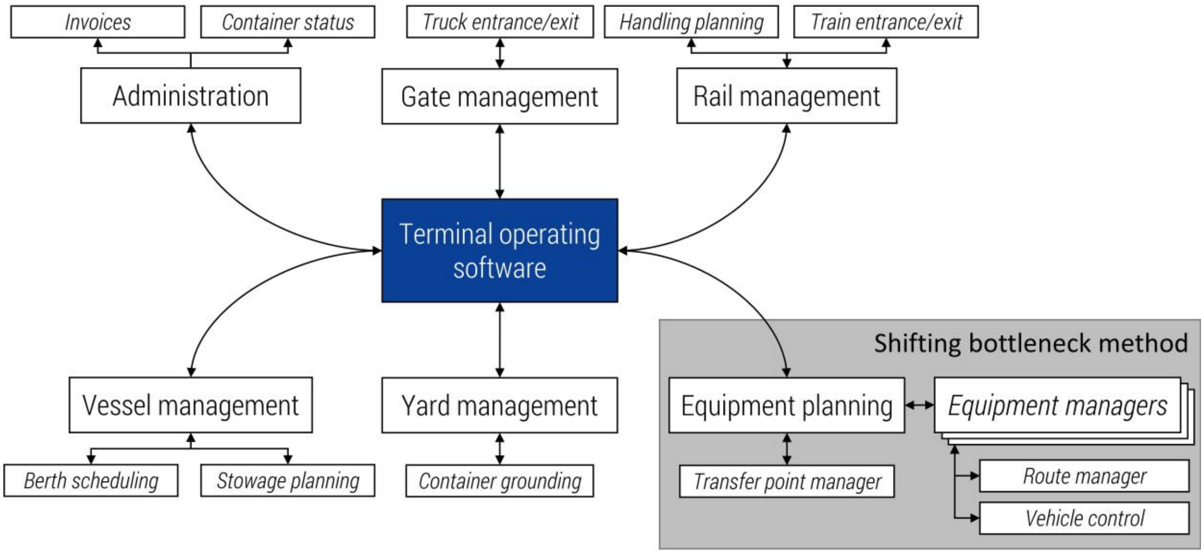


*Figure 3.5: Schematic representation of the control structure of a TOS. Uni-directional arrows indicate output from a component, and bi-directional arrows indicate communication between two components.*

### Determining the bottleneck state of a resource

For infrastructural and operational bottlenecks at a container terminal, two types of resources can be distinguished: equipment and locations. Since the literature review shows that equipment-related bottlenecks are more common at MCTs than location-related bottlenecks, the scope of this research is limited to equipment bottlenecks.

To detect the equipment-related bottleneck at an MCT, the longest uninterrupted active duration of the *bottleneck state* of all equipment needs to be determined. Every individual equipment at a container terminal is assigned a bottleneck state which is either active or inactive based on the information of the equipment planning and equipment managers in the TOS. 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 the equipment is on its way to a parking location, parked, or neither of the previous two.
- *Order control state:* the activity corresponding to part of the order assigned by the TOS to the equipment.
- *Drive state:* indicates the driving activity of the equipment.

At every moment in time, every individual 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*, all activities of the different types of equipment at the terminal studied are divided into mutually exclusive and collectively exhaustive discrete states. However, since the shifting bottleneck method has not yet been applied to MCTs in scientific literature, the following new definitions are used:

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

In literature, congestion is prevalent across the transport chain of an MCT and is therefore considered as an important potential bottleneck (Hoshino et al., 2007; Kiani Moghadam et al., 2010; Kourounioti & Polydoropoulou, 2018; Veenstra et al., 2008; Zhang et al., 2018; Zhen, 2016). Therefore, equipment is active when it is waiting on equipment of the same type, since this represents traffic congestion between equipment operating in parallel when comparing with a production system as depicted in Figure 3.4. When the equipment is of a different type, it would resemble the next production stage and therefore is defined as inactive.

The procedure of determining the bottleneck state for every individual equipment is graphically shown in Figure 3.6. Firstly, the parking state of the equipment is determined which can be either “parked” or “busy”. When the equipment is parked, the bottleneck state is inactive regardless of the order control or drive state of the equipment. Secondly, if the equipment is busy, the combination of the order control state and drive state determines the bottleneck state of the equipment. When this combination is inactive, the bottleneck state is inactive. When this combination is active, the bottleneck state is active. This procedure of determining the bottleneck state is performed repeatedly according to a specified refreshment interval and thus the bottleneck state changes over time. The equipment with the longest uninterrupted active duration of the bottleneck state is the momentary bottleneck. In the case that there are multiple equipment with the exact same uninterrupted active durations, there are multiple momentary bottlenecks at the same time.

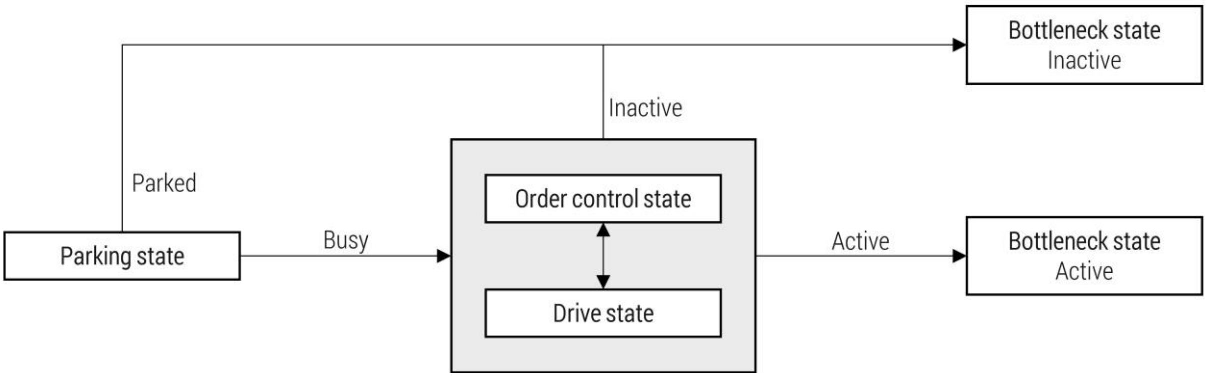


*Figure 3.6: Determination of the bottleneck state of equipment at an MCT.*

### Determination of shifting and sole bottlenecks

The duration of the time an individual equipment is the sole ($D_i^{sole}$) or shifting ($D_i^{shifting}$) bottleneck is determined using Equations (1) and (2), respectively. The set $I$ represents all individual equipment present at the container terminal studied.

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

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

in which $D_i^{sole}$ is the duration of time individual equipment $i$ is the sole bottleneck, in seconds; $D_i^{shifting}$ is the duration of time an individual equipment $i$ is the shifting bottleneck, in seconds; $d_i^{sole}(t)$ is the function of the sole bottleneck duration of individual equipment $i$ over time, in seconds; $d_i^{shifting}(t)$ is the function of the shifting bottleneck duration of individual equipment $i$ over time, in seconds; $T$ is the total simulation duration, in seconds; $n$ is the number of subintervals which equals the number refreshment intervals in the simulation duration, dimensionless; $r$ is the refreshment interval, in seconds. Since both the duration function for sole and shifting bottlenecks of the individual equipment is either 0 (it is not a sole or shifting bottleneck at that moment) or 1 (it is a sole or shifting bottleneck at that moment), the integral equals a summation over the simulation time with steps equal to the refreshment interval.

The probability that individual equipment $i$ of a specific type is either a sole ($P_i^{sole}$ with $i \in I$) or shifting bottleneck ($P_i^{shifting}$ with $i \in I$) during the period of time considered can be calculated using equations (3) and (4), respectively.

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

$$P_i^{shifting} = \frac{D_i^{shifting}}{T} \cdot 100, \qquad \forall i \in I \tag{4}$$

in which $P_i^{sole}$ is the probability that an individual equipment $i$ is the sole bottleneck during the simulated time, in %; $P_i^{shifting}$ is the probability that an individual equipment $i$ is the shifting bottleneck during the simulated time, in %; the other symbols are the same as in Equation (1) and (2).

C. Roser et al. (2002) do not provide information the procedure of aggregating sole and shifting bottlenecks of individual equipment of the same type. In this research, this issue is overcome by summing the shifting and sole bottleneck durations of the individual equipment of the same type. The percentage of simulated time an individual type of equipment is either a sole ($P_e^{sole}$ with $e \in E$) or shifting bottleneck ($P_e^{shifting}$ with $e \in E$) can be calculated using equations (5) and (6), respectively. The set $E$ represents all equipment types present at the container terminal studied. 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 $e_i$.

$$P_e^{sole} = \frac{\sum_{i \in I | e_i = e} D_i^{sole}}{T} \cdot 100 = \sum_{i \in I | e_i = e} P_i^{sole}, \qquad \forall e \in E \tag{5}$$

$$P_e^{shifting} = \frac{\sum_{i \in I | e_i = e} D_i^{shifting}}{T} \cdot 100 = \sum_{i \in I | e_i = e} P_i^{shifting}, \qquad \forall e \in E \tag{6}$$

in which $P_e^{sole}$ is the percentage of time a type of equipment is the sole bottleneck during the simulated time, in %; $P_e^{shifting}$ is the percentage of time a type of equipment is a shifting bottleneck during the simulated time, in %; the other symbols are the same as in Equations (1) and (2).

There are two important consequences of aggregating the equipment by its type in this way. Firstly, the percentage of shifting bottlenecks can exceed 100% for a specific type of equipment. This might seem counterintuitive but is easily explained using the results of an example experiment of a system consisting of one QC and three straddle carriers (SCs) as shown in Figure 3.7.

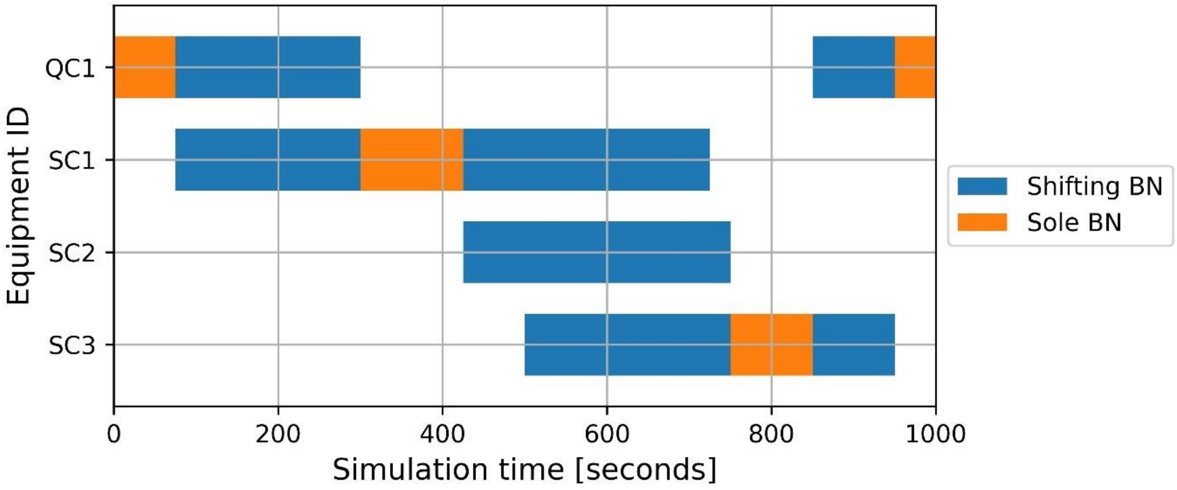


*Figure 3.7: Results of a fictive experiment with 1 quay crane (QC) and 3 straddle carriers (SC) showing the sole and shifting bottlenecks (BN) over time.*

In Figure 3.7, it can be observed that there are multiple occurrences in which the bottleneck shifts between the same type of equipment, causing the percentage shifting bottleneck for SCs to be larger than 100%. By definition, only one individual equipment in the whole system can be the sole bottleneck at the same time. Therefore, the sum of the aggregated sole bottleneck times over all types of equipment never exceeds 100%.

Secondly, the aggregated percentage of sole and shifting bottlenecks per type of equipment (Equations (5) and (6)) also represents the average number of sole and shifting bottlenecks present over the duration of the simulation. For example, the aggregated shifting bottleneck time of SCs is 120%, which means that on average 1.2 individual SCs have been the shifting bottleneck for the simulated time.

However, this way of aggregating the sole and shifting bottleneck percentages by type of equipment also brings a limitation. The shifting bottleneck percentage does not give the probability of a certain type of equipment being the bottleneck. For sole bottlenecks this still holds since there can only be one bottleneck at the same time.

The primary average bottleneck of the system is defined as the bottleneck with the highest sum of the sole and shifting bottleneck percentage over the time considered. The secondary bottleneck has the second highest percentage bottleneck, etc. For the fictive experiment, the primary average individual bottleneck is SC1 and primary average bottleneck by equipment type would be the SCs.

## 3.3 Bottleneck alleviation: empirical approach

There is no straightforward way to determine 'the most suitable or best' alleviation measure in scientific literature. Furthermore, using scientific literature to assess the potential of alleviation measures is difficult, since not one terminal is the same and interaction of bottlenecks makes selecting an effective alleviation measure even more complex.

As a result, often a trial-and-error approach is adopted. However, since this approach is time-consuming, this research uses an empirical approach based on the knowledge of field experts. Once the bottleneck has been detected, the cause is determined based on an analysis of the time spent in the different states of the equipment. After identifying the cause, discussions with field experts take place to determine promising alleviation measures. These alleviation measures are implemented to determine their effect and to select the best alleviation measure given a set of selection criteria.

Based on the results of the previous step in the BMC, a choice should be made which bottleneck is alleviated. Since the bottlenecks can be detected in real-time, the bottlenecks can also be alleviated in real-time. However, in this research, the scope is limited to alleviation of bottlenecks averaged over a period of time referred to as average bottlenecks (C. Roser et al., 2002).

### 3.3.1 Bottleneck shiftiness measure

For alleviation of bottlenecks, ideally a system contains a single prevalent bottleneck during the whole period of studying the system. Consequently, all efforts can be devoted to alleviating the specific bottleneck. On the other hand, a similar percentage of sole and shifting bottlenecks across different equipment of the system makes alleviation of the bottleneck more complex, since the bottleneck of the system is more likely to change in time and space. As a result, different measures have to be implemented to alleviate the bottleneck.

Lawrence and Buss (1994) introduced the *bottleneck shiftiness measure* to quantify the shiftiness of bottlenecks. In a way, this is a quantitative measure of the complexity of improving the system performance by alleviation of bottlenecks. It also provides information whether it is more effective to apply alleviation measures to specific individual equipment or to a type of equipment. The bottleneck shiftiness measure ($\beta$) can be calculated using the following equation (Lawrence & Buss, 1994):

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

in which $\beta$ represents the bottleneck shiftiness measure, dimensionless; $c_v$ represents the coefficient of variation of the bottleneck probabilities for the individual equipment ($P_i^{sole}$ and $P_i^{shifting}$), dimensionless; $N$ represents the number of equipment of the system studied ($N = |I|$), dimensionless; $\sigma$ and $\mu$ represent the standard deviation and mean of the bottleneck probabilities of all individual equipment ($P_i^{sole}$ and $P_i^{shifting}$) of the system, respectively, both dimensionless.

The bottleneck shiftiness measure can also be calculated for all types of equipment present in the system studied instead of the individual equipment. When the bottleneck shiftiness measure is calculated based on types of equipment in the system, the bottleneck probabilities to calculate the coefficient of variation ($c_v$), mean ($\mu$), and standard deviation ($\sigma$) are based on ($P_e^{sole}$ and $P_e^{shifting}$) 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 for the duration of the whole simulation to 1 for the case where all equipment of the system have the same probability to be the bottleneck. When multiple replications of an experiment are performed, for each replication the bottleneck shiftiness measure value is calculated which is averaged over the total number of replications of the respective experiment.

For the results of the fictive experiment presented in Figure 3.7, the bottleneck shiftiness measure is 0.86 based on the individual equipment, and 0.48 based on the types of equipment. In this case, applying alleviation measures to the type of equipment is more effective than applying the measure to an individual equipment.

### 3.3.2 Cause identification

The shifting bottleneck detection method detects which equipment or equipment type is the bottleneck, but not what the underlying cause of this bottleneck is. Since every bottleneck can have a wide range of possible causes, identifying the cause of the bottleneck is not trivial. For instance, when the horizontal transport equipment at the terminal is identified as the bottleneck, this can be caused by multiple events like inefficient equipment assignment by the TOS, congestion of equipment, or inefficient stacking of containers in the yard, amongst many others.

The shifting bottleneck method keeps track of the time spent in each state. For every individual and type of equipment can be calculated in which state (relatively) the most time is spent. States in which the most time is spent are likely causes of the bottleneck, since states in which only little time is spent have a limited effect on the performance of the equipment. To use the equipment to its maximum potential, the time equipment is active should be maximised, and the inactive time should be minimised. In other words, either the time spent in inactive states needs to be reduced, or the time spent in active states needs to be used more efficiently. An investigation of the causes behind the time spent in a state is performed in consultation with field experts. The result of this analysis is a list of (possible) causes of the selected bottleneck.

### 3.3.3 Alleviation measures

Based on this list of causes, one cause is selected to be addressed. The next step is to create a list of possible alleviation measures for the selected cause (and thus bottleneck). However, composing a list of alleviation measures is far from trivial. Due to interaction of processes at a container terminal, applying a measure to alleviate a specific bottleneck may deteriorate performance of the terminal since other equipment is significantly hindered by the implemented measure. Therefore, instead of using a time-consuming trial-and-error approach, field experts are consulted to compose a list of promising alleviation measures.

An alleviation measure can be selected from the list based on various selection criteria like the potential impact of the measure on performance improvement, costs of implementing the measure in reality, and time to implement the measure (operational or infrastructural measures). However, these criteria also depend on the extent of the alleviation measure. Due to the complexity of processes at a container terminal and its uniqueness, the selection of an alleviation measure and its extent is far from straightforward and depends greatly on the resources available and goal(s) of the terminal.

The final step of this empirical approach to alleviate a bottleneck is to implement the chosen measure and its extent to improve the performance of the container terminal. Once this measure is implemented, the performance of the terminal is determined and compared to the performance of the base scenario with which one cycle of the BMC is completed. After the first time of applying the alleviation measures, it is likely that the detected bottleneck will change. Therefore, first detection is performed again before a decision is made on the next alleviation measures to be implemented.

# 4 Application of the Bottleneck Mitigation Cycle to the Fergusson Container Terminal

In this section is described how the Bottleneck Mitigation Cycle (BMC) is applied to the Fergusson Container Terminal (FCT). Although the methodology of the BMC is generic, the FCT is used as a case study because at this terminal the target annual throughput of 1.1 million Twenty-foot Equivalent Units (TEU) could not be reached with the current infrastructure. Furthermore, this is a relatively complex case due to the amount of interaction between the (different types of) equipment present. Therefore, a proof of concept at this terminal is considered more meaningful.

In Section 4.1, an overview of the FCT is given and the approach to quantify its performance is explained. Section 4.2 describes the types of bottlenecks considered and the application of the shifting bottleneck method to the FCT. Based on the bottlenecks detected, a selection of alleviation measures is implemented to analyse the performance improvement in Section 4.3. To conclude, Section 4.4 reflects on both the performance improvement and the approach taken.

## 4.1 Case study: Fergusson Container Terminal

The FCT is situated at the Ports of Auckland (POAL), New Zealand. The modal split indicates that the main flows of containers go to and come from the landside, and therefore it can be categorised as an import-export terminal. A simulation model of the FCT developed by TBA Group is used to provide a proof-of-concept of the BMC.

### 4.1.1 Layout and equipment

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) of approximately 300 and 600 meter in length, respectively. There are two separate stacks dedicated to either 20ft or 40ft reefer (refrigerated) containers. In the other stacks, empty and full 20ft and 40ft containers are mixed. In Figure 4.1, an aerial view of the FCT is shown including the various container stacks and modes of transport served at the terminal.

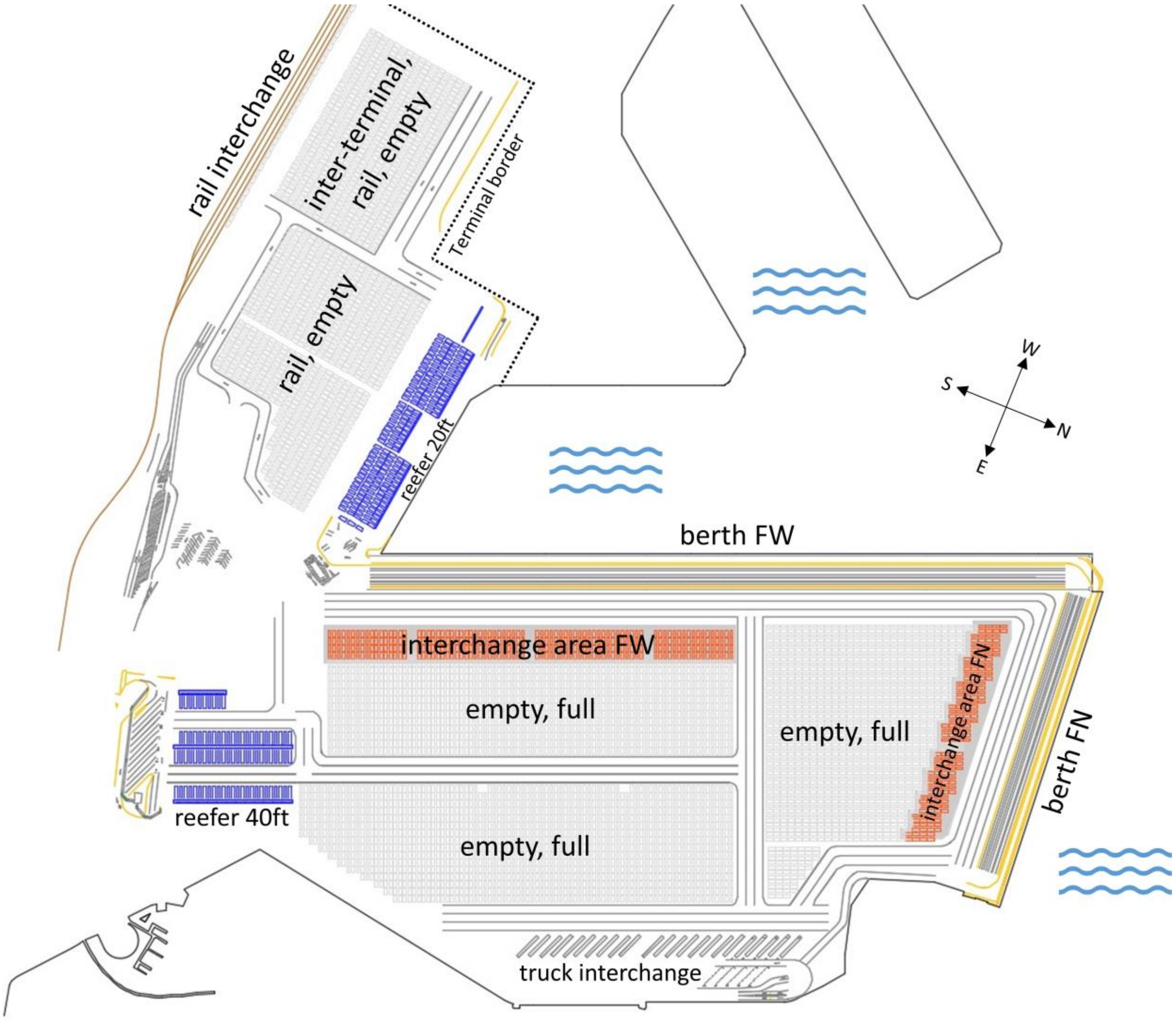


*Figure 4.1: Layout of the Fergusson Container Terminal indicating the designated areas of truck, rail, and stacks of the different types of containers.*

In the far southwest corner of the terminal, there is an area dedicated to inter-terminal, rail, and empty containers. Both the inter-terminal and rail containers can be either full or empty. Inter-terminal containers are containers which are exchanged with the adjacent terminals situated west of the FCT at the POAL. The interchange of rail containers between trains and the stacks, and the exchange of inter-terminal contains between terminals are out of scope of this research.

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

- *quay cranes (QC)*: perform single and twin lifts, but only the QCs on the FN quay can perform tandem lifts. All QCs perform single cycles (meaning that within one cycle either one or multiple containers are either loaded or unloaded). Hatch covers are stored in the backreach and all QCs work within their rail gauge. The QCs at the FN and FW berth have four and three transfer lanes, respectively.
- *manned straddle carriers (mSCs)*: transport containers to and from the quay cranes from and to the interchange areas, rail, inter-terminal, empty or 20ft reefer stacks. Manned straddle carriers can twin-lift 20ft containers.
- *automated straddle carriers (autoSCs)*: transport containers to and from the interchange area to and from the (reefer) stack or truck interchange. AutoSCs also perform reshuffles in both empty, full, and 40ft reefer stacks.

Since this terminal uses a combination of mSCs and autoSCs which are not operating across the entire terminal, an overview of the operating areas of the equipment at the FCT is indicated in Figure 4.2. Furthermore, the operation of mSCs and autoSCs is decoupled, i.e. no direct interaction of equipment is required to exchange containers. Therefore, interchange areas are used both by mSCs and autoSCs to exchange containers which form the boundaries between their operating areas. Trucks and trains are considered external equipment and their operating areas are therefore excluded from the figure.

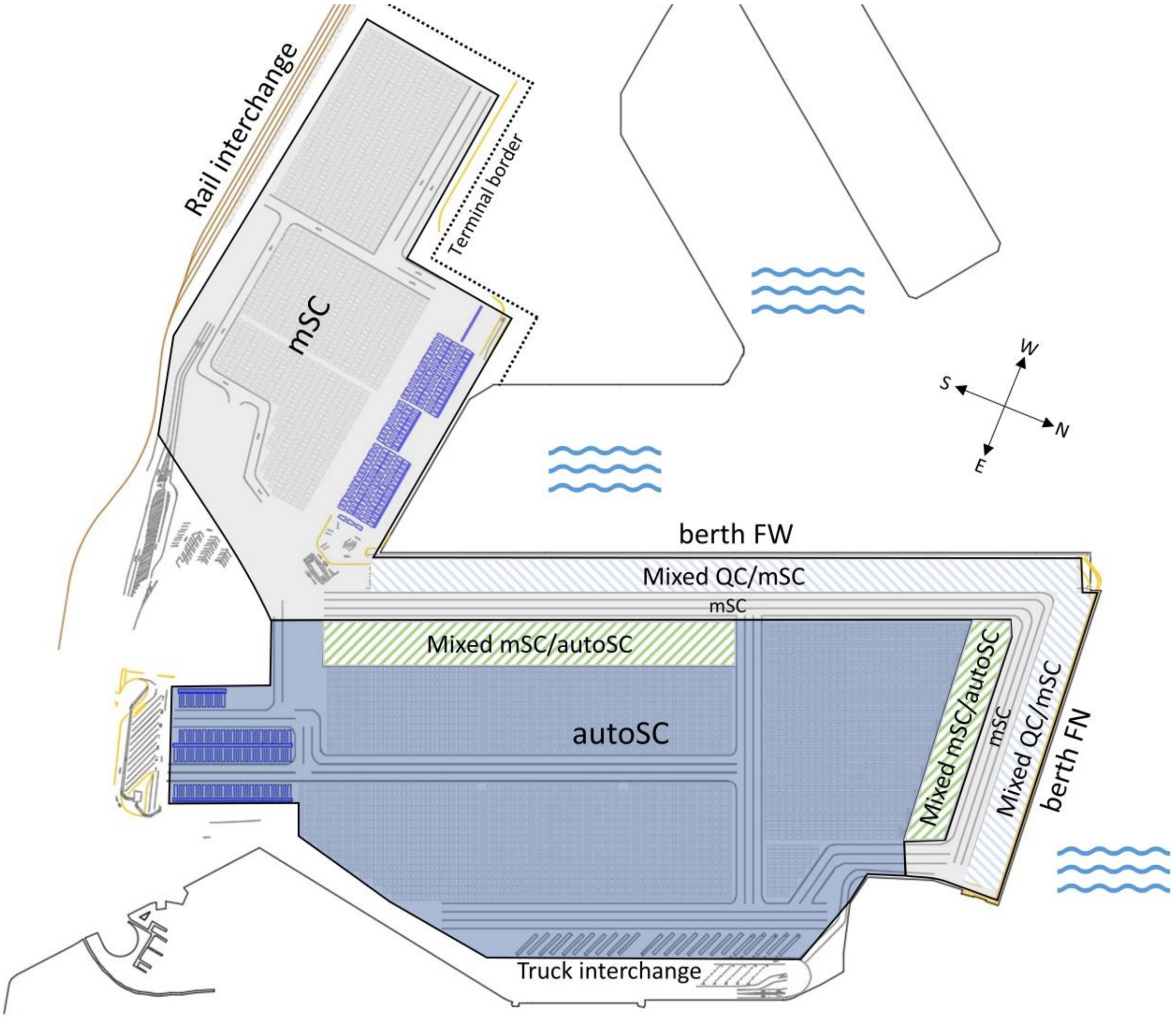


*Figure 4.2: Operating areas of the different types of equipment present at the Fergusson Container Terminal. mSC: manned straddle carrier, autoSC: automated straddle carrier, QC: quay crane.*

Trucks are served by autoSCs at the truck interchange. A single truck can deliver, pick up, or pick up and deliver one or multiple containers during one visit, up to a maximum of 2 TEU. Due to the large variety in shapes and sizes of the trucks present in New Zealand, autoSCs are not allowed to position containers on the trucks. As soon as an autoSC arrives with a container at the truck interchange, a tele-operator takes over control to accurately position the container on the truck. Four tele-operators are available at the truck interchange to perform these tasks. AutoSCs are allowed to grab containers from the trucks without interference of the tele-operators.

### 4.1.2 Simulation model

To apply the proposed methodology of the BMC to the FCT, a simulation model is used. A simulation model is chosen given the complexity of the processes occurring simultaneously at an MCT (Caballini & Sacone, 2015; Leporis & Králová, 2010; L. Li et al., 2009). Additionally, the flexibility of a simulation model in applying changes to operations and the terminal configuration, and the possibility of evaluation of performance of the terminal under various (workload) conditions make the simulation model a suitable approach (Caballini & Sacone, 2015; Kulak et al., 2013). It is created by TBA Group in collaboration with the FCT based on a library called Timesquare in the simulation package eM-Plant developed by Tecnomatix. This simulation package uses object-oriented discrete-event simulation.

In this research, a model is considered verified when the model represents a conceptual model, and validated when the model represents reality both within specified limits of accuracy (Schlesinger et al., 1979). Given the importance of the states of all equipment for application of the BMC, the equipment states used in the model of the FCT are verified by manual comparison of the description of the state and actual activities performed in the simulation model.

A validation study has been performed on the library of the simulation model on which the FCT is built by a team of experts from Delft University of Technology (Verbraeck, Seck, & Fumarola, 2009). They validated the assumptions of the library and used the techniques of black-box validation and a structured walk-through of the models. The built simulation model of the FCT is again validated by experts from TBA Group and the FCT using time-distance diagrams of vehicle driving behaviour, cycle times of the different types of equipment, and 3D-visualisation of the whole terminal. Furthermore, the behaviour of autoSCs has been validated specifically for this model by comparing experimental performance executed at the FCT and simulation results (Terstegge & De Waal, 2019). Based on the outcomes of the validation steps, it can be concluded that the simulation model is validated.

The verified and validated simulation model of the FCT is used to perform peak-scenario simulations. In this research, peak-scenario simulations consist of simulations of 8 hours in which both a waterside and landside peak in workload have to be handled at the same time under dense yard conditions. The waterside peak is represented by all quay cranes in operation for 8 consecutive hours. The landside peak is represented by using the busiest hour of the week in truck arrivals for 8 consecutive hours. Using a peak-scenario simulation gives an upper bound on the capacity of the terminal modelled which ensures that the terminal is not limited by its design in the absence of delays in operation. Furthermore, bottlenecks become more evident since the design of the terminal is pushed to its limit.

The simulation model already developed by TBA Group is used in which the following important assumptions are present:

- Human resources, except tele-operators, are available for the entire duration of simulation, i.e. personnel availability, shift changes, meal breaks, and other personnel-related delays of operation are excluded.
- Equipment is fully operational for the peak-scenario simulation of 8 hours, i.e. breakdowns of equipment are not modelled.
- Housekeeping moves are performed during off-peak hours and therefore excluded from the model.
- Interaction between QCs when working on the same ship is negligible and therefore the location of the QCs is fixed.
- No reshuffles are required on the vessels.
- QCs work all 8 consecutive hours of the peak-scenario simulation on the same vessel in multiple bays.
- There are no communication delays between the equipment and the TOS.

The assumption is made that a steady state is reached after the first hour of every simulated replication. The first hour is considered as a start-up hour and is therefore not included in the analysis of the results. Furthermore, due to some minor bugs present in the model, not every replication has been successfully simulated for 8 hours and the erroneously simulated hours are deleted. To calculate the statistics of replications of different durations, a weighted average and weighted standard deviation are used in which the weights are the number of correctly simulated hours of the respective replications.

### 4.1.3 Quantification of terminal performance

Based on the output of the simulation model, the performance of the FCT can be quantified. The main goal of the FCT is to maximise its throughput for the given layout. In this research, terminal throughput is defined as the number of billable ISO containers that are loaded on or unloaded from sea-going vessels (excluding landside transport) on a yearly basis. Since a peak-scenario simulation is used and terminal throughput is a direct consequence of equipment productivity, the productivity of the different types of equipment is used to quantify the performance of the FCT. The indicators used to quantify the performance of the terminal are shown in Table 4.1. Since uninterrupted operation is considered, net performance is used.

*Table 4.1: Overview of the performance indicators used for the FCT. [1]net performance is measured during uninterrupted operation. [2]excluding reshuffles and housekeeping moves. [3]measured from the moment the trucker is clear from the grid lane until they are allowed to walk to their truck again.*

| **Performance indicator (all net[1])** | **Units** |
|---|---|
| QC productivity | Boxes/hour |
| mSC productivity[2] | Boxes/hour |
|  | Moves/hour |
| autoSC productivity[2] | Boxes/hour |
| Truck interchange productivity | Boxes/hour |
| Truck handling time[3] | Minutes |

The productivity of QCs is measured in the net number of boxes handled per hour. The number of handled boxes per hour for a QC is defined as the number of boxes that are loaded onto or unloaded from a vessel per hour. Productivity may depend on whether a QC is performing single, twin, tandem, or quad lifts, but it is assumed that the ratio between these lift types corresponds with the specified distribution of lifts (input of the simulation model) when a sufficient number of experiments have been run.

Transport and yard productivity are measured in mSC and autoSC productivity. For both mSC and autoSC productivity, reshuffles and housekeeping moves between stacks which indirectly contribute to terminal performance are excluded. The productivity of mSCs is measured in both the number of boxes handled and the number of moves performed per hour, because mSCs can twin lift containers. For autoSCs, the number of boxes handled per hour equals the number of moves performed per hour since autoSCs can only perform single lifts. Every box that is dropped at its assigned destination counts as a box handled.

Landside productivity is measured in truck interchange productivity and truck handling time. The truck interchange productivity is measured in the total number of boxes handled per hour. For trucks, a box is handled if it is either loaded onto or unloaded from a truck. The truck handling time is important when the handling capacity of the autoSCs exceeds the number of incoming trucks, since the number of boxes handled per hour will not further increase when autoSCs become more efficient. The truck handling time is measured from the moment the trucker indicates that they are clear from the grid lane until they are allowed to walk to their truck again.

### 4.1.4 Terminal performance base scenario

The base scenario settings for a peak simulation are based on the current most efficient configuration for the given layout of the FCT. An overview of these settings is provided in Table 4.2. The vessel workload is unlimited, since it is assumed that in peak-scenario simulation all quay cranes work on the same vessel for 8 hours. The truck interchange workload is based on the busiest hour of the week. Earlier studies of TBA Group at the FCT have shown that global pooling of the mSCs is the most efficient which means that, in this case, all mSCs are assigned to all QCs.

*Table 4.2: An overview of the terminal settings used in the base scenario of the FCT.*

| Simulation model parameter | Value |
|---|---|
| Number of autoSCs 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% |

In this research, the yard density is defined as the percentage of the yard storage capacity used. The yard density is calculated using Equation 8.

$$Yard\ density\ [\%] = \frac{TEU_{yard}}{\sum_{stack} TGS_{stack} \cdot H_{stack}} \tag{8}$$

in which $TEU_{yard}$ represents the total number containers stored in the yard, in TEU; $TGS_{stack}$ represents the number of Twenty-foot Ground Slots (TGS) for each stack at the container terminal studied, dimensionless; and $H_{stack}$ gives the maximum stacking height of the respective stack, in containers. The set of stacks contains the stacking heights of all stacks present in the layout of the FCT.

To determine the yard density in a peak scenario, the number of TEUs in the yard in peak conditions is used. For straddle carrier stacks, an initial yard density higher than 72% is considered dense according to field experts. Therefore, the initial yard density of 74% used in the base scenario is relatively high. A high yard density decreases container accessibility since more reshuffles are required. This results in a decreased efficiency and thus productivity due to a congested yard (De Waal, 2019).

Using the terminal performance quantification presented in Section 4.1.3 along with the settings of the base scenario from Table 4.2, the base scenario performance of the FCT is determined using the simulation model of which the results are shown in Table 4.3. For the results presented in this research, a significance level (α) of 0.05 is used to determine a two-tailed confidence interval.

*Table 4.3: Average performance of the FCT including a two-tailed confidence interval using the base scenario parameters in Table 4.2. [1]net performance is measured during uninterrupted operation. [2]only productive moves are considered.*

| Performance indicator (all net[1]) | Average (α=0.05) | Units |
|---|---|---|
| QC productivity | [redacted] | Boxes/hour |
| mSC productivity[2] | [redacted] | Boxes/hour |
| | [redacted] | Moves/hour |
| autoSC productivity[2] | [redacted] | Boxes/hour |
| Truck interchange productivity | [redacted] | Boxes/hour |
| Truck handling time | [redacted] | Minutes |

## 4.2 Bottleneck classification & detection at the Fergusson Container Terminal

In the case study of the FCT, infrastructural and operational bottlenecks are considered in the application of the BMC. Further details on these types of bottlenecks can be found in Section 3.1. To detect these types of bottlenecks, the shifting bottleneck method is adopted. The generic description of applying the shifting bottleneck method to an MCT can be found in Section 3.2.2.

### 4.2.1 Implementation of the shifting bottleneck method in the simulation model

The shifting bottleneck method has been implemented in the simulation model of the FCT. This simulation model contains a TOS in which a bottleneck detection module is created. A simplified overview of the implemented bottleneck detection module is shown in Figure 4.3. A detailed overview of the underlying methods and tables used in the implementation is shown in Appendix A.

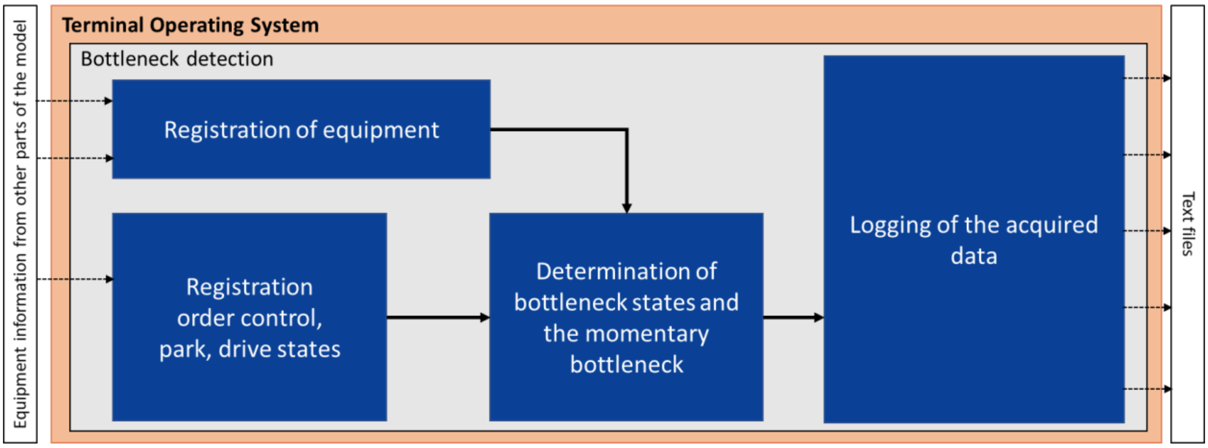


*Figure 4.3: Simplified representation of the implementation of the shifting bottleneck method in the simulation model of the FCT.*

Once the simulation is started, methods external to the TOS module activate the bottleneck detection submodule by starting registration of the equipment according to the current scenario settings. Once the equipment is registered, the current order control, drive, and park state are updated. After this first activation, these states are updated according to the refreshment interval defined in the model. In a collective table containing the registered equipment and their current states, the bottleneck states of all individual equipment are determined including the duration of the respective bottleneck state. The current longest uninterrupted active duration in this collective table gives the momentary bottleneck. For all equipment and states, the changes of states over time are logged in tables and exported to text files at the end of every replication of the respective experiment.

The value of the refreshment interval is a trade-off between simulation speed and accuracy. A lower refreshment interval results in higher accuracy but lower simulation speed, and vice versa. The refreshment interval should be as small as possible while still retaining an acceptable simulation speed. According to field experts, a refreshment interval of 0.5 seconds does not significantly decrease the simulation speed. To determine whether the accuracy is sufficient, the average duration of all park, drive, bottleneck, and order control states is compared to the set refreshment interval. The average duration of all states is 99.47 seconds based on more than 1.6 million states in 196 simulated hours. Thus, the refreshment is 0.50% of the average state duration. Therefore, the refreshment interval ($r$) used in Equations (1) and (2) is set to 0.5 seconds.

The text files of the simulation model are used as input to a Python script. Using the open-source libraries Pandas and Numpy, the sole and shifting bottleneck times for all equipment present in the scenario are determined and visualised using Equations (1)-(6) from Section 3.2.2. The Python code can be found in Appendix B.

As explained in Section 3.2.2, the bottleneck state is determined based on the parking state and a combination of the drive and order control state. Overviews of the parking, drive, and order control states of the mSCs and autoSCs are shown in Table 4.4, Table 4.5, and Table 4.6, respectively. Due to the assumption that the QCs have a fixed location in the simulation model, they only have an order control state and no drive state. An overview of the order control states of the QCs is provided in Table 4.7. A detailed description of these states is provided in Appendix C.

*Table 4.4: An overview of the park states of both mSCs and autoSCs.*

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

*Table 4.5: An overview of the drive states of both mSCs and autoSCs.*

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

*Table 4.6: An overview of the order control states of both mSCs and autoSCs. The combination with the drive states (see Table 4.5) in the last column determines whether the order control state is defined as active or inactive.*

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

*Table 4.7: 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 |

To illustrate the procedure of determining the bottleneck state, an example is given of an mSC which is assigned to collect a container discharged from a vessel at a QC (its order). The mSC is travelling to the QC, therefore its parking state is “busy”. Since the mSC is driving without containers, its order control state is “driving empty”. To determine whether this current state is active or inactive, its drive state is required. The mSC is currently driving and not hindered by other traffic, resulting in the drive state “driving”. Consequently, the combination of the drive and order control state results in an active bottleneck state. The evaluation of the bottleneck state starts again after a time interval defined by the refreshment interval. This procedure is the same for autoSCs and significantly simpler for QCs, since these only have an order control state.

Detection of the average bottleneck can be performed on two levels of detail:

- Individual equipment
- Aggregated by type of equipment

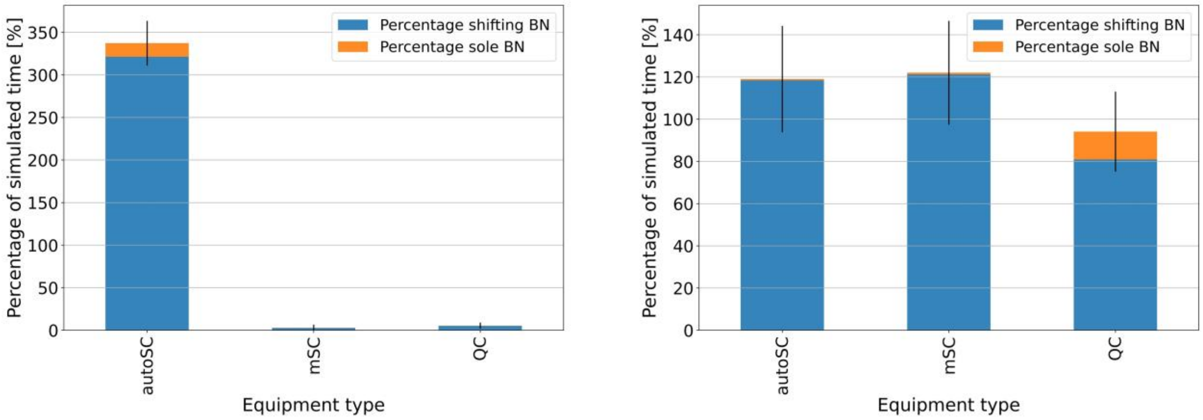
Since there is much interaction between equipment at the FCT, it is assumed that bottlenecks will often shift between equipment. Therefore, the shifting bottleneck method is applied to detect bottlenecks aggregated by type of equipment.

### 4.2.2 Verification of bottleneck detection

Verification of implementation of the shifting bottleneck method is performed by varying the definitions of the bottleneck states and parameters of the FCT (terminal parameters). The terminal parameters consist of the number of equipment and the workload.

The definition of the combination of the order control states with the drive state “waiting for equipment of the same type” is considered active to represent traffic congestion which prevalent in literature as shown in Table 2.3. Due to the large amount of interaction between equipment, this definition is assumed paramount in detecting bottlenecks at the FCT. When changing the definition of this combination to inactive, the hypothesis is that quay cranes become the average bottleneck more often compared to the base scenario since the active durations of mSCs and autoSCs are interrupted more often. To verify this setting, the results of bottleneck detection are compared and shown in Figure 4.4. The sum of the percentage of simulated time of the shifting and sole bottleneck is referred to as average bottleneck percentage.

Comparing Figure 4.4a (197 simulated hours) and Figure 4.4b (100 simulated hours), it can be seen that due to the change of this definition the results change significantly. In Figure 4.4a, the autoSCs are clearly the bottleneck. However, in Figure 4.4b, all confidence intervals overlap, and it cannot be ascertained which type of equipment is the bottleneck. The change between these scenarios is caused by the interruption of the active bottleneck state duration due to waiting on another autoSC. Based on these results, the hypothesis is confirmed, and an important part of the bottleneck state definitions is verified. Furthermore, the conclusions can be drawn that there is a lot of interaction between the autoSCs, and the shifting bottleneck method is very sensitive to the definition of (combinations of) states as either active or inactive.

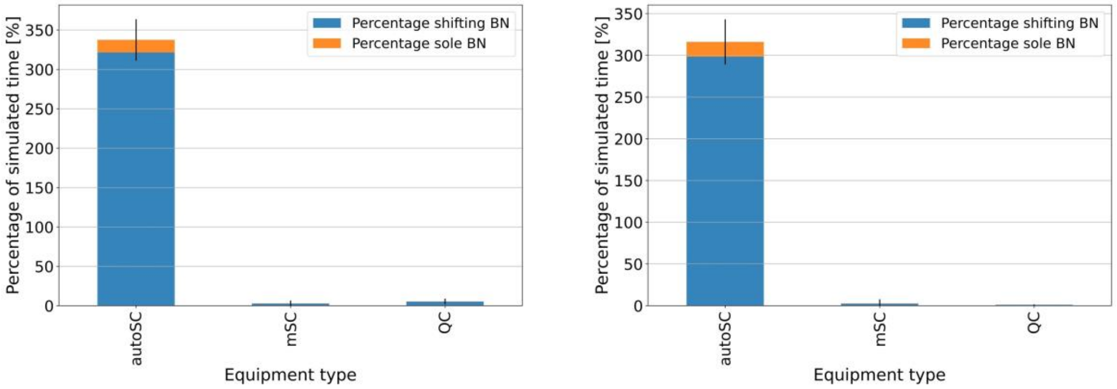


(a) Drive state "Waiting for equipment of the same type" in combination with some order control states *active* (base scenario)

(b) Drive state "Waiting for equipment of the same type" in combination with all order control states *inactive*

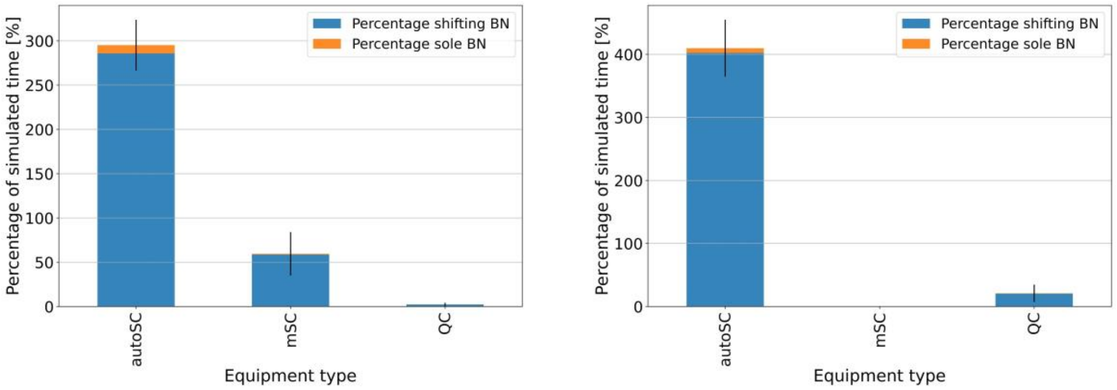
*Figure 4.4: Results of applying the shifting bottleneck method to the FCT by varying method parameters (α=0.05). BN: bottleneck*

Terminal parameters are also varied to verify the implementation of the shifting bottleneck method. Extreme values of the terminal parameters are chosen since it is expected that this causes larger differences in bottleneck detection results, making formulation of hypotheses and comparison of scenarios easier. An overview of the results of bottleneck detection by varying the terminal parameters is shown in Figure 4.5. For all scenarios, a refreshment interval of 0.5 seconds is used. In Figure 4.5a to Figure 4.5f, the number of equipment is varied and a constant truck interchange workload of 81 boxes per hour is used. In Figure 4.5g, the truck interchange workload is reduced to 8 boxes per hour. Consequently, the workload of the autoSCs is reduced. An overview of the terminal parameter verification results is provided in Table 4.8.



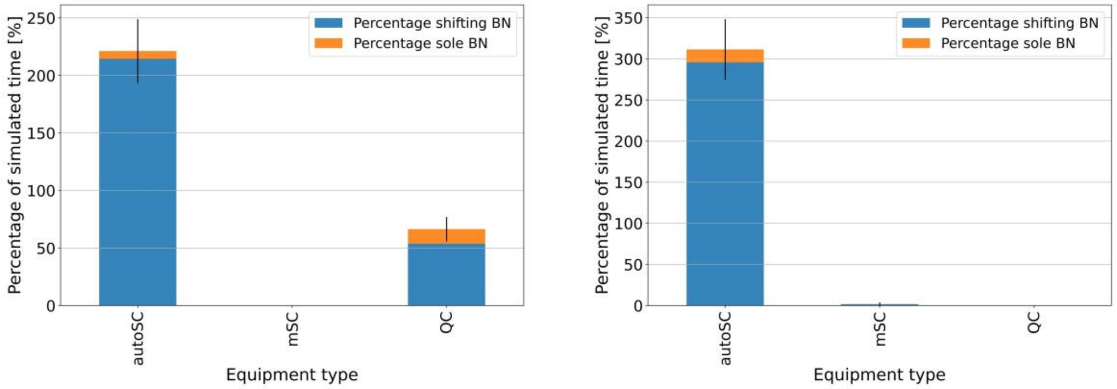
(a) 30 autoSCs, 24 mSCs, 6 QCs (base scenario)

(b) 13 autoSCs, 24 mSCs, 6 QCs



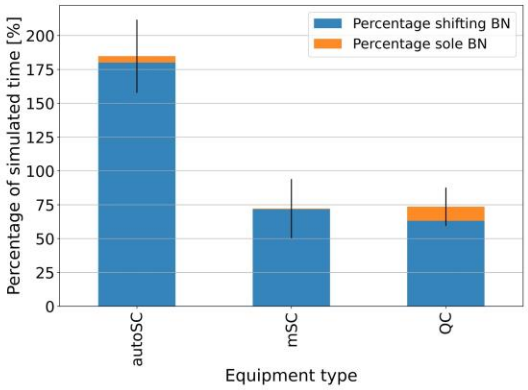
(c) 30 autoSCs, 10 mSCs, 6 QCs

(d) 30 autoSCs, 30 mSCs, 6 QCs



(e) 30 autoSCs, 24 mSCs, 2 QCs

(f) 30 autoSCs, 24 mSCs, 6 super QCs*



(g) 30 autoSCs, 24 mSCs, 6 QCs, truck interchange workload 8 boxes/hour**

*Figure 4.5: Results of applying the shifting bottleneck method to the FCT by varying terminal parameters (α=0.05). *super QCs have improved technical specifications **all scenarios except (g) have a truck interchange workload of 81 boxes/hour. BN: bottleneck.*

*Table 4.8: Overview of the results of bottleneck detection verification of terminal parameters corresponding to Figure 4.5.*

| **Verification scenarios (see Figure 4.5)** | **Terminal parameter varied (with respect to the base case)** | **Hypotheses** | **Result** |
|---|---|---|---|
| (a),(b) | Number of autoSCs<br>(a) N/A (base scenario)<br>(b) -17 autoSCs | • Increasing the number of autoSCs decreases the average bottleneck percentage of autoSCs and increases the average bottleneck percentage of mSCs and QCs. | Plausible |
| (a),(c),(d) | Number of mSCs<br>(a) N/A (base scenario)<br>(c) -14 mSCs<br>(d) +6 mSCs | • Increasing the number of mSCs decreases the average bottleneck percentage of mSCs, and vice versa.<br>• Increasing the number of mSCs increases the average bottleneck percentage of QCs. | Confirmed |
| (a),(e),(f) | Number of QCs and QC specifications<br>(a) N/A (base scenario)<br>(e) -4 QCs<br>(f) improved QC specifications | • Decreasing the number of QCs increases the average bottleneck percentage of QCs.<br>• Improving the specifications of QCs decreases the average bottleneck percentage of QCs. | Confirmed |
| (a),(g) | Truck workload<br>(a) N/A (base scenario)<br>(g) -73 boxes/hour | • Decreasing the truck interchange workload reduces the average bottleneck percentage of autoSCs and increases the average bottleneck percentage of mSCs and QCs. | Confirmed |

As can be seen in Table 4.8, all hypotheses except the first are confirmed by comparing results of the scenarios in Figure 4.5. It was expected that by decreasing the number of autoSCs, the average bottleneck percentage of autoSCs would increase and the average bottleneck percentage of mSCs and QCs would increase, but these changes are not statistically significant as the confidence intervals overlap. A possible reason for this is that the autoSCs are already the average bottleneck to an extent that it cannot increase any further. The average bottleneck percentage of mSCs and QCs increases slightly making this hypothesis more likely. Based on the results of Figure 4.4 and Table 4.8, the implemented shifting bottleneck method in the simulation model of the FCT is considered verified.

### 4.2.3 Validation of the base scenario

The verified shifting bottleneck method is applied to the FCT using the base scenario parameter values of which the result is shown in Figure 4.6. From this result, it is clear that the autoSCs are the average bottleneck of the terminal. Over the simulated time, on average 0.16 and 3.21 autoSCs are the sole and shifting bottleneck, respectively. Compared to the autoSCs, the average bottleneck percentage of mSCs and QCs is negligible.

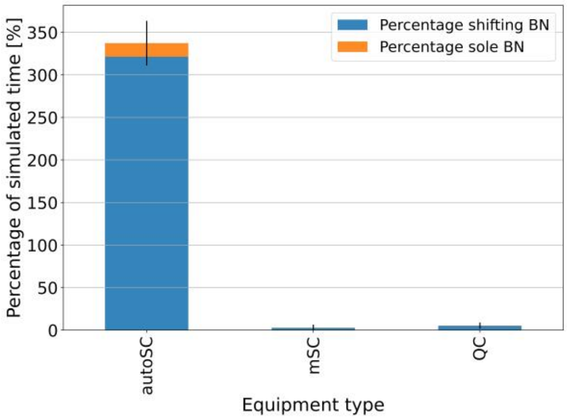


*Figure 4.6: Results aggregated by type of equipment of applying the shifting bottleneck method to the FCT (α=0.05) based on 197 simulated hours using the base scenario parameter values (see Table 4.2). BN: bottleneck.*

Due to the absence of historical data on the bottlenecks of the FCT, the face validity technique is used to validate the implementation of the shifting bottleneck method (Sargent, 2011; Verbraeck et al., 2009). This technique is based on the knowledge and experience from field experts to determine whether the model behaviour and the results are reasonable. The finding that the autoSCs are the average bottleneck is in line with the expectation of field experts. Furthermore, in scientific literature, the amount and technical specifications of yard equipment have also been identified as an infrastructural bottleneck by He et al. (2010) and Ha et al. (2007). Based on these findings, the implemented shifting bottleneck method is considered validated.

The large share of shifting bottlenecks in Figure 4.6 can be explained by applying the shifting bottleneck method to the FCT on an individual equipment level which is shown in Figure 4.7. From Figure 4.6 and Figure 4.7, it can be observed that the momentary bottleneck shifts repeatedly between equipment causing the percentage of shifting bottleneck to be significantly larger than of sole bottlenecks. This observation can be caused by the flexibility of both autoSCs and mSCs in moving across the terminal. Consequently, there is a lot of interaction between the equipment (types), and therefore the active bottleneck state of equipment is likely to be interrupted. This also confirms the assumption that the bottlenecks will often shift between individual equipment, and thus indicates to aggregate equipment by type for bottleneck detection for this case.

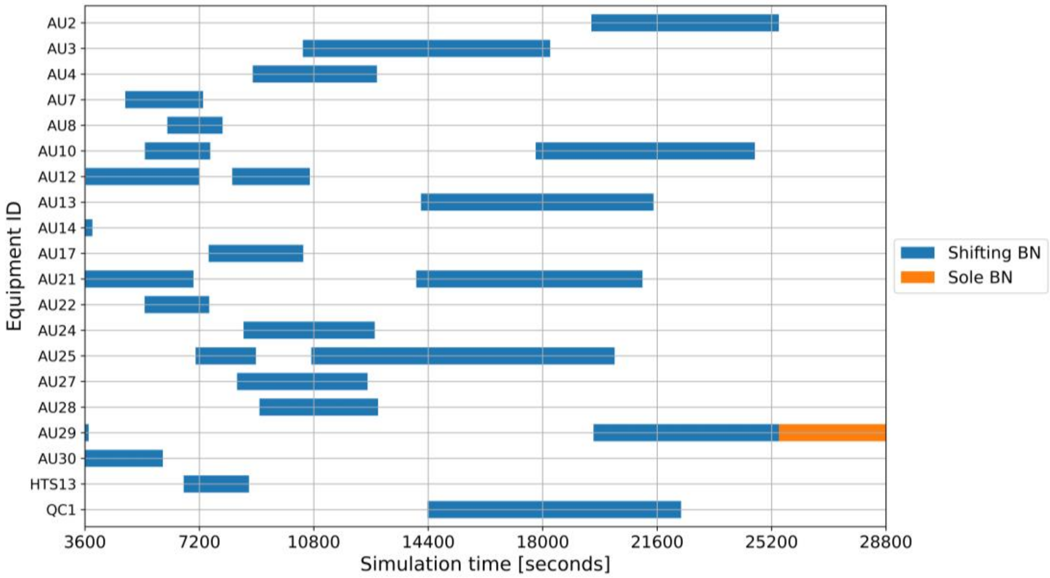


*Figure 4.7: Result of individual equipment over time by applying the shifting bottleneck method to the FCT based on 8 simulated hours using the base scenario parameter values (see Table 4.2). BN: bottleneck, AU: autoSC, HTS: mSC, QC: Quay Crane.*

## 4.3 Bottleneck alleviation at the Fergusson Container Terminal

In the previous section, the shifting bottleneck method is implemented, verified, and validated. AutoSCs are the current bottleneck of the FCT according to the results of applying the shifting bottleneck method. This section focusses on alleviating this bottleneck by applying an empirical approach, as explained in Section 3.3.

### 4.3.1 Bottleneck shiftiness measure

The bottleneck shiftiness measure, which is explained in more detail in Section 3.3.1, is used to determine whether the alleviation measures should apply to individual equipment or a type of equipment (autoSCs, mSCs, and QCs). A value close to 0 indicates a unique bottleneck while a value close 1 indicates that all equipment have an equal probability of being the bottleneck.

Based on the results of the shifting bottleneck method for the base scenario, the bottleneck shiftiness measure is calculated using Equation (7) (see Section 3.3.1) both for individual equipment and the equipment types. The results in Table 4.9 show that the bottleneck shiftiness measure of equipment types is significantly closer to 0. This means that the autoSCs as an equipment type are almost the unique bottleneck. A reason for this is the high percentage of shifting bottlenecks for autoSCs, which can also be observed in Figure 4.6. Based on these results, the alleviation measures should apply to all autoSCs rather than individual autoSCs to efficiently alleviate this bottleneck.

*Table 4.9: Average bottleneck shiftiness measure values including a two-tailed confidence interval for the base scenario of individual equipment and equipment types.*

| Scenario | Average bottleneck shiftiness measure of individual equipment (α=0.05) | Average bottleneck shiftiness measure of equipment type (α=0.05) |
|---|---|---|
| Base | 0.63±0.05 | 0.04±0.03 |

### 4.3.2 Cause of the detected bottleneck

To determine the cause of the detected bottleneck, the time spent in both the order control and drive states of autoSCs is analysed in more detail. The results of this analysis are shown in Table 4.10 and Table 4.11 for the order control and drive states, respectively.

From Table 4.10, it can be observed that the largest share of simulated time (69%) is spent driving. As the majority of time is spent in this state, it is thus logical to focus on reducing the time spent in this state since it is most likely to have the biggest impact on the productivity of autoSCs. Therefore, to increase the productivity of the autoSCs, alleviation measures are focussed on reducing the driving time.

Since the largest share of time is spent driving, analysis of the drive states (see Table 4.11) might provide more detail on the cause of the bottleneck. The driving engine is idle whenever it is not driving, but the autoSC can be grabbing or dropping containers for instance. Table 4.11 shows that most time is spent driving and that waiting on other equipment (congestion) only takes a small share of the time available.

Field experts explain that the speed of driving of autoSCs used at the FCT is relatively slow compared to other types of equipment and consequently a large share of time is spent driving. This is confirmed in scientific literature where the technical specifications of yard equipment are also identified as a potential bottleneck (Ha et al., 2007). Therefore, slow driving is considered as the cause that autoSCs are the bottleneck. By reducing the time spent driving, more time is available to complete orders increasing the productivity of the autoSCs.

*Table 4.10: Analysis of the average time spent in the order control states of the autoSCs including a two-tailed confidence interval based on 197 simulated hours. The states in which the largest percentage of simulated time is spent are shaded and have bold borders.*

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

*Table 4.11: Analysis of the average time spent in the drive states of the autoSCs including a two-tailed confidence interval based on 197 simulated hours. The state in which the largest percentage of simulated time is spent is shaded and has bold borders.*

| **Drive state** | **Equipment type** | **Average percentage of simulated time spent (α=0.05)** |
|---|---|---|
| Driving | autoSC | 55.45±0.35% |
| Idle driving engine | autoSC | 32.09±0.39% |
| Waiting due to equipment of the same type | autoSC | 12.28±0.55% |
| Waiting due to equipment of another type | autoSC | 0.18±0.01% |

### 4.3.3 Implementation of alleviation measures

Knowledge from field experts in combination with findings from scientific literature are used to determine suitable alleviation measures to reduce the driving time by autoSCs. In literature, the measure to change the amount or type of equipment is suggested. However, since it is expected by field experts that this will cause more congestion of autoSCs, the suggested measures focus on increasing the technical specifications of the autoSCs. The following three alleviation measures are suggested:

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

Due to the large amount of interaction and dependencies between the different terminal components, it is not known which measure will result in the largest performance improvement. Therefore, the measures are implemented in separate scenarios and the performance is evaluated according to the indicators specified in Section 4.1.3. The results are indexed based on the performance of the base scenario (197 simulated hours) and presented in Table 4.12. The results of the implemented alleviation measures 1, 2, and 3 are based on 119, 120, and 160 simulated hours, respectively.

*Table 4.12: An overview of the 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 & 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 |
| autoSC 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 |

In this case study, an alleviation measure is selected based on the highest productivity improvement. Table 4.12 shows that increasing the maximum allowed curve speed results in a performance improvement of 2 to 6% for the different performance indicators. For every performance indicator, this measure shows the largest performance improvement. Therefore, the bottleneck is best alleviated by increasing the maximum allowed curve speed of autoSCs by 20%.

## 4.4 Discussion

The next bottleneck mitigation cycle starts by, again, performing bottleneck detection on the scenario with the increased maximum allowed curve speed of which the results are shown in Figure 4.8. From this figure, it can be seen that autoSCs are still the bottleneck of the FCT. Comparing Figure 4.8 to Figure 4.6 shows that although the average bottleneck percentages of the QCs and mSCs have increased compared to the base scenario, the increase is not statistically significant since the confidence intervals overlap. The average bottleneck percentage for autoSCs has increased by applying the alleviation measures, but also for the autoSCs this change is not statistically significant.

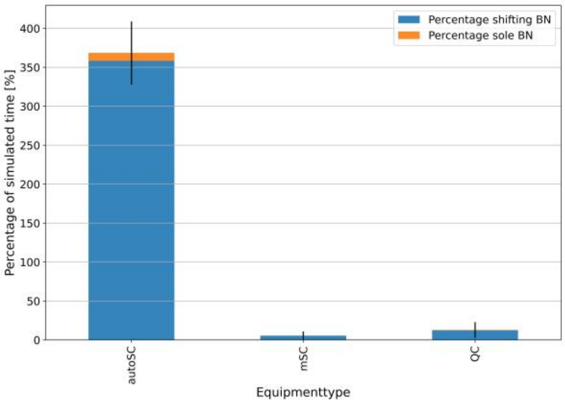


*Figure 4.8: Result of applying the shifting bottleneck method to the scenario of the FCT in which the parameters of the base scenario (see Table 4.2) are used and the maximum allowed curve speed is increased by 20% (111 simulated hours).*

To further improve the performance of the terminal, again alleviation measures should be applied to alleviate the autoSC bottleneck. The BMC is continued until the capacities of the different types of equipment are equal and the whole terminal has the same capacity. At that stage, it would be interesting to investigate whether alleviation measures specific to individual equipment could improve the performance even more until all equipment at the terminal has the same capacity.

The results of especially bottleneck detection show large confidence intervals even after more than 100 simulated hours. This is most likely the result of the variety and complexity of operations at MCTs caused by simulating the entire terminal containing 60 pieces of interacting equipment and several container flows. It can be concluded that both for the results of bottleneck detection and alleviation, more simulations are required to increase the accuracy.

Furthermore, it is important to note that the accuracy of the results of application of the BMC depends entirely on the quality of the simulation model. The assumptions made in the simulation model are implicitly included in application of the BMC. It is of major importance to be aware of the assumptions in the simulation model, as these could possibly prevent the detection or alleviation of an underlying bottleneck.

A limitation of the current application of the shifting bottleneck method is that it detects which equipment type is the bottleneck but does not provide the cause of the bottleneck. The current approach to identify the cause of the bottleneck has limitations in the sense that not all causes can be directly identified based on the information spent in each state. The reason for this is that the time spent in the states is the result of all operations at the container terminal which makes it difficult to pinpoint a cause for a large share of time spent in a state. For instance, the large share of driving times observed for the autoSCs could also have been caused by an inefficient layout of the terminal or inefficient assignment of orders by the TOS resulting in large driving distances. Future research could focus on expanding the shifting bottleneck method to be able to also determine the cause of the bottleneck detected.

From discussion with field experts, it follows that improving equipment specifications, like the suggested measures used in this research, is usually not possible. Since the aim of this study is to provide a proof of concept of the BMC, future research could focus on performance improvement by applying the BMC and to focus on other measures suggested in scientific literature. Examples of these measures are more efficient allocation of equipment and changes in storage yard space allocation (see also Table 2.8). When pursuing this direction, the selection criteria for alleviation measures can also elaborated by adding criteria like the costs of physical implementation of the measures.

# 5 Conclusions and future research directions

Research specifically focusing on bottlenecks at maritime container terminals (MCTs) is still at an early stage. Scientific studies often primarily focus on a single bottleneck, but it is concluded that this may be ineffective and may produce suboptimal terminal performance. Therefore, this research adds value to scientific literature and practice by introducing and applying the concept of the *bottleneck mitigation cycle* (BMC); a holistic approach to effectively mitigate bottlenecks at MCTs to improve their performance. The bottleneck mitigation cycle 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) to improve its performance.

## 5.1 Main findings

An extensive literature review on bottlenecks at MCTs shows that there is no contemporary and comprehensive classification of bottlenecks at MCTs, and that bottlenecks and their causes are difficult to distinguish. A new structure to classify bottlenecks at MCTs is introduced consisting of *infrastructural*, *operational*, and *managerial* bottlenecks. This classification structure is used to effectively select a bottleneck detection method and to give a structured overview of bottlenecks at MCTs currently identified in scientific literature. It shows that infrastructural and operational bottlenecks occur throughout the transport chain, while managerial bottlenecks are mainly found at the landside. Because information about managerial bottlenecks is not available, this research focusses on infrastructural and operational bottlenecks in the application of the BMC to the FCT.

The potential of different methods to detect infrastructural and operational bottlenecks at MCTs is evaluated based on a synthesis of various methods available in literature including not only MCTs but also other types of terminals and production networks. The shifting bottleneck method is selected based on its high accuracy and its ability to detect momentary bottlenecks. However, since this method is not yet applied to MCTs, new generic definitions for active and inactive states of equipment have been formulated to determine the bottleneck based on the combination of the parking, drive, and order control states of every equipment. These definitions have been successfully verified and used to detect both momentary and long-term bottlenecks using a simulation model of the FCT.

Applying the verified and validated shifting bottleneck method to detect equipment-related bottlenecks at the FCT shows that the outcome of the shifting bottleneck method is very sensitive with respect 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. This is expected in general at MCTs given the large amount of equipment and the degree of interaction. In contrast to studies in literature which indicate that quay cranes are often a bottleneck at MCTs, the automated straddle carriers are identified as the current infrastructural bottleneck at the FCT.

In scientific literature, there is no straightforward way to determine 'the most suitable or best' alleviation measure for the detected bottleneck at an MCT. Interaction between bottlenecks and the fact that not one MCT is the same make it particularly complex to use literature to quantitatively assess the potential of an alleviation measure. Since the often-adopted trial-and-error approach is time-consuming, an empirical approach is used based on the knowledge of field experts to determine suitable measures to alleviate the detected bottleneck.

The results of bottleneck detection combined with the bottleneck shiftiness measure are used to determine that alleviation measures should apply to all automated straddle carriers. The cause of the detected bottleneck is identified by performing an analysis of the time spent in the respective states of the different equipment to determine suitable alleviation measures in consultation with field experts. From this analysis follows that slow driving is the cause that autoSCs have become the bottleneck. Despite that the analysis of the time spent in the different states might not reveal all causes of the bottleneck and that identifying suitable alleviation measures is time-consuming, this research shows that the resulting alleviation measures are effective in mitigating the effect of bottlenecks and improving the performance of the FCT.

To complete the BMC, three alleviation measures are implemented for automated straddle carriers: 20% increase of acceleration and deceleration, 20% increase of maximum curve speed, and 20% increase of maximum speed on straight sections. The measures are evaluated by analysing the improvement of a set of performance indicators of the FCT shown in Table 5.1. Improving the maximum allowed curve speed for automated straddle carriers by 20% results in the largest performance improvement. Based on these results, it can be concluded that the BMC can be used to improve the performance of the FCT with significant improvement ranging from 2% to 6% for the different performance indicators on average.

*Table 5.1: Results of improving the maximum allowed curve speed for automated straddle carriers by 20% on the performance indicators of the FCT based on 197 simulated hours.*

| Performance indicator | Average improvement | Units |
|---|---|---|
| QC productivity | +4.07% | Boxes/hour |
| mSC productivity | +3.32% | Boxes/hour |
|  | +3.35% | Moves/hour |
| autoSC productivity | +1.96% | Boxes/hour |
| Truck interchange productivity | +4.05% | Boxes/hour |
| Truck handling time | +5.52% | Minutes |

Since the simulation model of the FCT contains relevant software components of an MCT and the communication between these, it can be considered a relevant end-to-end environment to demonstrate the concept of the BMC. In combination with the results provided in Table 5.1, it can be concluded that a proof of concept of the BMC is given in this environment and therefore its Technology Readiness Level (TRL) has increased from 1 to 6 with this research.

Because the concept of the BMC is generically formulated, it is expected that the BMC can be applied to other MCTs as well. Furthermore, based on the proof of concept provided by successful application of the BMC to the FCT, it is anticipated that applying the BMC to other terminals will improve their performance. The complexity of applying the BMC to other terminals depends on a variety of factors, like the amount and types of equipment used, and the different types of containers with corresponding storage areas considered.

## 5.2 Future research

To bring the concept of the BMC to practice, several steps still have to be made. A first step to bring the concept of the BMC from TRL 6 to TRL 7-8, is to apply it to an actual operational environment. This operational environment can be an emulated environment in which a virtual MCT in combination with the real control system is used as explained by Boer and Saanen (2012). Using emulation is a meanwhile proven approach which is safe and relatively inexpensive to test and debug software components at a container terminal. Once the concept of the BMC has been verified and validated by emulation, the final steps to bring it to practice (TRL 9) would be to successfully operate it at a real MCT and to provide all necessary software support and documentation.

Multiple future research directions can be identified to improve the application of the BMC to MCTs. The concept of the BMC in this research detects average equipment-related bottlenecks. It focuses on long-term improvement of terminal processes under peak conditions. However, it would be interesting to investigate the possibilities of increasing the agility of the terminal to cope with variations in arrival patterns of containers by distinguishing between specific flows of containers across the terminal like deep sea-deep sea and deep sea-landside (truck or rail) or by applying the concept of the BMC in real-time.

Distinguishing between flow-specific bottlenecks potentially allows to temporarily increase the performance of the terminal with respect to specific flows of containers. This is especially relevant when irregular workloads are prevalent for instance due to the arrival of large deep-sea vessels or a peak in truck arrivals. However, it should be noted that to show the improvement of MCT performance due to this distinction by applying the BMC, long-term simulations should be used instead of the peak-scenario simulation model of this research. The results should be determined per hour and not averaged over all hours of the day. The reason for this is that arrival patterns are paramount while in peak-scenario simulation models these are often assumed constant.

Application of the BMC in real-time can potentially also improve the agility of an MCT. Moreover, given the dynamism of bottlenecks both in space and time, it is expected that applying the BMC in real-time can improve the performance of MCTs even more compared to the longer time horizon considered in this research. Although the shifting bottleneck method can detect bottlenecks in real-time, the empirical approach is not yet able to alleviate bottlenecks in real-time. Therefore, to apply the BMC in real-time, a more efficient (scientific) bottleneck alleviation approach is required.

An important challenge that has to be overcome to alleviate bottlenecks in real-time is the fact that not one container terminal is the same. As a result, the implementation of the same measure at a different terminal might have significantly different effects. Therefore, to implement effective measures, the alleviation method should be able to learn from (historical) results of implemented measures at the specific terminal to determine effective measures for bottlenecks in the present. In addition, as the steps of the bottleneck mitigation cycle interact, so do the bottlenecks.

For this purpose, a machine learning model seems an interesting approach. The historical data of implemented measures could be used as a start to train the machine learning model on. After that, an emulation environment could be used to determine the effect of measures which are often applied in practice to alleviate different types of bottlenecks at the terminal studied. An emulation environment is preferred as it is close to reality. Although implementation of the machine learning model requires manual input from field experts at the start, it will become more automated over time as more alleviation measures and corresponding data become available.

However, since applying the BMC in real-time will mainly focus on operational bottlenecks, attention also has to be paid to average bottlenecks for long-term improvement of the terminal. Alleviation of infrastructural bottlenecks can for instance mean that the layout of the terminal should be changed. Therefore, when this research direction is pursued, it would be interesting to investigate the relation between the occurrence of momentary and average bottlenecks. Furthermore, research on interactions between bottlenecks should be included because this could significantly improve the effect and selection of suitable alleviation measures to improve the performance of the terminal.

After successful implementation of the BMC in real-time, the next step would be to use a digital twin of the MCT studied to determine the bottlenecks that would occur in the future. These future bottlenecks can then be prevented from arising by taking measures in the present. Nevertheless, a significant amount of research is still to be conducted to create a digital twin of a terminal, to apply the BMC to a digital twin of the terminal as well as to determine the effect of alleviation measures on future bottlenecks before these have actually arisen.

The BMC could also be improved by considering location-related bottlenecks next to the equipment-related bottlenecks considered in this research. The literature review of this research has shown that especially critical locations, like the layout of the storage yard or transfer points at quay cranes, would be interesting to investigate with this method. A possible approach to detect location-related bottlenecks is to divide the terminal layout in discrete locations, determine the states of the locations based on their occupation by containers or equipment, and define whether these are active or inactive. When these definitions are formulated, the principles of the shifting bottleneck method can be applied to detect location-related bottlenecks. However, it has to be determined whether the duration of the active states of equipment and locations can be analysed together or separately. Since location-related bottlenecks are mainly of the infrastructural type, the long-term time horizon considered in this research might be a valid starting point. On the other hand, with application in real-time, certain locations like busy roads or stacks in the storage yard can be detected and orders can possibly be assigned differently.

In this research, the BMC is used to improve the performance of MCTs. However, especially for quiet (off-peak) hours, the hypothesis is suggested that the BMC can potentially also be used to reduce the costs of the terminal while maintaining the same performance. Firstly, the bottleneck of the terminal should be detected and its accompanying performance determined. Secondly, the superfluous performance of the non-bottlenecks can be determined by subtracting the bottleneck performance. The bottleneck alleviation step could then focus on reducing the performance of the non-bottlenecks to match it with the performance of the detected bottleneck. Costs could then possibly be saved by reducing for instance the amount of equipment or personnel currently in use for the non-bottlenecks. The line of reasoning behind this is that terminal performance is limited by the performance of the bottleneck. Future research could focus on confirming this hypothesis.

Lastly, future research could consider including managerial bottlenecks in the application of the BMC. However, the detection and alleviation approaches used in this research are expected to be unsuitable for managerial bottlenecks. The information on container terminal operations of one terminal alone is not sufficient. A broader perspective needs to be adopted to identify the information flows and contractual commitments between other relevant parties of the supply chain, like shipping lines, truck operators, train operators, and federal institutions. If information flows and contractual commitments between the relevant parties are known, the focus could be put on the terminal studied again to determine their effect on and the bottleneck caused in terminal operations.

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# Appendix A. Implementation of bottleneck detection in Timesquare

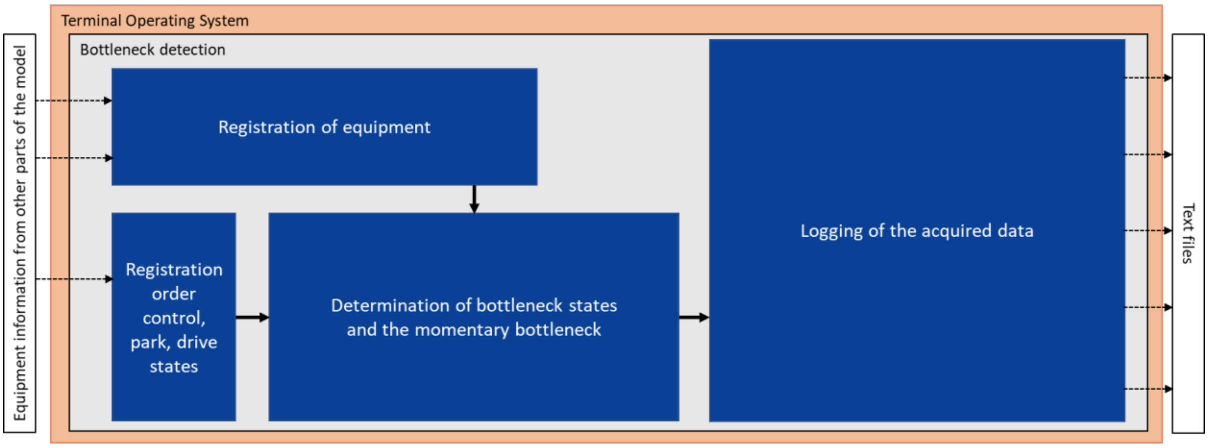

*Figure A.1: Schematic representation of the implementation of the shifting bottleneck method in the simulation model of the FCT.*

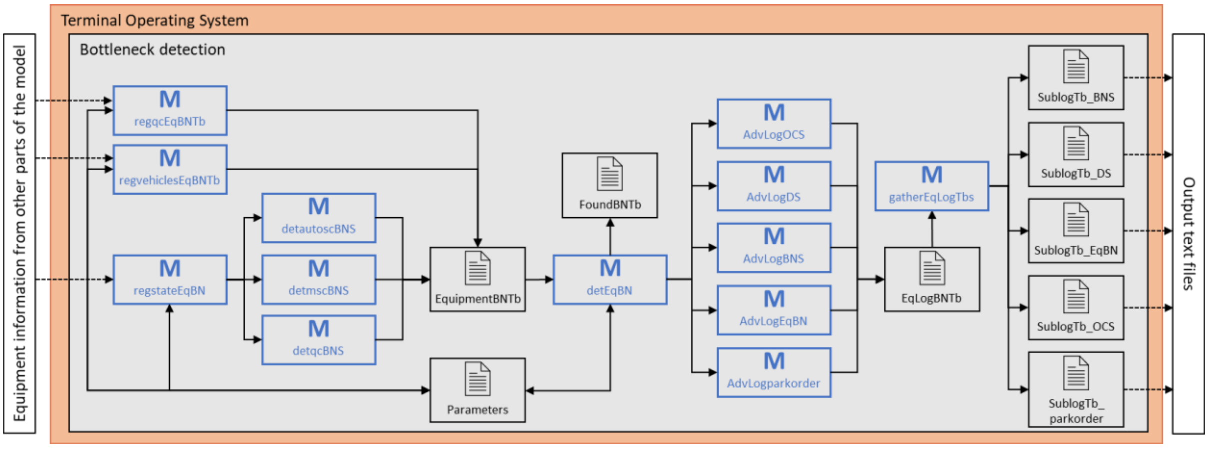

*Figure A.2: Detailed schematic representation of the implementation of the shifting bottleneck method in the simulation model of the Fergusson Container Terminal.*

*Table A.1: Detailed functional description of the methods implemented for bottleneck detection in the simulation model of the Fergusson Container Terminal corresponding to Figure A.2.*

| Method | Functional description |
|---|---|
| regqcEqBNTb | Register mSCs and autoSCs in the EquipmentBNTb |
| regvehiclesEqBNTb | Register QCs in the EquipmentBNTb |
| regstateEqBN | For all equipment, log the parking, the order control, and drive state |
| detautoscBNS | Determine the BN state and duration of the autoSCs |
| detmscBNS | Determine the BN state and duration of the mSCs |
| detqcBNS | Determine the BN state and duration of the QCs |
| detEqBN | Determine the momentary BN |
| AdvLogOCS | Log for all individual equipment their order control state over time |
| AdvLogDS | Log for all individual mSCs and autoSCs their drive state over time |
| AdvLogBNS | Log for all individual equipment their bottleneck state over time |
| AdvLogEqBN | Log for all individual equipment when they are the momentary bottleneck |
| AdvLogparkorder | Log for all individual equipment their parking state over time |
| gatherEqLogTbs | Collect all subtables in the EqLogBNTb to write them to text files |

*Table A.2: Detailed description of the contents of the tables implemented for bottleneck detection in the simulation model of the Fergusson Container Terminal corresponding to Figure A.2.*

| Table | Contents |
|---|---|
| EquipmentBNTb | Table to store the parking, order control, drive, and bottleneck state of all individual equipment including the duration of the bottleneck state. |
| Parameters | Settings specific to the shifting bottleneck method like the refreshment interval and whether it is currently active or not. |
| FoundBNTb | Contains the momentary bottleneck(s) |
| EqLogBNTb | Contains the development of all states for all individual equipment. |
| SublogTb_BNS | Conversion of a part of the EqLogBNTb to a single table containing the changes of the bottleneck state for all individual equipment over time. |
| SublogTb_DS | Conversion of a part of the EqLogBNTb to a single table containing the changes of the drive state for all individual equipment over time. |
| SublogTb_EqBN | Conversion of a part of the EqLogBNTb to a single table containing the changes of the momentary equipment bottleneck for all individual equipment over time. |
| SublogTb_OCS | Conversion of a part of the EqLogBNTb to a single table containing the changes of the order control state for all individual equipment over time. |
| SublogTb_parkorder | Conversion of a part of the EqLogBNTb to a single table containing the changes of the parking state for all individual equipment over time. |

# Appendix B. Python code for analysis of Timesquare text files

### Python script 1: Determination of sole and shifting bottlenecks

```python
#Import required libraries
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from scipy import stats
import os
import re

# Step 1: Import data for analysis

#Input parameters
scenario='v12_30AutoSC_24mSCpool_Basev2_BNA_AU_curve_v_2'
create_indiv_graphs=True

#Change directory location
folder='TQ_textfiles\\'+scenario

#TBA pc settings
os.chdir('C:\\Users\\cvanbattum\\OneDrive - Konecranes Plc\\Graduation assignment Coen van Battum files\\Python results analysis\\'+folder)

#Input parameters for import and processing of textfile
df_parameters=pd.read_csv(scenario+'_v18_input.csv',header=None)
df_parameters.columns=['experimentid','correct_simhrs','first_exp']

#Function to split equipmentid into equipment type and abbrevation string
def eqid_split(x):
    equip_abr = x.equipmentid[0:re.search(r"\d", x.equipmentid).start()]
    equip_num = int(x.equipmentid[re.search(r"\d", x.equipmentid).start():])
    return pd.Series([equip_abr,equip_num])

for i in (df_parameters.index.values):
    experimentid=df_parameters.loc[i,'experimentid']
    correct_simhrs=df_parameters.loc[i,'correct_simhrs']
    first_exp=df_parameters.loc[i,'first_exp']

    #Import data from text files to dataframe specific to the experiment id
    df_EqBN=pd.read_table(str(experimentid)+'_SubLogTb_EqBN.txt')
    df_EqBN.columns=['EqBN','starttime','endtime','duration','equipmentid','equipmenttype']
    df_BNS=pd.read_table(str(experimentid)+'_SubLogTb_BNS.txt')
    df_BNS.columns=['BNS','starttime','endtime','duration','equipmentid', 'equipmenttype']

    # Step 2: Pre-process imported data

    #Check the maximum value of the endtime column
    sim_endtime=3600*correct_simhrs

    #Replace NaN values by the endtime (corresponding to maximum number of simulated hours)
    df_EqBN['endtime']=df_EqBN['endtime'].fillna(sim_endtime)
    df_BNS['endtime']=df_BNS['endtime'].fillna(sim_endtime)

    #Delete all rows that have an endtime >correct_simhrs*3600
    df_EqBN.drop(df_EqBN[df_EqBN.starttime > sim_endtime].index, inplace=True)
    df_BNS.drop(df_BNS[df_BNS.starttime > sim_endtime].index, inplace=True)

    #Delete all rows that have an endtime <3600 (first hour of simulation)
    df_EqBN.drop(df_EqBN[df_EqBN.endtime <= 3600].index, inplace=True)
    df_BNS.drop(df_BNS[df_BNS.endtime <= 3600].index, inplace=True)
```

```

    #Re-index data frame
    df_EqBN.reset_index(drop=True,inplace=True)
    df_BNS.reset_index(drop=True,inplace=True)

    # Determine the unique equipment IDs
    EqID_unique=df_EqBN['equipmentid'].unique()
    # print(EqID_unique)

    #Set starttime of first row of equipmentid to 3600 secondsf
    if (df_EqBN.starttime<3600).any():
        for k in EqID_unique:
            idx=df_EqBN[df_EqBN.equipmentid ==k].index.min()
            df_EqBN.iloc[idx, df_EqBN.columns.get_loc('starttime')]=3600
    if (df_BNS.starttime<3600).any():
        for k in EqID_unique:
            idx=df_BNS[df_BNS.equipmentid ==k].index.min()
            df_BNS.iloc[idx, df_BNS.columns.get_loc('starttime')]=3600

    #Set endtime of last row of equipmentid to sim_endtime
    if (df_EqBN.endtime>sim_endtime).any():
        for k in EqID_unique:
            idx=df_EqBN[df_EqBN.equipmentid ==k].index.max()
            df_EqBN.iloc[idx, df_EqBN.columns.get_loc('endtime')]=sim_endtime
    if (df_BNS.endtime>sim_endtime).any():
        for k in EqID_unique:
            idx=df_BNS[df_BNS.equipmentid ==k].index.max()
            df_BNS.iloc[idx, df_BNS.columns.get_loc('endtime')]=sim_endtime

    #Calculate new durations based on updated dataframe (removed first and uncorrectly simulated hours)
    df_EqBN['duration'] = df_EqBN['endtime']-df_EqBN['starttime']
    df_BNS['duration'] = df_BNS['endtime']-df_BNS['starttime']

    ##Step 3: Analysis of pre-processed data

    ##Step 3.1: Create new dataframes for analysis
    #Create dataframe for calculation of shifting bottleneck times: df_shBN
    df_shBN=pd.DataFrame(columns=['bottleneck','equipmentid','equipmenttype','starttime_BN','endtime_BN','duration_BN'])
    df_shBN=df_shBN.astype({"bottleneck":"object","equipmentid":"object","equipmenttype":"object","starttime_BN":"float64","endtime_BN":"float64","duration_BN":"float64"})

    #Create dataframe for calculation of sole bottleneck times: df_sBN
    df_sBN=pd.DataFrame(columns=['bottleneck','equipmentid','equipmenttype','starttime_BN','endtime_BN','duration_BN'])
    df_sBN=df_shBN.astype({"bottleneck":"object","equipmentid":"object","equipmenttype":"object","starttime_BN":"float64","endtime_BN":"float64","duration_BN":"float64"})

    #Create dataframe for calculation of sole bottleneck times: df_nonBN
    df_nonBN=pd.DataFrame(columns=['bottleneck','equipmentid','equipmenttype','starttime_BN','endtime_BN','duration_BN'])
    df_nonBN=df_nonBN.astype({"bottleneck":"object","equipmentid":"object","equipmenttype":"object","starttime_BN":"float64","endtime_BN":"float64","duration_BN":"float64"})

    #Create dataframe for aggregated sole/shifting/non-BN times per individual vehicle
    df_aggBN=pd.DataFrame(columns=['equipmentid','equipmenttype','Total time sole BN','Total time shifting BN','Total time non-BN','Percentage sole BN','Percentage shifting BN','Percentage non-BN'])
    df_aggBN=df_aggBN.astype({"equipmentid":"object","equipmenttype":"object","Total time sole BN":"float64","Total time shifting BN":"float64","Total time non-BN":"float64","Percentage sole BN":"float64",
```

```
                                            "Percentage shifting BN":"float64","Percentage non-BN":"float64"})

        #Create dataframe for aggregated sole/shifting/non-BN times per vehicle type for all run experiments
        if first_exp:
            df_eqtype_exp=pd.DataFrame(columns=['experimentid','numhrs','qc_sBNp','qc_shBNp','qc_nBNp','autosc_sBNp','autosc_shBNp','autosc_nBNp','msc_sBNp','msc_shBNp','msc_nBNp','BN_shiftiness','BN_shiftiness_eqtype'])
            df_eqtype_exp=df_eqtype_exp.astype({"experimentid":"object","numhrs":"float64","qc_sBNp":"float64","qc_shBNp":"float64","qc_nBNp":"float64",
                                            "autosc_sBNp":"float64","autosc_shBNp":"float64","autosc_nBNp":"float64","msc_sBNp":"float64",
                                            "msc_shBNp":"float64","msc_nBNp":"float64","BN_shiftiness":"float64","BN_shiftiness_eqtype":"float64"})

        ##Step 3.2: Determine the order of occurrence of the bottlenecks

        #Create a copy of the processed EqBN table to extract the order of occurrence of bottlenecks
        df_EqBN_BN=df_EqBN.copy()
        #Sort based on starttime and "bottleneck"
        df_EqBN_BN.sort_values(by=['EqBN','starttime','endtime'],inplace=True,ignore_index=True)
        #Remove "non-bottleneck" rows
        df_EqBN_BN.drop(df_EqBN_BN[df_EqBN_BN.EqBN =='Non-bottleneck'].index, inplace=True)
        #Check for multiple bottlenecks at the same time
        duplicate_check= df_EqBN_BN['starttime'].duplicated().any()
        print(duplicate_check)

        ##Step 3.3: Determine the shifting and sole bottleneck times
        for i in range(df_EqBN_BN.shape[0]):
            if i==0 and df_EqBN_BN.shape[0]==1:
                #First bottleneck and only bottleneck (i=0)
                #Determine the current bottleneck vehicle in the sorted EqBN dataframe
                currBN_vehicle=df_EqBN_BN.iloc[i]['equipmentid']
                currBN_equipmenttype=df_EqBN_BN.iloc[i]['equipmenttype']

                #Determine the current bottleneck endtime from the sorted EqBN table to find the index in the BNS table
                currBN_endtime_EqBN=df_EqBN_BN.iloc[i]['endtime']

                #Determine the current bottleneck index from the BNS table
                currBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==currBN_vehicle) & (df_BNS['endtime']==currBN_endtime_EqBN)].index.min()

                #Determine the starttime of the active BNS of the current bottleneck from the BNS table
                currBN_starttime_ABNS=df_BNS.iloc[currBN_idx_BNS]['starttime']

                #Determine the endtime of the active BNS of the current and next bottleneck from the BNS table
                currBN_endtime_ABNS=df_BNS.iloc[currBN_idx_BNS]['endtime']

                #First bottleneck (i=0): sole bottleneck
                starttime_sBN=currBN_starttime_ABNS
                endtime_sBN=currBN_endtime_ABNS
                duration_sBN=endtime_sBN-starttime_sBN
                #Write values to sole bottleneck dataframe (df_sBN)
                wr_index_sBN=df_sBN.shape[0]
                df_sBN.loc[wr_index_sBN]=['sole',currBN_vehicle,currBN_equipmenttype,starttime_sBN,endtime_sBN,duration_sBN]
            elif i==0:
                #First bottleneck (i=0)
```

```
                #Determine the current and next bottleneck vehicle in the sorted EqBN dataframe
                currBN_vehicle=df_EqBN_BN.iloc[i]['equipmentid']
                currBN_equipmenttype=df_EqBN_BN.iloc[i]['equipmenttype']
                nextBN_vehicle=df_EqBN_BN.iloc[i+1]['equipmentid']

                #Determine the current and next bottleneck endtime from the sorted EqBN table to find the index in the BNS table
                currBN_endtime_EqBN=df_EqBN_BN.iloc[i]['endtime']
                nextBN_endtime_EqBN=df_EqBN_BN.iloc[i+1]['endtime']

                #Determine the current and next bottleneck index from the BNS table
                currBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==currBN_vehicle) & (df_BNS['endtime']==currBN_endtime_EqBN)].index.min()
                nextBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==nextBN_vehicle) & (df_BNS['endtime']==nextBN_endtime_EqBN)].index.min()

                #Determine the starttime of the active BNS of the current and next bottleneck from the BNS table
                currBN_starttime_ABNS=df_BNS.iloc[currBN_idx_BNS]['starttime']
                nextBN_starttime_ABNS=df_BNS.iloc[nextBN_idx_BNS]['starttime']

                #Determine the endtime of the active BNS of the current and next bottleneck from the BNS table
                currBN_endtime_ABNS=df_BNS.iloc[currBN_idx_BNS]['endtime']
                nextBN_endtime_ABNS=df_BNS.iloc[nextBN_idx_BNS]['endtime']

                #First bottleneck (i=0): sole bottleneck
                starttime_sBN=currBN_starttime_ABNS
                endtime_sBN=nextBN_starttime_ABNS
                duration_sBN=endtime_sBN-starttime_sBN
                #Write values to sole bottleneck dataframe (df_sBN)
                wr_index_sBN=df_sBN.shape[0]
                df_sBN.loc[wr_index_sBN]=['sole',currBN_vehicle,currBN_equipmenttype,starttime_sBN,endtime_sBN,duration_sBN]

                #First bottleneck (i=0): shifting bottleneck
                starttime_shBN=nextBN_starttime_ABNS
                endtime_shBN=currBN_endtime_ABNS
                duration_shBN=endtime_shBN-starttime_shBN
                #Write values to shifting bottleneck dataframe (df_shBN)
                wr_index_shBN=df_shBN.shape[0]
                df_shBN.loc[wr_index_shBN]=['shifting',currBN_vehicle,currBN_equipmenttype,starttime_shBN,endtime_shBN,duration_shBN]
            elif i==df_EqBN_BN.shape[0]-1 and df_EqBN_BN.shape[0]!=1:
                #Last bottleneck (i=df_EqBN_BN.shape[0])
                #Determine the previous, current, and next bottleneck vehicle in the sorted EqBN dataframe
                prevBN_vehicle=df_EqBN_BN.iloc[i-1]['equipmentid']
                currBN_vehicle=df_EqBN_BN.iloc[i]['equipmentid']
                currBN_equipmenttype=df_EqBN_BN.iloc[i]['equipmenttype']

                #Determine the previous, current, and next bottleneck endtime from the sorted EqBN table to find the index in the BNS table
                prevBN_endtime_EqBN=df_EqBN_BN.iloc[i-1]['endtime']
                currBN_endtime_EqBN=df_EqBN_BN.iloc[i]['endtime']

                #Determine the previous, current, and next bottleneck index from the BNS table
                prevBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==prevBN_vehicle) & (df_BNS['endtime']==prevBN_endtime_EqBN)].index.min()
                currBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==currBN_vehicle) & (df_BNS['endtime']==currBN_endtime_EqBN)].index.min()

                #Determine the starttime of the active BNS of the previous, current, and next bottleneck from the BNS table
```

```
                currBN_starttime_ABNS=df_BNS.iloc[currBN_idx_BNS]['starttime']

                #Determine the endtime of the active BNS of the previous, current, and next from the BNS table
                prevBN_endtime_ABNS=df_BNS.iloc[prevBN_idx_BNS]['endtime']
                currBN_endtime_ABNS=df_BNS.iloc[currBN_idx_BNS]['endtime']

                #Last bottleneck (i=df_EqBN_BN.shape[0]): shifting bottleneck
                starttime_shBN=currBN_starttime_ABNS
                endtime_shBN=prevBN_endtime_ABNS
                duration_shBN=endtime_shBN-starttime_shBN
                #Write values to shifting bottleneck dataframe (df_shBN)
                wr_index_shBN=df_shBN.shape[0]
                df_shBN.loc[wr_index_shBN]=['shifting',currBN_vehicle,currBN_equipmenttype,starttime_shBN,endtime_shBN,duration_shBN]

                #Last bottleneck (i=df_EqBN_BN.shape[0]): sole bottleneck
                starttime_sBN=prevBN_endtime_ABNS
                endtime_sBN=currBN_endtime_ABNS
                duration_sBN=endtime_sBN-starttime_sBN
                #Write values to sole bottleneck dataframe (df_sBN)
                wr_index_sBN=df_sBN.shape[0]
                df_sBN.loc[wr_index_sBN]=['sole',currBN_vehicle,currBN_equipmenttype,starttime_sBN,endtime_sBN,duration_sBN]
            else:
                #Second to penultimate bottleneck(i=all other cases)
                #Determine the previous, current, and next bottleneck vehicle in the sorted EqBN dataframe
                prevBN_vehicle=df_EqBN_BN.iloc[i-1]['equipmentid']
                currBN_vehicle=df_EqBN_BN.iloc[i]['equipmentid']
                nextBN_vehicle=df_EqBN_BN.iloc[i+1]['equipmentid']
                currBN_equipmenttype=df_EqBN_BN.iloc[i]['equipmenttype']

                #Determine the previous, current, and next bottleneck endtime from the sorted EqBN table to find the index in the BNS table
                prevBN_endtime_EqBN=df_EqBN_BN.iloc[i-1]['endtime']
                currBN_endtime_EqBN=df_EqBN_BN.iloc[i]['endtime']
                nextBN_endtime_EqBN=df_EqBN_BN.iloc[i+1]['endtime']

                #Determine the previous, current, and next bottleneck index from the BNS table
                prevBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==prevBN_vehicle) & (df_BNS['endtime']==prevBN_endtime_EqBN)].index.min()
                currBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==currBN_vehicle) & (df_BNS['endtime']==currBN_endtime_EqBN)].index.min()
                nextBN_idx_BNS=df_BNS[(df_BNS['equipmentid']==nextBN_vehicle) & (df_BNS['endtime']==nextBN_endtime_EqBN)].index.min()

                #Determine the starttime of the active BNS of the previous, current, and next bottleneck from the BNS table
                prevBN_starttime_ABNS=df_BNS.iloc[prevBN_idx_BNS]['starttime']
                currBN_starttime_ABNS=df_BNS.iloc[currBN_idx_BNS]['starttime']
                nextBN_starttime_ABNS=df_BNS.iloc[nextBN_idx_BNS]['starttime']

                #Determine the endtime of the active BNS of the previous, current, and next from the BNS table
                prevBN_endtime_ABNS=df_BNS.iloc[prevBN_idx_BNS]['endtime']
                currBN_endtime_ABNS=df_BNS.iloc[currBN_idx_BNS]['endtime']
                nextBN_endtime_ABNS=df_BNS.iloc[nextBN_idx_BNS]['endtime']

                #Second to penultimate bottleneck(i=all other cases): shifting bottleneck 1
                starttime_shBN1=currBN_starttime_ABNS
                endtime_shBN1=prevBN_endtime_ABNS
                duration_shBN1=endtime_shBN1-starttime_shBN1
                #Write values to shifting bottleneck dataframe (df_shBN)
```

```
                wr_index_shBN1=df_shBN.shape[0]
                df_shBN.loc[wr_index_shBN1]=['shifting',currBN_vehicle,currBN_equipmenttype,starttime_shBN1,endtime_shBN1,duration_shBN1]

                #Second to penultimate bottleneck(i=all other cases): shifting bottleneck 2
                starttime_shBN2=nextBN_starttime_ABNS
                endtime_shBN2=currBN_endtime_ABNS
                if starttime_shBN2 < endtime_shBN1:
                    starttime_shBN2=endtime_shBN1
                duration_shBN2=endtime_shBN2-starttime_shBN2
                #Write values to shifting bottleneck dataframe (df_shBN)
                wr_index_shBN2=df_shBN.shape[0]
                df_shBN.loc[wr_index_shBN2]=['shifting',currBN_vehicle,currBN_equipmenttype,starttime_shBN2,endtime_shBN2,duration_shBN2]

                #Second to penultimate bottleneck(i=all other cases): sole bottleneck
                starttime_sBN=endtime_shBN1
                endtime_sBN=starttime_shBN2
                duration_sBN=endtime_sBN-starttime_sBN
                #Write values to sole bottleneck dataframe (df_sBN)
                wr_index_sBN=df_sBN.shape[0]
                df_sBN.loc[wr_index_sBN]=['sole',currBN_vehicle,currBN_equipmenttype,starttime_sBN,endtime_sBN,duration_sBN]

        ##Step 4: Aggregation of data for plotting

        #Step 4.1.1: Long-term data - individual vehicles
        #Fill in list of unique equipmentids present in the experiment
        df_aggBN['equipmentid']=EqID_unique

        #Find corresponding equipmenttype to equipmentid
        for m in df_aggBN['equipmentid']:
            df_aggBN.loc[df_aggBN['equipmentid']==m,['equipmenttype']]=df_BNS.loc[df_BNS['equipmentid']==m,['equipmenttype']].min()[0]

        #Aggregate sole bottleneck times and set in aggregated dataframe
        df_sBN_agg=df_sBN.copy()
        df_sBN_agg=df_sBN_agg.groupby(['equipmentid']).sum()

        for m in df_aggBN['equipmentid']:
            if m in df_sBN_agg.index.values:
                df_aggBN.loc[df_aggBN['equipmentid']==m,['Total time sole BN']]=df_sBN_agg['duration_BN'][m]
            else:
                df_aggBN.loc[df_aggBN['equipmentid']==m,['Total time sole BN']]=0

        #Aggregate shifting bottleneck times and set in aggregated dataframe
        df_shBN_agg=df_shBN.copy()
        df_shBN_agg=df_shBN_agg.groupby(['equipmentid']).sum()

        for m in df_aggBN['equipmentid']:
            if m in df_shBN_agg.index.values:
                df_aggBN.loc[df_aggBN['equipmentid']==m,['Total time shifting BN']]=df_shBN_agg['duration_BN'][m]
            else:
                df_aggBN.loc[df_aggBN['equipmentid']==m,['Total time shifting BN']]=0

        #Determine simulated time
        sim_time=(correct_simhrs*3600)-3600

        #Determine non-bottleneck time based on sole and shifting bottleneck time
        df_aggBN['Total time non-BN']=sim_time-df_aggBN['Total time sole BN']-df_aggBN['Total time shifting BN']

        #Calculation of percentages in aggregated dataframe
```

```python
        df_aggBN['Percentage sole BN']=round(df_aggBN['Total time sole BN']/sim_time*100,2)
        df_aggBN['Percentage shifting BN']=round(df_aggBN['Total time shifting BN']/sim_time*100,2)
        df_aggBN['Percentage non-BN']=round(df_aggBN['Total time non-BN']/sim_time*100,2)

        ##Step 4.1.2: Long-term data - equipment type
        #Create dataframe for results grouped by equipmenttype
        df_aggBN_eqtype=df_aggBN.groupby(by=['equipmenttype'],as_index=False).sum()

        #Calculate the percentages of sole/shifting/non-bottlenecks per equipmenttype
        df_aggBN_eqtype['Percentage sole BN']=round(df_aggBN_eqtype['Total time sole BN']/(sim_time)*100,2)
        df_aggBN_eqtype['Percentage shifting BN']=round(df_aggBN_eqtype['Total time shifting BN']/(sim_time)*100,2)
        df_aggBN_eqtype['Percentage non-BN']=round(df_aggBN_eqtype['Total time non-BN']/(sim_time)*100,2)

        #For each experiment, write values to new dataframe to determine the confidence intervals
        df_aggBN_eqtype_wi=df_aggBN_eqtype.copy()
        df_aggBN_eqtype_wi.set_index('equipmenttype', inplace=True)

        #Get values from aggregated bottleneck equipmenttype table (df_aggBN_eqtype)
        qc_sBNp=df_aggBN_eqtype_wi.loc['qc','Percentage sole BN']
        autosc_sBNp=df_aggBN_eqtype_wi.loc['autosc','Percentage sole BN']
        sc_sBNp=df_aggBN_eqtype_wi.loc['sc','Percentage sole BN']
        qc_shBNp=df_aggBN_eqtype_wi.loc['qc','Percentage shifting BN']
        autosc_shBNp=df_aggBN_eqtype_wi.loc['autosc','Percentage shifting BN']
        sc_shBNp=df_aggBN_eqtype_wi.loc['sc','Percentage shifting BN']
        qc_nBNp=df_aggBN_eqtype_wi.loc['qc','Percentage non-BN']
        autosc_nBNp=df_aggBN_eqtype_wi.loc['autosc','Percentage non-BN']
        sc_nBNp=df_aggBN_eqtype_wi.loc['sc','Percentage non-BN']

        #Determine the bottleneck shiftiness measure of individual resources for each experiment
        df_aggBN['Percentage sum']=df_aggBN['Percentage sole BN']+df_aggBN['Percentage shifting BN']
        mean=df_aggBN['Percentage sum'].mean()
        stdev=df_aggBN['Percentage sum'].std()
        num_equipment=df_aggBN['Percentage sum'].count()
        BN_shiftiness=round(1-stdev/(mean*np.sqrt(num_equipment)),2)

        #Determine the bottleneck shiftiness measure of the types of resources for each experiment
        df_aggBN_eqtype['Percentage sum']=df_aggBN_eqtype['Percentage sole BN']+df_aggBN_eqtype['Percentage shifting BN']
        mean_eqtype=df_aggBN_eqtype['Percentage sum'].mean()
        stdev_eqtype=df_aggBN_eqtype['Percentage sum'].std()
        num_eqtype=df_aggBN_eqtype['Percentage sum'].count()
        BN_shiftiness_eqtype=round(1-stdev_eqtype/(mean_eqtype*np.sqrt(num_eqtype)),2)

        #Determine the number of correctly simulated hours
        writing_index=df_eqtype_exp.shape[0]
        sim_hrs=correct_simhrs-1
        df_eqtype_exp.loc[writing_index]=[str(experimentid),sim_hrs,qc_sBNp,qc_shBNp,qc_nBNp,autosc_sBNp,autosc_shBNp,autosc_nBNp,sc_sBNp,sc_shBNp,sc_nBNp,BN_shiftiness,BN_shiftiness_eqtype]

        #Plot individual graphs for each experiment
        if create_indiv_graphs==True:
            #Find number of occurrences of equipmenttype in df_aggBN
            num_qc=df_aggBN['equipmenttype'].value_counts().loc['qc']
            num_sc=df_aggBN['equipmenttype'].value_counts().loc['sc']
```

```
            num_autosc=df_aggBN['equipmenttype'].value_counts().loc['autosc']
            num_equipment={'qc':num_qc,'sc':num_sc,'autosc':num_autosc}

            #Create graph for every individual vehicle
            title="Experiment "+str(experimentid)+': '+str(num_qc)+' QCs, '+str(num_autosc)+' autoSCs, '+str(num_sc)+' mSCs'
            xlabel="Equipment ID"
            ylabel="Percentage of simulated time [%]"
            ax=df_aggBN.plot.bar(x='equipmentid',y=['Percentage shifting BN','Percentage sole BN'],stacked=True,figsize=(12,8))
            ax.set_xlabel(xlabel,fontsize=16,labelpad=10)
            plt.setp(ax.get_xticklabels(),fontsize=14)
            ax.set_ylabel(ylabel,fontsize=16)
            plt.setp(ax.get_yticklabels(),fontsize=14)
            ax.set_title(title,fontsize=18,fontweight='bold',pad=10)
            box = ax.get_position()
            ax.set_position([box.x0, box.y0, box.width*2, box.height])
            ax.legend(loc='center left', bbox_to_anchor=(1, 0.5))
            ax.figure.savefig('C:\\Users\\cvanbattum\\OneDrive - Konecranes Plc\\Graduation assignment Coen van Battum files\\Python results analysis\\Analysed_results\\'+scenario+'\\'+str(experimentid)+'.jpeg',bbox_inches='tight',dpi=600)

            #Merge df_shBN and df_sBN dataframes
            df_BN=df_shBN.append(df_sBN,ignore_index=True)

            #Remove all rows with 0 duration
            df_BN.drop(df_BN[df_BN.duration_BN==0].index, inplace=True)

            df_BN[["equipment_abr","equipment_num"]] = df_BN[["equipmentid"]].apply(lambda x: eqid_split(x),axis=1)
            df_BN.sort_values(by=['equipment_abr','equipment_num'],inplace=True,ascending=False)

            #Create new graphs over BN over time
            fig, ax=plt.subplots(figsize=(12,8))
            title="Experiment "+str(experimentid)+': '+str(num_qc)+' QCs, '+str(num_autosc)+' autoSCs, '+str(num_sc)+' mSCs'
            xlabel="Simulation time [seconds]"
            ylabel="Equipment ID"
            xmin=df_BN['starttime_BN'].min()
            xmax=df_BN['endtime_BN'].max()

            y_start=-2
            y_width=2
            labels=[]
            y_start_list=[]
            lbl_pool = []

            for equipmentid, entries in df_BN[["bottleneck","equipmentid","starttime_BN","duration_BN"]].groupby("equipmentid",sort=False):
                y_start +=3
                labels.append(equipmentid)
                y_start_list.append(y_start+y_width/2)
                for entry in entries[["bottleneck","starttime_BN","duration_BN"]].itertuples(index=False):
                    if entry[0]=='shifting':
                        color='tab:blue'
                        ax.broken_barh([(entry[1],entry[2])],(y_start,y_width),facecolors=color,label="Shifting BN")
                    elif entry[0]=='sole':
                        color='tab:orange'
                        ax.broken_barh([(entry[1],entry[2])],(y_start,y_width),facecolors=color,label="Sole BN")

            plt.xticks(np.arange(xmin, xmax+3600, step=3600),fontsize=12)
            ax.set_xlim(xmin, xmax)
```

```
            ax.set_ylim(0,y_start+y_width+1)
            ax.set_yticks(y_start_list)
            ax.set_yticklabels(labels,fontsize=10)
            ax.set_title(title,fontsize=20,fontweight='bold',pad=10)
            ax.set_xlabel(xlabel,fontsize=16)
            ax.set_ylabel(ylabel,fontsize=16)

            #Prevent duplicates in the legend
            handles, labels = plt.gca().get_legend_handles_labels()
            by_label = dict(zip(labels, handles))
            plt.legend(by_label.values(), by_label.keys(),fontsize=14,loc='center left', bbox_to_anchor=(1, 0.5))
            ax.grid(True)

            #Save figures
            ax.figure.savefig('C:\\Users\\cvanbattum\\OneDrive - Konecranes Plc\\Graduation assignment Coen van Battum files\\Python results analysis\\Analysed_results\\'+scenario+'\\'+str(experimentid)+'_BNovertime.jpeg',bbox_inches='tight',dpi=600)
            plt.close()

    #Save overview of calculated percentages of sole and shifting bottlenecks for every experiment
    df_eqtype_exp.to_csv('C:\\Users\\cvanbattum\\OneDrive - Konecranes Plc\\Graduation assignment Coen van Battum files\\Python results analysis\\Analysed_results\\'+scenario+'\\'+scenario+'.csv',index=False)
```

### Python script 2: Visualisation of sole and shifting bottleneck times aggregated by type of equipment

```
#Import required libraries
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import os
from scipy import stats

#Step 1: Import data for analysis

#Input parameters
scenario='v12_30AutoSC_24mSCpool_Basev2_BNA_AU_curve_v_2'

#Change directory location
folder='Analysed_results\\'+scenario
os.chdir('C:\\Users\\cvanbattum\\OneDrive - Konecranes Plc\\Graduation assignment Coen van Battum files\\Python results analysis\\'+folder)

#Import data from csv files
df_analysed=pd.read_csv(scenario+'.csv')
df_analysed.columns=['experimentid','numhrs','qc_sBNp','qc_shBNp','qc_nBNp','autosc_sBNp','autosc_shBNp','autosc_nBNp','msc_sBNp','msc_shBNp','msc_nBNp','BN_shiftiness','BN_shiftiness_eqtype']
df_analysed=df_analysed.astype({"experimentid":"object","numhrs":"float64","qc_sBNp":"float64","qc_shBNp":"float64","qc_nBNp":"float64",
                                   "autosc_sBNp":"float64","autosc_shBNp":"float64","autosc_nBNp":"float64","msc_sBNp":"float64",
                                   "msc_shBNp":"float64","msc_nBNp":"float64","BN_shiftiness":"float64","BN_shiftiness_eqtype":"float64"})

#Step 2: Calculation of the weighted average

#Create new dataframe to create graph from
df_analysed_agg_avg=pd.DataFrame(columns=['equipmenttype','Percentage sole BN','Percentage shifting BN','Percentage non-BN'])
df_analysed_agg_avg=df_analysed_agg_avg.astype({"equipmenttype":"object","Percentage sole BN":"float64","Percentage shifting BN":"float64","Percentage non-BN":"float64"})

```

```python
#Insert equipmenttypes
df_analysed_agg_avg['equipmenttype']=['autoSC','mSC','QC']

#Calculate the weighted average percentages for sole/shifting/non-BN
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='autoSC',['Percentage sole BN']]=np.average(df_analysed['autosc_sBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='autoSC',['Percentage shifting BN']]=np.average(df_analysed['autosc_shBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='autoSC',['Percentage non-BN']]=np.average(df_analysed['autosc_nBNp'],weights=df_analysed['numhrs'])

df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='QC',['Percentage sole BN']]=np.average(df_analysed['qc_sBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='QC',['Percentage shifting BN']]=np.average(df_analysed['qc_shBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='QC',['Percentage non-BN']]=np.average(df_analysed['qc_nBNp'],weights=df_analysed['numhrs'])

df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='mSC',['Percentage sole BN']]=np.average(df_analysed['msc_sBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='mSC',['Percentage shifting BN']]=np.average(df_analysed['msc_shBNp'],weights=df_analysed['numhrs'])
df_analysed_agg_avg.loc[df_analysed_agg_avg['equipmenttype']=='mSC',['Percentage non-BN']]=np.average(df_analysed['msc_nBNp'],weights=df_analysed['numhrs'])

#Calculate the sum of the percentage sole and shifting BN of every experiment to determine standard deviation
df_analysed['autosc_(sBNp+shBNp)']=df_analysed['autosc_sBNp']+df_analysed['autosc_shBNp']
df_analysed['qc_(sBNp+shBNp)']=df_analysed['qc_sBNp']+df_analysed['qc_shBNp']
df_analysed['msc_(sBNp+shBNp)']=df_analysed['msc_sBNp']+df_analysed['msc_shBNp']

#Determine the confidence interval of the sum of the shifting and sole bottleneck percentage
num_exp=df_analysed['experimentid'].shape[0] #Number of experiments ran

#Determine the weighted average of the summed percentage sole and shifting BN
autosc_sum_wavg=np.average(df_analysed['autosc_(sBNp+shBNp)'],weights=df_analysed['numhrs'])
qc_sum_wavg=np.average(df_analysed['qc_(sBNp+shBNp)'],weights=df_analysed['numhrs'])
msc_sum_wavg=np.average(df_analysed['msc_(sBNp+shBNp)'],weights=df_analysed['numhrs'])
BN_shift_wavg=np.average(df_analysed['BN_shiftiness'],weights=df_analysed['numhrs'])
BN_shift_eqtype_wavg=np.average(df_analysed['BN_shiftiness_eqtype'],weights=df_analysed['numhrs'])

#Determine the weighted standard deviation of the summed percentage sole and shifting BN
autosc_sum_wstdev=np.sqrt(np.average(((df_analysed['autosc_(sBNp+shBNp)']-autosc_sum_wavg)**2),weights=df_analysed['numhrs'])*df_analysed.shape[0]/(df_analysed.shape[0]-1))
qc_sum_wstdev=np.sqrt(np.average(((df_analysed['qc_(sBNp+shBNp)']-qc_sum_wavg)**2),weights=df_analysed['numhrs'])*df_analysed.shape[0]/(df_analysed.shape[0]-1))
msc_sum_wstdev=np.sqrt(np.average(((df_analysed['msc_(sBNp+shBNp)']-msc_sum_wavg)**2),weights=df_analysed['numhrs'])*df_analysed.shape[0]/(df_analysed.shape[0]-1))
BN_shift_wstdev=np.sqrt(np.average(((df_analysed['BN_shiftiness']-BN_shift_wavg)**2),weights=df_analysed['numhrs'])*df_analysed.shape[0]/(df_analysed.shape[0]-1))
BN_shift_eqtype_wstdev=np.sqrt(np.average(((df_analysed['BN_shiftiness_eqtype']-BN_shift_eqtype_wavg)**2),weights=df_analysed['numhrs'])*df_analysed.shape[0]/(df_analysed.shape[0]-1))

autosc_sum_wstdev_norm=autosc_sum_wstdev/np.sqrt(num_exp)
qc_sum_wstdev_norm=qc_sum_wstdev/np.sqrt(num_exp)
```

```
msc_sum_wstdev_norm=msc_sum_wstdev/np.sqrt(num_exp)
BN_shift_wstdev_norm=BN_shift_wstdev/np.sqrt(num_exp)
BN_shift_eqtype_wstdev_norm=BN_shift_eqtype_wstdev/np.sqrt(num_exp)

#Retrieve t-value according to the number of experiments
t_value=stats.t.ppf(1-0.025, num_exp)

#Calculate the length of half the confidence interval
autosc_error=autosc_sum_wstdev_norm*t_value
qc_error=qc_sum_wstdev_norm*t_value
msc_error=msc_sum_wstdev_norm*t_value
BN_shift_error=BN_shift_wstdev_norm*t_value
BN_shift_eqtype_error=BN_shift_eqtype_wstdev_norm*t_value
errors=[autosc_error,msc_error,qc_error]
errors0=[0,0,0]

#Create graph aggregated per equipmenttype
title=scenario
xlabel="Equipmenttype"
ylabel="Percentage of simulated time [%]"
ax=df_analysed_agg_avg.plot(kind='bar',x='equipmenttype',y=['Percentage shifting BN','Percentage sole BN'],alpha=0.9,
                            stacked=True,yerr=[errors0,errors],figsize=(12,8))
ax.set_xlabel(xlabel,fontsize=16)
plt.setp(ax.get_xticklabels(),fontsize=14)
ax.set_ylabel(ylabel,fontsize=16)
plt.setp(ax.get_yticklabels(),fontsize=14)
ax.set_title(title,fontsize=20,fontweight='bold',pad=10)
ax.grid(axis='y')
ax.set_ylim(0,)
ax.legend(fontsize=14,loc='center left', bbox_to_anchor=(1, 0.5))

ax.figure.savefig(scenario+'_lines_v3.jpeg',bbox_inches='tight',dpi=600)
```

# Appendix C. Equipment states of the shifting bottleneck method

*Table C.1: An overview of the park states of both mSCs and autoSCs.*

| # | Equipment | Parking state | Description | Bottleneck state |
|---|---|---|---|---|
| 1 | autoSC, mSC | Parked | Parked or on its way to a parking location. | Inactive |
| 2 | autoSC, mSC | Busy | Currently performing a productive order assigned by the TOS. | Depends on the combination of order control and drive state |

*Table C.2: An overview of the drive states of both mSCs and autoSCs including a detailed description of the state. The column equipment indicates to whether the state applies to mSCs, autoSCs, or both.*

| # | Equipment | Drive state | Description |
|---|---|---|---|
| 1 | autoSC, mSC | Driving | Starting engine, accelerating, driving at constant speed, or braking. |
| 2 | autoSC, mSC | Idle | Waiting at its current location for the next order. |
| 3 | autoSC, mSC | Waiting for claim at autosc | Waiting for an activity performed by an autoSC which prevents the autoSC or mSC from claiming the required area to drive to its destination. |
| 4 | autoSC | Spreader hoisting | Adjusting the spreader height to enter or leave a stack or the truck IC (either hoisting or lowering). |
| 5 | autoSC, mSC | Waiting for claim at msc | Waiting for an activity performed by an mSC which prevents the autoSC or mSC from claiming the required area to drive to its destination. This represents the manual ability to prevent collisions during driving. |
| 6 | mSC | Waiting for claim at qc | Waiting for the quay crane to clear the transfer point within its gauge. |

*Table C.3: An overview of the order control states of both mSCs and autoSCs. The column equipment indicates to whether the state applies to mSCs, autoSCs, or both.*

| **#** | **Equipment** | **Order control state** | **Description** | **Bottleneck state (combination with drive state)** |
|---|---|---|---|---|
| 1 | autoSC, mSC | Driving empty | Driving without a container loaded to an assigned location. | autoSC: Active (1,3,4), Inactive (5)<br>mSC: Active (1,5), Inactive (3,6) |
| 2 | autoSC, mSC | Driving loaded | Driving with a container loaded to an assigned location. | autoSC: Active (1,3,4), Inactive (5)<br>mSC: Active (1,5), Inactive (3,6) |
| 3 | mSC | Driving twin loaded | Driving with two 20ft containers to an assigned location. | mSC: Active (1,5), Inactive (3,6) |
| 4 | autoSC, mSC | Dropping container(s) | Dropping the container(s) at the assigned location in a stack, interchange area, truck IC (autoSC), or QC transfer point (mSC) and disconnecting the spreader from the container(s). | Active (all) |
| 5 | autoSC, mSC | Grabbing container(s) | Positioning and connecting the spreader to hoist the container(s) located in a stack, interchange area, truck IC (autoSC), or QC transfer point (mSC). | Active (all) |
| 6 | autoSC, mSC | Idle equipment | Waiting for an order to be assigned by the TOS. | Inactive (all) |
| 7 | mSC | Waiting for container | Waiting for the quay crane for a container to be grounded by the quay crane on one of the transfer points within its gauge. | Inactive (all) |
| 8 | mSC | Waiting for departure | Waiting for permission from the mSC manager to depart from a stack or interchange area to a buffer before a QC depending on the handling sequence of containers of the QC. | Inactive (all) |
| 9 | autoSC, mSC | Waiting for grounding location | Waiting for the TOS to assign a grounding location for the container(s) currently loaded. | Inactive (all) |
| 10 | mSC | Waiting for route to buffer | Waiting for a route from the mSC route manager to the buffer location after the quay crane. | Inactive (all) |
| 11 | autoSC | Waiting for teleoperator | Waiting for a teleoperator to drop a container carried by an autoSC through remote control on a truck. | Active (all) |
| 12 | mSC | Waiting for TP at QC | Waiting for the QC to create a free transfer point within its gauge or on other mSCs that are either grabbing on dropping containers at the QC TPs | Inactive (all) |

*Table C.4: An overview of the order control states of QCs.*

| # | Equipment | Order control state | Description | Bottleneck state |
|---|---|---|---|---|
| 1 | QC | Bay change | The QC drives along the quay to serve a different bay within the ship. | Active |
| 2 | QC | Dropping at quay TP | Dropping the container(s) at the transfer point underneath the QC. | Active |
| 3 | QC | Dropping at vessel | Dropping the container(s) retrieved from the quay into the ship. | Active |
| 4 | QC | Grabbing at quay TP | Grabbing the container(s) at the transfer point within gauge of the QC. | Active |
| 5 | QC | Grabbing at vessel | Grabbing the container(s) from the vessel. | Active |
| 6 | QC | Idle equipment | Waiting for an order to be assigned to the QC. | Inactive |
| 7 | QC | Moving to quay TP | Moving the trolley and container(s) to the TP underneath the QC. | Active |
| 8 | QC | Moving to vessel | Moving the trolley and container(s) to the vessel. | Active |
| 9 | QC | Tandemswitch | Only occurs for QCs on the FN berth when the next bay is (un)loaded with tandem lifts and the previous or next was not. | Active |
| 10 | QC | Twistlock handling | Twistlocks are used for containers stacked above vessel deck. In the yard, twistlocks are not used and therefore have to be removed when discharging and installed when loading the container(s) when stacked above deck. | Active |
| 11 | QC | Waiting for claim to drop | When discharging, waiting for an mSC to clear the transfer point (including adjacent transfer points for FN berth QCs) within gauge of the QC to drop the container(s). | Inactive |
| 12 | QC | Waiting for claim to grab | When loading, waiting for an mSC to clear the transfer point (including adjacent transfer points for FN berth QCs) within gauge of the QC to grab the container(s). | Inactive |
| 13 | QC | Waiting for container | When loading, waiting for a container to be delivered by an mSC. | Inactive |
| 14 | QC | Waiting for TP | Waiting for an unoccupied transfer point within gauge of the QC by containers or mSCs. | Inactive |

# Appendix D. Research paper

# Performance Improvement of Maritime Container Terminals Through the Bottleneck Mitigation Cycle

Coen H.H. van Battum, Bilge Atasoy, Bart Wiegmans, Erwin van Wingerden, Arjen de Waal, and
Lóránt A. Tavasszy

***Abstract*— Scarcity of maritime container terminal (MCT) capacity can become a problem for global supply chains. Bottlenecks limit the capacity of these terminals and should therefore be detected and alleviated. However, there is no structured approach available in literature to mitigate the effects of bottlenecks at MCTs. Therefore, this research introduces a holistic approach called the bottleneck mitigation cycle (BMC) which consists of three steps: bottleneck classification, bottleneck detection, and bottleneck alleviation. A proof of concept of the BMC is provided. Scientific value is added by proposing a contemporary and comprehensive classification structure of bottlenecks at MCTs which consists of infrastructural, operational, and managerial bottlenecks. Infrastructural and operational bottlenecks are the focus of this research. Furthermore, while literature often only focuses on alleviation of a single bottleneck and skips bottleneck detection, 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 results in productivity improvements of 2-6%. To make the BMC even more effective and efficient, future research directions are to improve the empirical approach used for bottleneck alleviation and to apply the BMC in real-time.**

***Index Terms*—bottleneck alleviation, bottleneck classification, bottleneck detection, maritime container terminals, terminal efficiency**

## I. INTRODUCTION

Over the last decade, container port throughput has grown steadily reaching 793 million Twenty-foot Equivalent Units (TEU) worldwide in 2018 [1]. Maritime Container Terminals (MCTs), sometimes referred to as container terminals, are nodes in the transport network where container vessels are (un)loaded and where containers can be temporarily stored. A schematic overview of a transport chain at an MCT is shown in Fig. 1. Import containers arrive by (deep-)sea vessel and are often 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 the containers further into the hinterland. For export containers, the order is reversed as indicated by the bi-directional arrows.

Due to growing container trade, scarcity of terminal capacity can become a problem for the transport of goods in global supply chains. However, development of port infrastructure is hindered by rising environmental and social concerns. There have not been significant improvements in the basic design of equipment. As a result, improving terminal productivity has increasingly become a matter of terminal management [2].

The use of information technology at MCTs creates the opportunity to implement (automated) methods to detect and alleviate *bottlenecks*. In this research, the term "*alleviate*" is used because bottlenecks cannot be prevented; at any given point in time there is always a process that is the bottleneck. There is no universal definition of a bottleneck [3, 4] and depending on the actor and its perspective, the bottleneck can be different within the same system [4]. Therefore, the following definition is used: "*the resource or process within a maritime container terminal of which the capacity limits the output of the terminal*". This definition is deliberately somewhat loose as there is a wide variety of bottlenecks possible, and they move in time and space throughout an MCT.

As it is observed that integrated approaches are lacking in practice and literature, this research introduces the bottleneck mitigation cycle (BMC) to improve the performance of MCTs. The BMC is a holistic approach to mitigate the effects of bottlenecks at MCTs. The BMC consists of three steps as schematically shown in Fig. 2. Firstly, a classification of bottlenecks at a terminal is required as input to select the most

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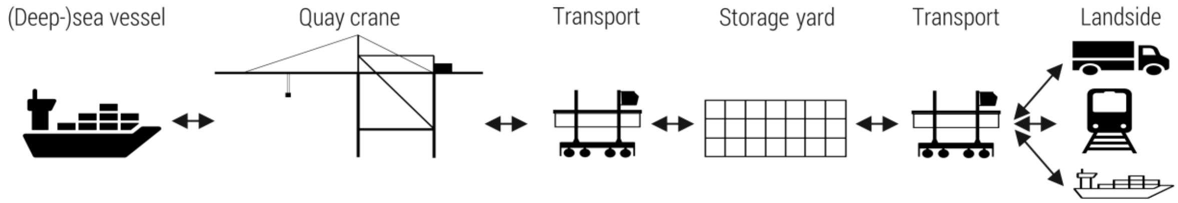

Fig. 1: Schematic representation of a transportation chain at a maritime container terminal.

appropriate bottleneck detection method. Secondly, the bottlenecks at the terminal studied can be detected and ranked. Thirdly, causes of the most stringent bottleneck are identified, and one or multiple alleviation measures are selected and implemented. After a certain delay in time, which depends on the measure implemented, the cycle starts again by detecting bottlenecks as the bottleneck may have moved to another resource or process. Thirdly, causes of the most stringent bottleneck are identified, and one or multiple alleviation measures are selected and implemented. After a certain delay in time, which depends on the measure implemented, the cycle starts again by detecting bottlenecks as the bottleneck may have moved to another resource or process.

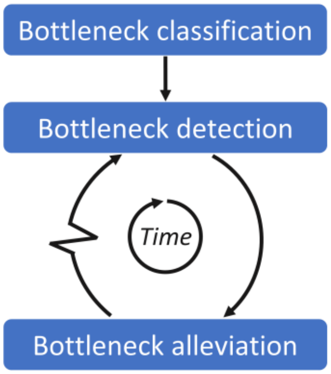

Fig. 2: The bottleneck mitigation cycle.

This research aims to provide a proof of concept of the application of the BMC to enhance the performance of an MCT. To provide a proof of concept, a case study has been performed at the Fergusson Container Terminal (FCT) in the Port of Auckland (POAL).

To assess the incremental contributions made in this research, as part of the larger innovation roadmap regarding the development of the concept of the BMC, the measurement system of the Technology Readiness Level (TRL) is adopted using the definitions from NASA Earth Science Division [5]. It starts at level 1 (ideas underpinning the technology) and increases until level 9 (successful operation of the final product). This research starts at TRL 1 by borrowing basic ingredients for the BMC available in scientific literature. The introduction of the concept of the BMC increases the maturity of the BMC to TRL 2.

The central contribution of this research is the introduction and application of the BMC, which is a holistic approach to improve MCT performance. Furthermore, the following contributions are made:

- A contemporary and comprehensive classification of bottlenecks at MCTs is proposed.
- New definitions of active and inactive states of equipment are formulated to apply the shifting bottleneck method to MCTs.
- The potential of the BMC is shown to improve the performance of the FCT in a simulation model.
- Promising future research directions towards increasing the TRL of the BMC and more efficient MCTs are formulated.

The remainder of this paper is organised as follows. In Section II a brief overview of the literature is provided on which the approaches of BMC are based. The proposed methodology of the BMC is presented in Section III and applied to a simulation model of the FCT in Section IV. Finally, Section V presents the main findings of this research together with future research directions towards more efficient terminals.

## II. LITERATURE REVIEW

This literature review provides the scientific knowledge underpinning the approaches of the three steps of the BMC (TRL 1).

### A. *Classification Structure of Bottlenecks at Maritime Container Terminals*

To the best of the authors' knowledge, Dowd and Leschine [6] were the first to categorise bottlenecks. They distinguish two types of bottlenecks: *physical* and *institutional*. A more recent classification structure is proposed by Veenstra, et al. [7] 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 [8]: *resource*, *market* and *statutory* bottlenecks.

An important common problem of the structures found in literature is that definitions and examples are remarkably limited, and that there is no distinction between bottlenecks due to decisions in infrastructure of the terminal (long-term) and operational decisions (real-time). Therefore, a classification structure is devised 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., the 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.

### B. Comparison and Evaluation of Bottleneck Detection Methods

Due to the sheer complexity and dynamism of an MCT, a structured approach is required to detect the bottlenecks present. To the best of the authors' knowledge, only three simulation-based methods to detect bottlenecks are used in MCTs (1-3). Due to the limited number of bottleneck detection methods applied to MCTs, the scope of bottleneck detection methods is expanded to other types of terminals as well as manufacturing (4-7). The following seven methods have been identified:

1. Capacity utilization method [8-11]
2. Queue length and waiting time method [12]
3. Sensitivity analysis method [13-16]
4. Average active duration method [17]
5. Shifting bottleneck detection method [18]
6. Arrow-based method [19]
7. Turning point method [20]

The potential of each detection method is assessed based on the following attributes: accuracy of detection of bottlenecks, requirements imposed by the method on the system studied, ability to distinguish between primary, secondary, tertiary and non-bottlenecks, ability to detect momentary and long-term bottlenecks, and difficulty of implementation of the method of which an overview can be found in [21]. Based on the comparison, the shifting bottleneck method is selected given its high accuracy and ability to detect momentary bottlenecks.

### C. Bottleneck Alleviation Methods

There is no straightforward way to determine 'the most suitable or best' alleviation measure in scientific literature. Furthermore, using scientific literature to assess the potential of alleviation measures is difficult, since not one terminal is the same and interaction of bottlenecks makes selecting an effective alleviation measure even more complex. As a result, often a trial-and-error approach is adopted.

## III. PROPOSED METHODOLOGY: THE BOTTLENECK MITIGATION CYCLE

In this section, the application of the BMC to an MCT is described to bring the concept to TRL 2.

### A. Bottleneck Classification

It is important to classify the bottlenecks at an MCT to effectively select a method to detect bottlenecks and select corresponding alleviation measures. The distinctive nature of bottlenecks makes it difficult to study all three types of bottlenecks at the same time. Since infrastructural and operational bottlenecks are within control of the terminal operator, the information necessary to detect and alleviate these types of bottlenecks is directly available. Therefore, in this research, the BMC focuses on infrastructural and operational bottlenecks.

### B. 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 [18]. Due to variability and randomness of terminal operations, bottlenecks move in time and space across the terminal [22]. Therefore, it is interesting to analyse terminal operations over a longer period of time.

Then a distinction can be made between *sole* and *shifting* bottlenecks which can be defined as follows [18]:

- *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.

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.

#### 1) Determination of the Bottleneck State

For infrastructural and operational bottlenecks at a container terminal, two types of resources can be distinguished: equipment and locations. This research focuses on equipment-related bottlenecks.

To detect equipment-related bottlenecks at an MCT, the longest uninterrupted active duration of the *bottleneck state* of all equipment needs to be determined. Every individual equipment at a container terminal is assigned a bottleneck state which is either active or inactive. 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 the 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:* the driving activity of the equipment.

At every moment in time, every individual 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 MCTs in scientific literature, the following definitions are used:

- *Active state*: when current activities of the equipment contribute to terminal performance or when the equipment is waiting on equipment of the same type.
- *Inactive state*: when the equipment is idle, parked, or waiting on 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 an MCT [7, 11, 12, 23-25].

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

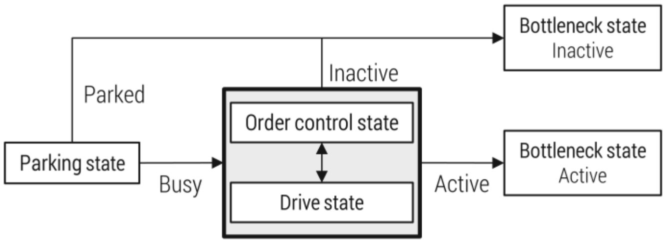

Fig. 3: Determination of the bottleneck state of equipment at an MCT.

### 2) Determination of Shifting and Sole Bottleneck Times

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

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

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

in which $d_i^{sole}(t)$ and $d_i^{shifting}(t)$ represent the function of the sole and shifting bottleneck duration of individual 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 studied.

The probability that individual 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, as percentage, can be calculated using the following equations:

$$P_i^{sole} = \frac{D_i^{sole}}{T} \cdot 100, \qquad \forall i \in I \qquad (3)$$

$$P_i^{sole} = \frac{D_i^{sole}}{T} \cdot 100, \qquad \forall i \in I \qquad (4)$$

Roser, et al. [18] do not provide information on the procedure of aggregating bottlenecks of individual equipment of the same type. In this research, this issue is overcome by summing the shifting and sole bottleneck durations of the individual equipment of the same type. The percentage of time an individual type of equipment is either a sole ($P_e^{sole}$ with $e \in E$) or shifting bottleneck ($P_e^{shift}$ with $e \in E$), as percentage, can be calculated using (5) and (6), respectively. The set $E$ represents all equipment types present at the container terminal studied. 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 $e_i$.

$$P_e^{sole} = \frac{\sum_{i \in I | e_i = e} D_i^{sole}}{T} \cdot 100 = \sum_{i \in I | e_i = e} P_i^{sole} \qquad \forall e \in E \ (5)$$

$$P_e^{shift} = \frac{\sum_{i \in I | e_i = e} D_i^{shift}}{T} \cdot 100 = \sum_{i \in I | e_i = e} P_i^{shift} \qquad \forall e \in E \ (6)$$

Due to aggregation of the equipment by its type in this way, the percentage of shifting bottlenecks can exceed 100% for a specific type of equipment. This means that the shifting bottleneck percentage of a certain type of equipment does not give the probability of it being the shifting bottleneck during the time studied.

The primary average bottleneck of the system is defined as the bottleneck with the highest sum of the sole and shifting bottleneck percentage over the time considered. The secondary bottleneck has the second highest percentage bottleneck, etc.

## C. Bottleneck alleviation: Empirical Approach

In this research, the scope is limited to alleviation of bottlenecks averaged over a period of time referred to as average bottlenecks [18].

### 1) Bottleneck Shiftiness Measure

Lawrence and Buss [22] introduced the *bottleneck shiftiness measure* to quantify the shiftiness of bottlenecks. In a way, this is a quantitative measure of the complexity of improving the system performance by alleviation of bottlenecks. It also provides information whether it is more effective to apply alleviation measures to specific individual equipment or to a type of equipment. The bottleneck shiftiness measure ($\beta$) can be calculated using the following equation [22]:

$$\beta = 1 - \frac{c_v}{\sqrt{N}} = 1 - \frac{\sigma}{\mu\sqrt{N}} \qquad (7)$$

in which $\beta$ represents the bottleneck shiftiness measure, dimensionless; $c_v$ 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; $\sigma$ and $\mu$ 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 ($\mu$), and standard deviation ($\sigma$) 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.

### 2) *Cause Analysis of the Bottleneck*

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. An investigation of the cause(s) behind the time spent in a state is performed in consultation with field experts.

### 3) *Alleviation Measures*

Based on the identified cause, composing a list of alleviation measures is 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 performance of the terminal since other equipment is significantly hindered by the implemented measure. Therefore, the experience of field experts is used to determine promising alleviation measures. These alleviation measures are implemented in a virtual environment 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 in time 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.

## IV. CASE STUDY

To obtain a proof of concept of the BMC and thereby increase the TRL to 6, the BMC is applied to a simulation model of the FCT situated in the POAL, New Zealand.

### A. *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). The interchange of rail containers between trains and the stacks is outside the scope of this research.

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

- *quay cranes (QC)*: interact with mSCs through load and discharge containers of vessels.
- *manned straddle carriers (mSCs)*: transport containers to and from the quay cranes from and to the interchange area or mSC stacks. MSCs can twin-lift containers.
- *automated straddle carriers (autoSCs)*: transport containers to and from the interchange area to and from the (reefer) stack or truck interchange. Trucks are served by autoSCs at the truck interchange. A tele-operator takes over control to position import containers on the trucks.

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

The simulation model of the FCT is created by TBA Group in collaboration with the FCT in 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 is validated by Verbraeck, et al. [26], and the model itself is validated by TBA Group and the FCT [27]. Based on the outcomes of the validation steps, it can be concluded that the simulation model is validated.

Peak-scenario simulations are carried out in which both a waterside and landside peak in workload have to be handled at the same time under dense yard conditions for 8 hours. The base scenario settings for a peak simulation are based on the current most efficient configuration for the given layout of the FCT of which an overview is provided in Table I.

### B. *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, autoSCs, and QCs are shown in Table V-Table VIII in the Appendix, respectively.

TABLE I
AN OVERVIEW OF THE TERMINAL SETTINGS USED IN THE BASE SCENARIO OF THE FERGUSSON CONTAINER TERMINAL.

| Simulation model parameter | Quantity |
|---|---|
| Number of autoSCs 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% |

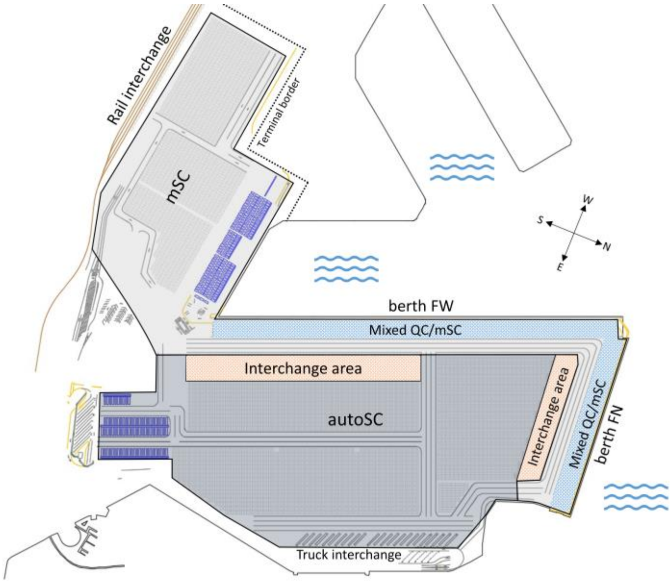

Fig. 4: Operating areas of the different types of equipment present at the Fergusson Container Terminal. mSC: manned straddle carrier, autoSC: automated straddle carrier, QC: quay crane.

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

### 1) *Verification*

Verification of implementation of the shifting bottleneck method is performed 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 autoSCs 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 autoSCs are interrupted more often. A comparison of the results of Fig. 5 (base scenario) and Fig. 6 (change in definition) confirms this.

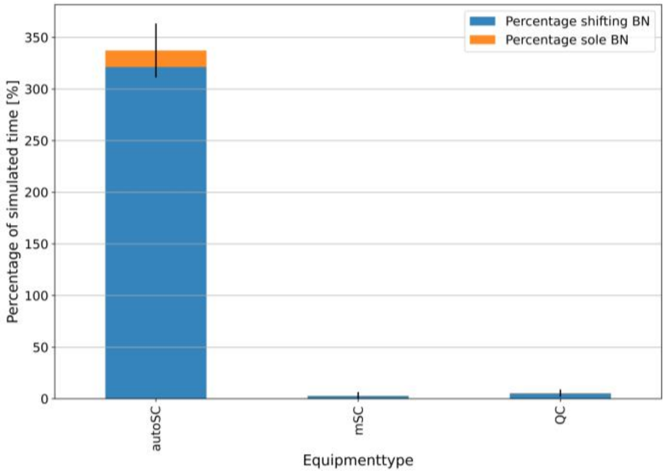

Fig. 5: Results of application of the shifting bottleneck method to the base scenario with a significance level of 0.05. BN: bottleneck.

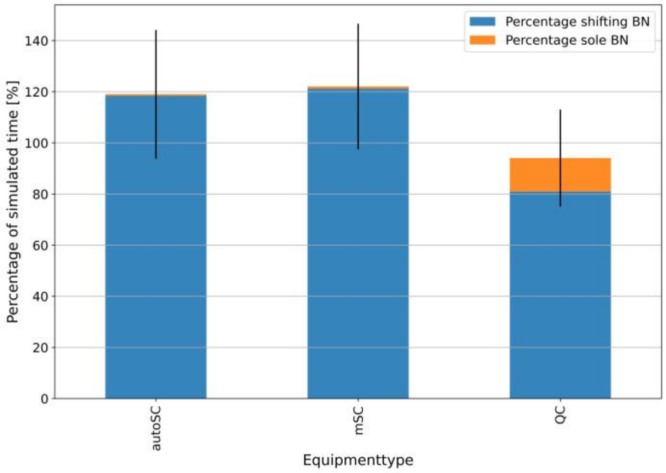

Fig. 6: Results of application of the shifting bottleneck method to base scenario with the drive state "waiting for equipment of the same type" as inactive. BN: bottleneck

The terminal parameters consist of the number of equipment and the workload. By comparing extreme values of the terminal parameters shown in Fig. 8-13 in the Appendix, all results but decreasing the number of autoSCs match the hypotheses. A possible reason for this is that the autoSCs are already the average bottleneck to an extent that it cannot increase any further and the results are not statistically significantly different. With these results, the implementation is considered verified.

### 2) *Validation*

The results of the base scenario (Fig. 5) indicate that the autoSCs are the average bottleneck of the terminal. Over the simulated time, on average 0.16 and 3.21 autoSCs are the sole and shifting bottleneck, respectively.

Due to the absence of historical data on the bottlenecks of the FCT, the face validity technique is used to validate the implementation of the shifting bottleneck method [26, 28]. The finding that the autoSCs are the average bottleneck is in line with the expectation of field experts. Therefore, the implemented shifting bottleneck method is considered validated.

## C. *Bottleneck alleviation*

The bottleneck shiftiness measure values for individual equipment and the equipment types (mSC, autoSC, and QC) with a significance level of 0.05 are 0.63±0.05 and 0.04±0.03, respectively. This means that the autoSCs as an equipment type are almost the unique bottleneck. A reason for this is the high percentage of shifting bottlenecks for autoSCs, which can also be observed in Fig. 5. Based on these results, the alleviation measures should apply to all autoSCs rather than individual autoSCs 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 autoSCs is analysed. From Table II, it can be observed that the largest share of simulated time (69%) is spent driving. The drive states in Table III show that most time is spent driving and not waiting on other equipment (congestion). Field experts confirm that the driving speed of autoSCs used at the FCT is relatively slow compared to other types of equipment. Therefore, slow driving is considered to be the cause that autoSCs are the bottleneck.

To reduce the time spent driving, field experts are consulted to determine the following three alleviation measures:

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

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

TABLE II
ANALYSIS OF THE AVERAGE TIME SPENT IN THE ORDER CONTROL STATES OF THE AUTOSCS 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 III
ANALYSIS OF THE AVERAGE TIME SPENT IN THE DRIVE STATES OF THE AUTOSCS 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% |
| Driving | 55.45±0.35% |

The measures are implemented in separate scenarios and the results are indexed based on the performance of the base scenario (197 simulated hours) and presented in Table IV. The results of the implemented alleviation measures 1, 2, and 3 are 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 IV 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 autoSCs by 20%.

### D. *Discussion*

The next bottleneck mitigation cycle starts by, again, performing bottleneck detection on the scenario with the increased maximum allowed curve speed of which the results are shown in Fig. 7. From this figure, it can be seen that autoSCs are still the bottleneck of the FCT. To further improve the performance of the terminal, again alleviation measures should be applied to alleviate the autoSC 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.

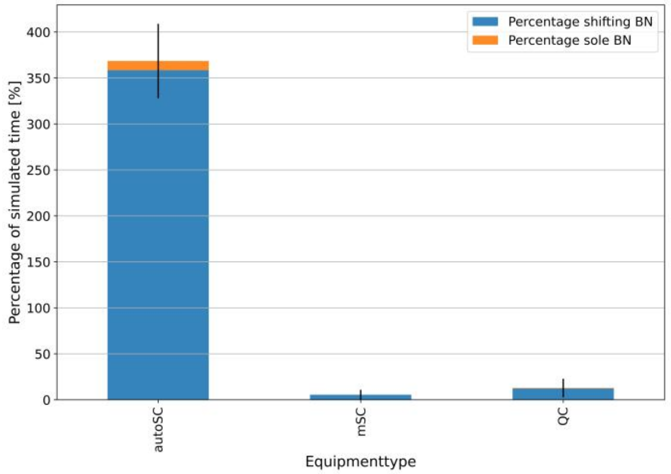

Fig. 7: Result of applying the shifting bottleneck method to the scenario in which the parameters of the base scenario are used and the maximum allowed curve speed is increased by 20%. BN: bottleneck

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 information 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.

## V. CONCLUSIONS AND FUTURE RESEARCH DIRECTION

This research introduced and applied the concept of the *bottleneck mitigation cycle* (BMC); a holistic approach to effectively mitigate bottlenecks at MCTs to improve their performance. Such a holistic approach is missing in literature about MCTs 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) to improve its performance.

First, a new structure to classify bottlenecks at MCTs 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 MCTs is evaluated based on a synthesis of various methods available in literature including not only MCTs but also other types of terminals and production networks. The shifting bottleneck method is selected based on its high accuracy and its ability to detect momentary bottlenecks. However, since this method is not yet applied to MCTs, new generic definitions for active and inactive states of

TABLE IV
RESULTS OF THE IMPLEMENTATION OF THE DIFFERENT ALLEVIATION MEASURES AT THE FERGUSSON CONTAINER TERMINAL INDEXED BASED ON THE PERFORMANCE INDICATOR VALUES OF THE BASE SCENARIO (100).

| PERFORMANCE INDICATOR | UNITS | BASE SCENARIO | INCREASE ACCELERATION & 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 |
| autoSC 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 |

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 shows that the outcome of the shifting bottleneck method is very sensitive with respect 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. The results of bottleneck detection combined with the bottleneck shiftiness measure are used to determine that alleviation measures should apply 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.

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 hypothesis is suggested that the BMC can potentially also be used to reduce the costs of the terminal while maintaining the same performance.

The simulation model of the FCT can be considered a relevant end-to-end environment to demonstrate the concept of the BMC. In combination with the performance improvement achieved, it can be concluded that a proof of concept of the BMC is given in this environment. As a result, its Technology Readiness Level (TRL) has increased from 1 to 6 with this research.

A first step to bring the concept of the BMC from TRL 6 to TRL 7-8 in future research, is to apply it to an actual operational environment. This operational environment can be an emulated environment in which a virtual MCT in combination with the real control system is used as explained by Boer and Saanen [29]. Once the concept of the BMC has been verified and validated by emulation, the final steps to bring it to practice (TRL 9) would be to successfully operate it at a real MCT and to provide all necessary software support and documentation.

Multiple future research directions can be identified to improve the application of the BMC to MCTs. It would 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 to temporarily increase the performance of the terminal with respect to specific flows of containers. Application of the BMC in real-time can potentially also improve the agility of an MCT. Moreover, given the dynamism of bottlenecks both in space and time, applying the BMC in real-time can possibly improve the performance of MCTs 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 locations prone to bottlenecks, like the layout of the storage yard [30] or transfer points at quay cranes [31], would be interesting to include. Furthermore, research on interactions between bottlenecks should be included because 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 federal institutions.

## APPENDIX

TABLE V
AN OVERVIEW OF THE PARK STATES OF MSCS AND AUTOSCS.

| # | EQUIPMENT | PARKING STATE | BOTTLENECK STATE |
|---|---|---|---|
| 1 | autoSC, mSC | Parked | Inactive |
| 2 | autoSC, mSC | Busy | Depends on the combination of the order control and drive state |

TABLE VI
AN OVERVIEW OF THE DRIVE STATES OF MSCS AND AUTOSCS.

| # | EQUIPMENT | DRIVE STATE |
|---|---|---|
| 1 | autoSC, mSC | Driving |
| 2 | autoSC, mSC | Idle driving engine |
| 3 | autoSC, mSC | Waiting due to equipment of the same type |
| 4 | autoSC, mSC | Waiting due to equipment of another type |

TABLE VII
AN OVERVIEW OF THE ORDER CONTROL STATES OF MSCS AND AUTOSCS. THE COMBINATION WITH THE DRIVE STATES (SEE TABLE VI) DETERMINES WHETHER THE ORDER CONTROL STATE IS DEFINED AS ACTIVE OR INACTIVE.

| # | EQUIPMENT | ORDER CONTROL STATE | BOTTLENECK STATE |
|---|---|---|---|
| 1 | autoSC, mSC | Driving empty | Active (1,4), Inactive (3) |
| 2 | autoSC, mSC | Driving loaded | Active (1,4), Inactive (3) |
| 3 | autoSC, mSC | Dropping container(s) | Active (all) |
| 4 | autoSC, mSC | Grabbing container(s) | Active (all) |
| 5 | autoSC, mSC | Idle equipment | Inactive (all) |
| 6 | mSC | Waiting for free transfer point at QC | Inactive (all) |
| 7 | autoSC | Teleoperator handling | Active (all) |
| 8 | autoSC, mSC | Waiting for TOS routing or grounding decision | Inactive (all) |

TABLE VIII
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 |

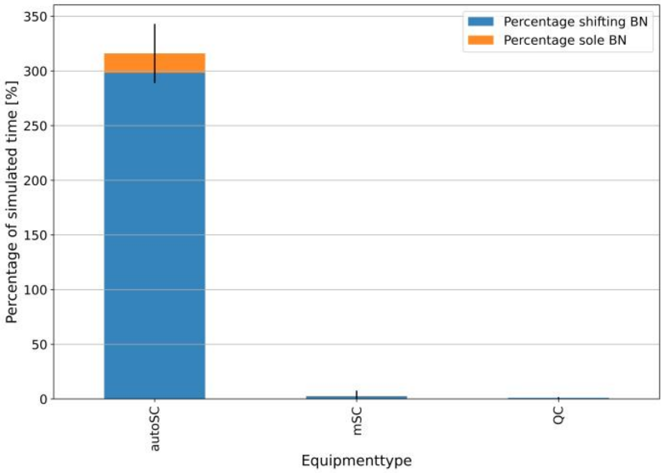

Fig. 8: Results of application of the shifting bottleneck method using 13 autoSCs, 24 mSCs, 6 QCs and a truck workload of 81 boxes per hour with a significance level of 0.05. BN: bottleneck

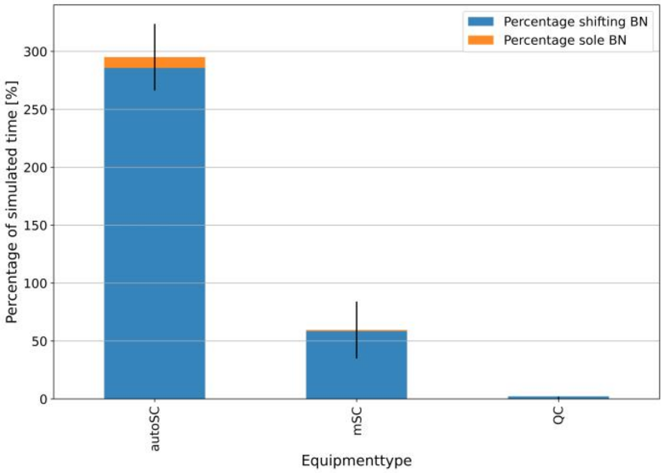

Fig. 9: Results of application of the shifting bottleneck method using 30 autoSCs, 10 mSCs, 6 QCs and a truck workload of 81 boxes per hour with a significance level of 0.05. BN: bottleneck

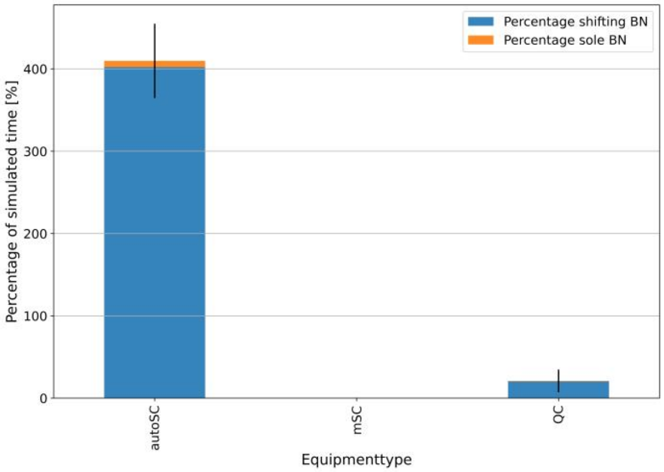

Fig. 10: Results of application of the shifting bottleneck method using 30 autoSCs, 30 mSCs, 6 QCs and a truck workload of 81 boxes per hour with a significance level of 0.05. BN: bottleneck

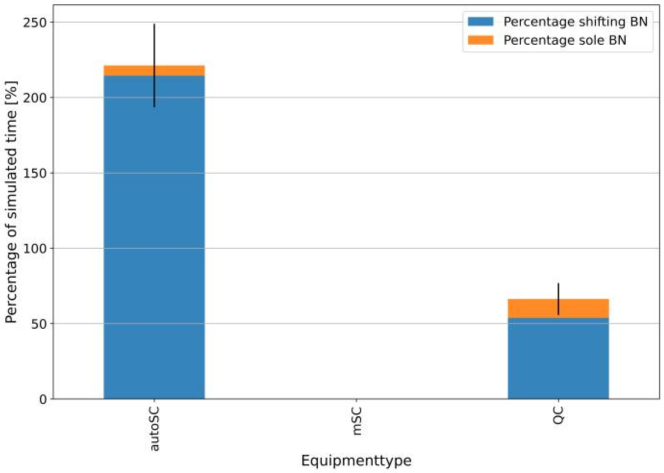

Fig. 11: Results of application of the shifting bottleneck method using 30 autoSCs, 24 mSCs, 2 QCs and a truck workload of 81 boxes per hour with a significance level of 0.05. BN: bottleneck

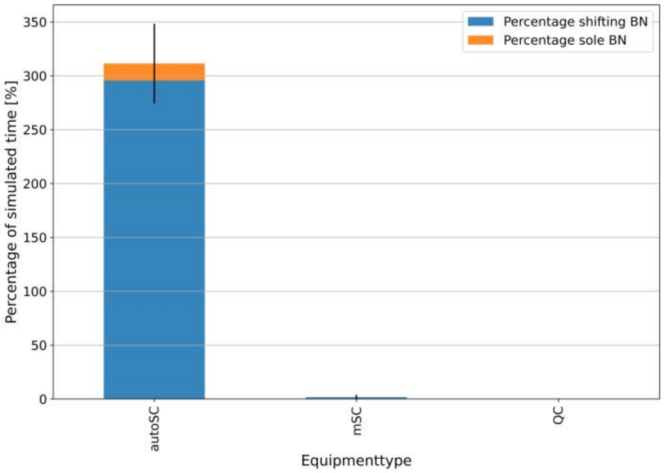

Fig. 12: Results of application of the shifting bottleneck method using 30 autoSCs, 24 mSCs, 6 QCs with improved technical specifications and a truck workload of 81 boxes per hour with a significance level of 0.05. BN: bottleneck

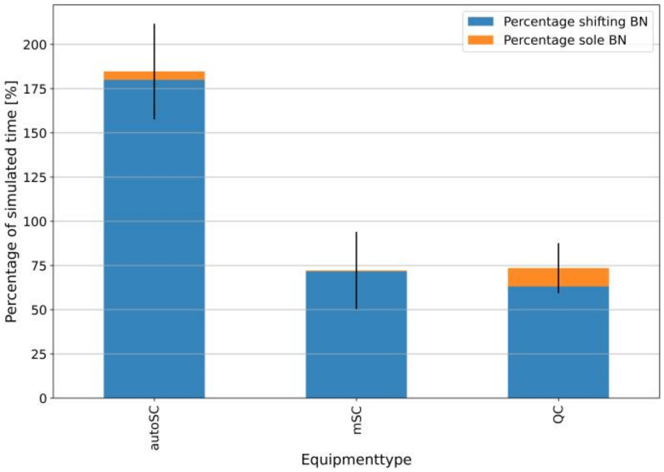

Fig. 13: Results of application of the shifting bottleneck method using 30 autoSCs, 24 mSCs, 6 QCs and a truck workload of 8 boxes per hour with a significance level of 0.05. BN: bottleneck

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