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Simulation-Based Analysis of Conflicting Objectives of Quay Cranes and Terminal Trucks at Container Terminals

Simulationsbasierte Analyse von Zielkonflikten von Containerbrücken und Terminal-Trucks auf Containerterminals

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Abstract: Quay cranes are essential operating systems at container terminals. Their scheduling involves conflicting objectives, such as minimising vessel handling times, maximising productivity, and reducing the number of required terminal trucks. Logistic Operating Curves, known from production logistics, offer a suitable method for analysing such trade-offs and can be derived and validated through simulation. This paper proposes a simulation model of a container terminal to develop and parameterise characteristic Logistic Operating Curves. The analysis focuses on the conflict between quay cranes productivity and number of terminal trucks. Different assignment procedures for terminal truck are considered to examine their impact on system productivity.

1 Introduction and Problem Definition

Ports face growing operational challenges due to the increasing size of container vessels, which affects capacity planning and cargo handling efficiency. Negotiations between terminal operators and shipping lines require a clear understanding of operational costs to enable informed decision-making (UNCTAD 2024).

This paper presents a first step towards this by applying Logistic Operating Curves (LOC) to container terminals. Unlike complex and costly simulations, LOC provide a simplified approach to identifying the optimal operating point without the need for immediate optimality. While terminal operations have already been analysed using mathematical models and simulations. For instance, Dragovic et al. (2017) present a comprehensive review of simulation-based studies related to port development, highlighting the growing importance of simulation models in analysing and improving operational aspects of container terminals. However, before deriving LOC for container terminals, it is necessary to create a simulation environment to initially parametrise and validate the LOC within the container terminal context. This step is essential for establishing the methodology. The developed model highlights the importance of accurately representing various process elements and processing times to create effective LOC. Simulation models help terminal operators better understand their operations, make well-informed decisions, and improve container handling efficiency. With this approach to transfer the LOC to container terminals, a proven method from production logistics could provide a less complex method for the port operators. Although container terminals are highly dynamic systems, there is currently no straightforward method to illustrate how operational performance depends on key influencing factors as the LOC does. In manufacturing LOC have proven useful for this kind of analysis, offering a clear view of performance trade-offs (Nyhuis and Schmidt 2025).

This paper introduces a simulation model specifically designed to capture the essential processes of container terminals and to lay the groundwork for applying and validating LOC in this context. At this stage, the model focuses exclusively on seaside operations, allowing for a targeted productivity analysis between quay cranes (QC) and terminal trucks (TT). To reflect operational realities and assess their impact on performance, different assignment procedures for TT are considered from the outset.

2 Theoretical Background and State of Research

In the following, the subject of the study, container terminals, is addressed first (Section 2.1), followed by the LOC (Section 2.2).

2.1 Container Terminals

Container terminals are complex systems divided into functional areas: seaside handling (ship-to-terminal), yard storage, and landside handling (e.g., rail loading). Various equipment combinations are used across these areas. This study presents a simulation model focused on seaside operations, including ship-to-shore cranes QC and horizontal transport TT between quay and yard (see Figure 1).

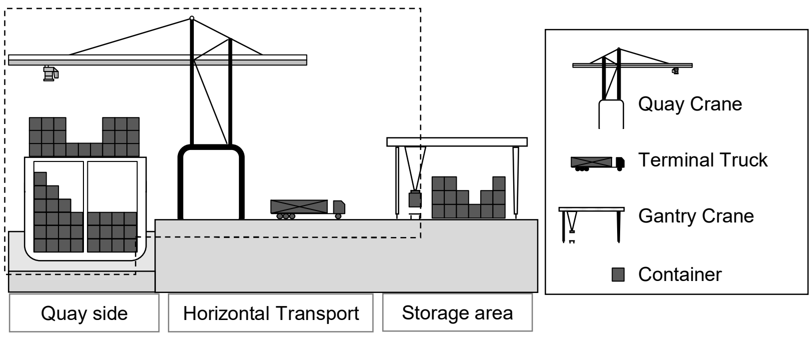

Figure 1: *Schematic overview of a container terminal (cf. (Schwientek 2022))*

Container terminals face increasing pressure to remain competitive in a rapidly evolving maritime logistics environment. In light of intense competition, maintaining high service quality while minimizing operational costs has become essential (Lun et al. 2023). QC productivity depends heavily on the coordination with horizontal transport TT. If no TT is available, QCs experience delays and reduced efficiency. In this context, the simulation model and the application of LOC are used to systematically investigate how the number of TTs affects QC productivity and to what extent different TT assignment procedures influence this interdependence. Kizilay et al. (2017) propose integrated Mixed Integer Programming and Constraint Programming models to jointly optimize QC assignment, scheduling, yard location assignment, and vehicle dispatching in container terminals, aiming to minimize vessel turnaround times and enhance terminal throughput. Zhang et al. (2019) investigate key logistical performance indicators of container terminals by modelling terminal operations using a closed queuing network and analysing system performance bounds based on generally distributed service times. While this provides valuable theoretical insights, the present approach complements it by focusing on the operational implications of different TT assignment procedures and explicitly modelling the dynamic interaction between QC and TT through simulation.

2.2 Logistic Operating Curves

LOC show logistical objectives over a control variable (Nyhuis and Schmidt 2025). These are typically used in production logistics. There, logistical objectives such as mean output rate, mean capacity utilisation or mean throughput time are usually shown as a function of mean work in progress (Lödding 2013). The LOC thus represent a large number of possible operating points that can be achieved by changing the mean work in progress. LOC can be created either for individual work stations or for the entire production. The typical relationship between the mean work in progress and the mean output rate is as follows in Figure 2.

With low mean work in progress, only a low output rate can be achieved by the system under consideration. As the mean work in progress increases, the output rate initially rises proportionally in the so-called underload zone. In the transition zone, the output rate increases more slowly and gradually approaches its maximum. In the overload zone, where sufficient work is always available and no interruptions occur due to a lack of work in progress, the output rate remains approximately constant at its maximum value (Lödding 2013; Nyhuis and Schmidt 2025; Nyhuis and Wiendahl 2009).

When the First In – First Out principle is applied, the throughput time is calculated according to Bechte's (1984) funnel formula from the mean work in progress divided by the mean output rate. The mean throughput time therefore initially has a constant, minimal value for low mean work in progress, which cannot be undershot due to the process times before it rises proportionally with the mean work in progress from the transition zone onwards.

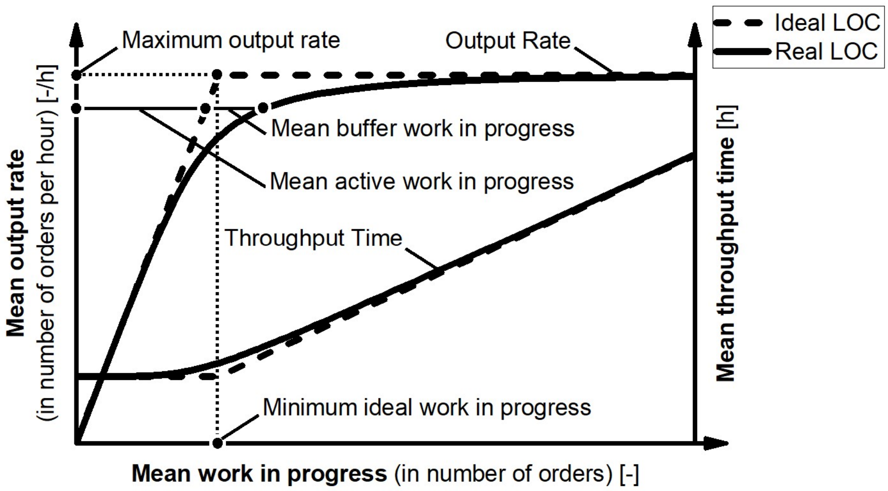

Figure 2: *Ideal and real Logistic Operating Curve (cf. (Nyhuis and Wiendahl 2009))*

These diagrams quickly reveal a number of conflicting objectives, particularly the trade-off between output rate and throughput time. Companies must therefore position themselves accordingly, and LOC help them to do so (Lödding 2013; Nyhuis and Schmidt 2025; Nyhuis and Wiendahl 2009). LOC can also be used in the context of seaport container terminals. For example, logistical objectives such as the productivity of QC or vessel handling times can be plotted against the number of equipment used for horizontal transport, such as TT. To create such LOC, a deductive-experimental approach is usually followed (Nyhuis and Wiendahl 2009). First, an ideal state of the system is considered, assuming the following conditions: At any given time, there is exactly one order at the system under consideration. The order is processed immediately upon receipt. Under these conditions, both the maximum possible output rate of the system and the ideal minimum work in progress level, and thus the ideal LOC, can be determined. Since real processes deviate from these conditions due to factors such as scattered process times, approximation equations are derived in a second step. In order to achieve the same mean output rate as in the ideal case, a buffer work in progress is required in addition to the mean active work in progress (see Fig.2) (Lödding 2013; Nyhuis and Schmidt 2025; Nyhuis and Wiendahl 2009). When multiple work stations operate in parallel, queueing theory shows that using a common queue for all parallel work stations reduces work station idle times and thus leads to higher mean output rates with the same mean work in progress, or in other words: It stands to reason that using a shared queue instead of one queue per work station reduces the buffer work in progress required to achieve the same output rate (Smith and Whitt 1981).

Simulations are generally used to enable this and to validate the approximation equations determined (Nyhuis and Wiendahl 2009). Therefore Nyhuis and Wiendahl (2009) use the simulation software PROSIM III and show the relationship between the mean work in progress and the mean output rate of a production system. Grafelmann and Alieksieiev (2023) used Tecnomatix Plant Simulation to address logistics objective conflicts at intermodal terminals. As far as the authors are aware, no LOC-based analysis of the objective conflicts on the sea side of container terminals has been carried out to date, so this will be addressed in this paper. The simulation model presented in this paper should thus enable the development and validation of an approximate LOC for QC productivity as a function of the number of TT and investigate the effects of different order assignment procedures for TT to QC.

3 Methodological Approach

As illustrated in the following Figure 3, the simulation model aims to analyse the conflict between the number of available TT and the productivity of the QC. Based on the results of the simulation runs, the LOC are set up, which show the target conflicts between the number of available TT and the productivity of the QC in consideration of different assignment procedures for the transport orders for the TT in more detail.

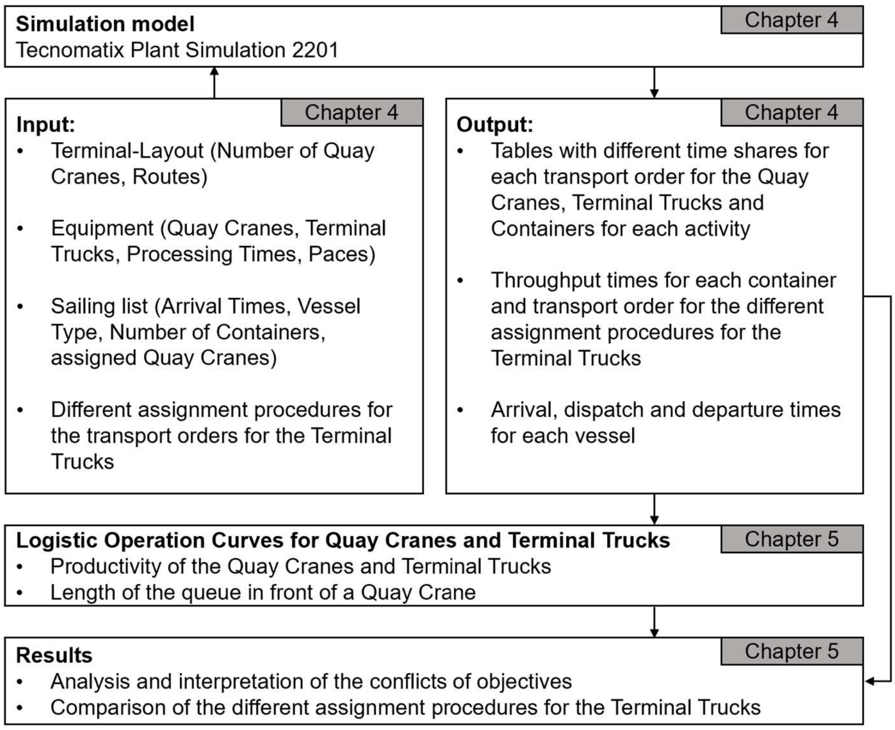

Figure 3: *Methodological framework*

A discrete-event simulation with Tecnomatix Plant Simulation 2201 software is used to visualise and simulate the necessary resources and process sequences. Time stamps and other statistical time values can be recorded in the software and tables can be written after the simulation. These tables with the time values are essential for the creation of the LOC, as they are used as the basis for the LOC and provide the necessary statistical values and time elements of the simulation.

This study presents a simulation model that represents a seaport container terminal with various QC and TT. The model includes all necessary resources and processes to perform evaluations and generate LOC. A literature review provides the statistical values and processing times for individual throughput elements. Many parameters that are important for our experiments can be set and adjusted. Tables with individual times for the various throughput elements can also be written automatically in the software and the entire throughput evaluated at the end.

4 Model Description

In order to generate the necessary statistical values for creating the LOC, the model has been set up in such a way that statistical values and times for both the TT and QC are automatically recorded using time stamps and saved in tables.

The following Figure 4 shows the way in which the vessel handling process works in the simulation model. One constant in the simulation runs is the sailing list, which always remains the same and specifies the incoming vessels. A distinction is made between the vessel types feeder, small deep-sea vessel and large deep-sea vessel. The different vessel types trigger a different number of import and export containers in the model. The simulation run starts with the arrival of the first two vessels in the harbour. The respective vessels have fixed QC assigned in the sailing list, which are responsible for handling the vessels. The containers of a vessel are evenly distributed to the relevant QC. All the vessel's import containers are unloaded first and then all the export containers from the storage area are loaded onto the vessel. The TT for the transport processes belong to the general TT pool of the terminal. Once a QC has finished handling the vessel, it`s status is switched back to available. The vessels that arrive later in the simulation wait at anchorage until all the QC assignments for them are available. They can then enter the port and moor at the quayside. Once all the vessels on the sailing list have been completed, the simulation is finished.

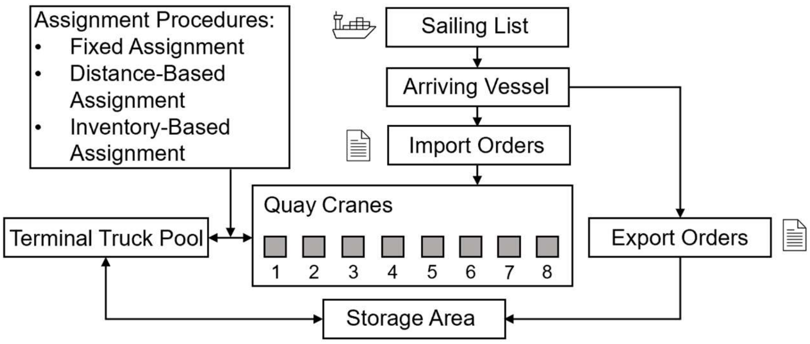

Figure 4: *Vessel handling process*

The simulation model implements various assignment procedures for assigning the TT to the transport orders. One procedure is, that the TT are permanently assigned to the respective QC. This is the standard version found at most container terminals today. As described in section 2.2, there is potential for improvement here based on queueing theory. It may be possible to reduce the number of TT required to achieve the same mean productivity of the QC by not assigning the TT to a specific QC, but instead making them available to all QC in the form of a shared queue. To exploit this potential, two different assignment procedures have been implemented. The first is the distance-based assignment. With this procedure, after each transport order completed by a TT, a new assignment is made to one of the QC, whereby the TT is assigned to the QC with the shortest distance. This procedure aims to reduce the travel distances of the TT and thus increase the time they spend at the QC, protecting them from productivity losses. The second procedure is the inventory-based assignment. With this method, after each completed transport order, the TT check which QC has the smallest inventory of TT and are assigned to it. In this context, the number of TT that are currently assigned to the respective QC or are on their way to it is referred to as the inventory. Simulation runs are carried out with these three assignment methods for TT. After the simulation runs have been carried out, these assignment procedures are compared with each other in order to determine the most effective procedure and thus to be able to make recommendations for practical implementation. A further variance in the simulation runs is the number of TT used in the simulation. Simulation runs are carried out with 8, 16, 24, 32 and 40 TT. For each of the scenarios, 50 simulation runs are carried out.

In this step, the simulation model considers fonly variations in operating times. These occur, for example, during vessel berthing or in the handling of transport orders at the QC and by the TT, which result in waiting times. However, other types of disturbances or exceptional events that could cause extreme values are not considered at this point. This fact leads to only minor deviations and thus to a process that is relatively close to the ideal process.

5 Results and Discussion

To generate a simulated LOC for QC productivity, the simulated value pairs from the mean QC productivity and the number of TT from the simulation runs. These pairs are plotted in a coordinate system (see Fig. 5).

The number of TT is an input value for the simulation. The mean QC productivity is determined from the number of containers, i.e. the number of transport orders, and the duration of the vessel handling orders per QC, and averaged over the number of simulation runs. In addition, the vessel handling times, also averaged over the number of runs per number of TT, can be plotted against the number of TT to obtain the LOC of the vessel handling time in a second diagram (see Fig. 6)

As already described in section 2.2, and as is usual for LOC, productivity initially rises sharply below the increase in horizontal transport equipment before approaching a maximum value of 26.34 transport orders per hour in the transition area, which is not exceeded even in the overload area when transport capacities are further increased. It can also be seen that the course of the LOC depends heavily on the assignment procedure chosen for the TT to the QC. For example, the transition area is much wider for distance-based assignment than for fixed and inventory-based assignment. It can also be seen that the mean QC productivity in the underload and transition areas is higher for fixed assignment than for distance-based and inventory-based assignment. The values for distance-based assignment are significantly lower than those for the other procedures.

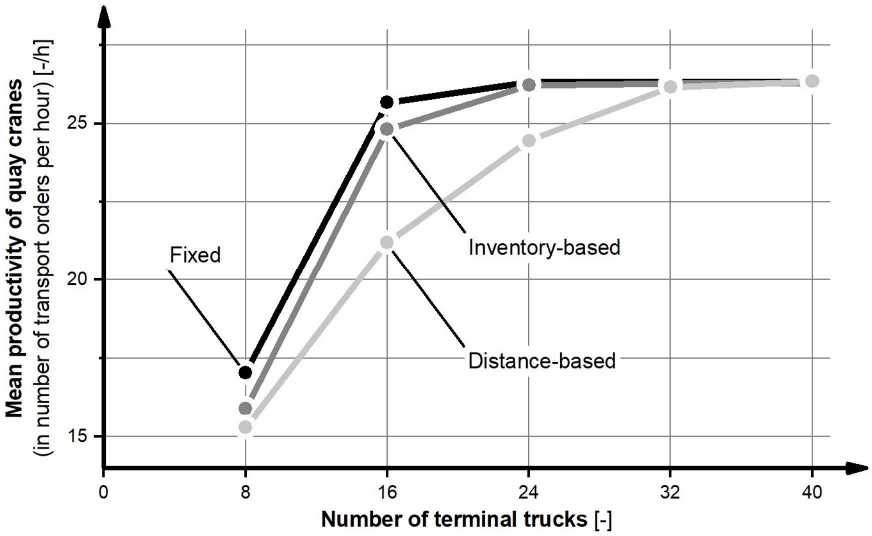

Figure 5: *Comparison of mean productivities of quay cranes for fixed, distance-based and inventory-based assignment over number of terminal trucks*

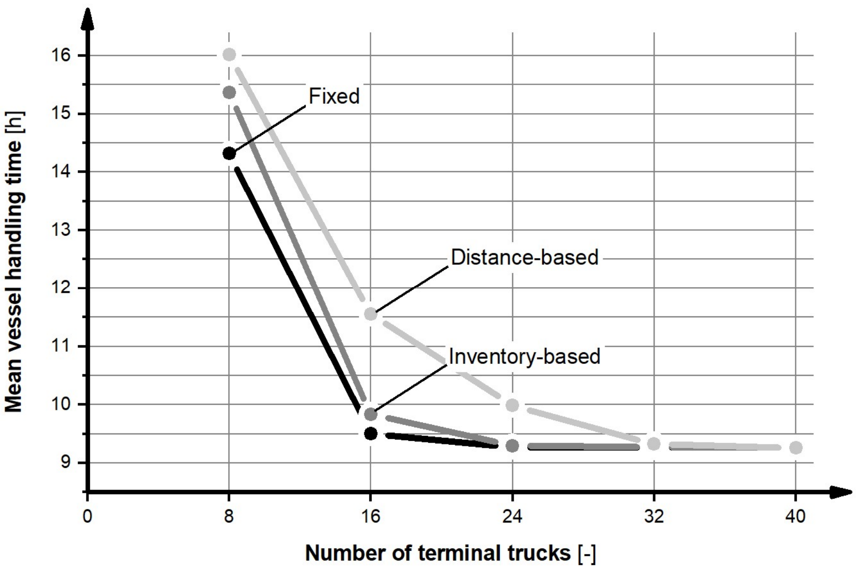

Figure 6: *Comparison of mean vessel handling times for fixed, distance-based and inventory-based assignment over number of terminal trucks*

The simulation-based LOC for vessel handling times also show a comparison of the assignment procedures. The expected trend is also evident in this logistics objectives. The more equipment is provided, the shorter the mean vessel handling time becomes. This correlation applies up to a certain number of TT, after which the mean vessel handling time decreases only slightly and then approaches a minimum value.

This minimum value is not exceeded even if the number of equipment is increased further. For the assumptions described in this publication, this minimum value is 9.26 hours. Both the fixed and inventory-based assignment achieve this value with 24 TT i.e., 3 TT per QC. In the case of distance-based assignment, it is achieved with 32 TT i.e., 4 TT per QC.Both forms of representation thus support the positioning of terminal operators with regard to the logistics objectives of QC productivity, vessel handling time and the number of equipment used for horizontal transport and the associated costs. These simulated LOC can also be used to illustrate the assignment procedures and their effects on positioning. Contrary to our expectations, the results show that fixed assignment works better than inventory-based assignment and, in particular, distance-based assignment. We attribute this to the following points: Although distance-based assignment reduces the average travel distances of TT, giving them more time to protect the QC from productivity losses, the method also leads to TT repeatedly gathering at a few centrally located QC over time, thereby neglecting all other QC. The method therefore improves the situation for a few QC, but at the same time worsens it for the rest, resulting in overall poorer performance than with fixed assignment. The expected benefit of inventory-based assignment was that this assignment would be able to leverage the potential of the shared queue. This has not happened either. The poor performance of this method is attributed to its implementation. While in a shared queue, the assignment of a TT to a QC would only take place at the last moment, i.e. at the very front of the queue, in the procedure we implemented, the assignment takes place after the last transport order of the TT has been completed and thus at the point in time when the TT would ideally only join the shared queue. This time difference means that the TT is assigned to the QC with the lowest inventory, but the inventory of the QC changes until the TT actually arrive, which means that a different situation may have arisen by that time. Furthermore, the number of TT in the inventory of a QC is not defined solely as the TT that are currently queuing at the QC or are currently being handled by it. Rather, it also includes TT that are already or still assigned and are transporting containers to or from it. This definition has also been found to lead to poorer functioning of the assignment procedure. This means that the concrete implementation of the procedure is not able to function better than the fixed assignment. It should also be noted that, as described in Chapter 4, the process implemented in the simulation does not contain any disturbances. It is quite likely that the performance of the different procedures will change in the event of disturbances.

6 Conclusion and Outlook

This study modelled the key seaside operations of container terminals in Siemens Plant Simulation, laying the foundation for the application LOC in this context. Various assignment procedures for TT were implemented and evaluated. The simulation results confirm well-known relationships from production logistics: increasing the number of TTs initially improves QC productivity and reduces vessel handling times, up to a saturation point. Moreover, the different assignment procedures significantly influence the LOC curves and thus directly impacts the number of required TT to achieve high QC productivity. Fixed and inventory-based procedures consistently outperformed distance-based approaches under the given assumptions.

In future work, the assignment procedures will be refined using the knowledge gained in order to improve their performance and analysed under the influence of disturbances. We have gained concrete insights into how to better design inventory-based assignment in particular, and are confident that we can translate the described potential of a shared queue into a practical procedure. Additionally, the simulated LOC will serve as the basis for deriving a parameterised approximation equation. This approximation will later be tested and evaluated using simulation experiments based on a structured experimental design. These steps aim to make the LOC approach a robust decision support tool for terminal operators in balancing equipment use and performance objectives.

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