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Sustainable Synchronization of Truck Arrival and Yard Crane Scheduling in Container Terminals: An Agent-Based Simulation of Centralized and Decentralized Approaches Considering Carbon Emissions

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Abstract: Background: Container terminal congestion is often measured by the average turnaround time for external trucks. Reducing the average turnaround time can be resolved by controlling the yard crane operation and the arrival times of external trucks (truck appointment system). Because the truck appointment system and yard crane scheduling problem are closely interconnected, this research investigates synchronization between the approaches used in truck appointment systems and yard crane scheduling strategies. Rubber-tired gantry (RTG) operators for yard crane scheduling operations strive to reduce RTG movement time as part of the container retrieval service. However, there is a conflict between individual agent goals. While seeking to minimize truck turnaround time, RTGs may travel long distances, ultimately slowing down the RTG service. Methods: We address a method that balances individual agent goals while also considering the collective objective, thereby minimizing turnaround time. An agent-based simulation is proposed to simulate scenarios for yard crane scheduling strategies and truck appointment system approaches, which are centralized and decentralized. This study explores the combined effects of different yard scheduling strategies and truck appointment procedures on performance indicators. Various configurations of the truck appointment system and yard scheduling strategies are modeled to investigate how those factors affect the average turnaround time, yard crane utilization, and CO_2 emissions. Results: At all levels of truck arrival rates, the nearest-truck-first-served (NTFS) scenario tends to provide lower external truck turnaround times than the first-come-first-served (FCFS) and nearest-truck longest-waiting-time first-served (NLFS) scenario. Conclusions: The decentralized truck appointment system (DTAS) generally shows slightly higher efficiency in emission reduction compared with centralized truck appointment system (CTAS), especially at moderate to high truck arrival rates. The decentralized approach of the truck appointment system should be accompanied by the yard scheduling strategy to obtain better performance indicators.

Keywords: agent-based simulation; decentralized; carbon emissions; synchronization; truck appointment system; yard scheduling strategy

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1. Introduction

Ports are vital to the global logistics network, handling approximately 80% of international trade by volume [1] and playing a distinct role in promoting sustainability within the shipping industry [2]. Recognizing sustainability as a global concern, the United Nations (UN) introduced the sustainable development goals (SDGs) in 2015, setting 17 goals, 169 targets, and 230 indicators to drive global change by 2030. The International Maritime Organization (IMO) has highlighted the significance of the shipping industry in achieving all SDGs by facilitating global trade and economic growth [3]. As hubs of activity and key economic centers, ports contribute significantly to the global SDG agenda. Sciberras and Silva [3] provided a UNSDG-based sustainability framework for ports, addressing actions aligned with specific SDGs. Several sustainability actions related to drayage operation are reducing related traffic congestion (SDG 11: sustainable cities and communities), optimizing freight traffic (SDG 9: industry innovation and infrastructure and SDG 12: responsible consumption and production), and controlling pollution through all activities (SDG 6: clean water and sanitation).

However, despite these sustainability efforts in the drayage operation, real-world conditions present significant challenges. Many ports experience significant delays in container transportation due to capacity constraints in both ports and road networks, leading to congestion. The congestion that occurs both inside and outside the port causes various losses, including a decline in productivity in container terminal operations, high logistics costs, longer truck operating times, and increased pollution (fuel emissions). Chen et al. [4] stated that congestion causes emissions from idling trucks. Idle trucks operate inefficiently, with an energy efficiency level of around 3% compared with trucks that operate at 40% energy efficiency. Idle trucks produce high levels of NOx and particulate matter (PM), both of which are substances that significantly contribute to air pollution.

A key factor contributing to terminal congestion is the fluctuating arrival of external trucks, which can result in mismatches between resource constraints and container transportation activities [5]. Shipping companies own external trucks that move containers between depots and terminals [6]. When container transportation activity exceeds resources, turnaround times are delayed, and when resources exceed container transportation activity, resources are wasted [5].

Port congestion causes significant losses for container terminals, shipping companies, and consignees. For container terminals, severe congestion can delay or even halt yard operations as yard cranes struggle to move among the many external trucks, making these terminals less attractive to shipping companies seeking efficient pick-up and delivery services [7]. Shipping companies also incur losses due to port congestion, facing increased shipping times and higher costs for loading and unloading activities, and may need to reroute ships, further degrading service quality [8]. Consignees and trucking companies experience delays in pick-up and delivery times due to high congestion levels, leading to increased fuel and labor costs, and container shortages can drive up rental costs when demand outpaces supply [9]. Port congestion is often measured by the average turnaround time for external trucks, which encompasses the period from a truck's entry to its exit after completing a container transaction. Increased turnaround times indicate higher congestion, impacting terminal efficiency and trucking company performance [6]. Congestion at both the gate and in the yard causes high truck turnaround times within the terminal [10]. Reducing congestion can significantly shorten these turnaround times, leading to improved customer satisfaction [11]. Researchers in [12] describe the cost of yard congestion in terms of truck turnaround times. When yard cranes are occupied due to congestion in yard blocks, this results in longer turnaround times for external trucks being serviced in those areas. There is a clear connection between available time for the container terminal and the trucking company with container terminal space related to truck densities and storage spaces, as coordinating the arrival of external trucks can help reduce congestion in the terminal's storage areas [6].

To manage growing container volumes, ports must achieve faster turnaround times and greater container throughput, which refers to the efficiency and speed of moving goods through the transport chain [11]. The efficiency of a container terminal is typically evaluated by two key metrics: (1) the duration of vessel berthing and (2) the turnaround time for external trucks [6]. Reducing truck turnaround time in terminals is a critical concern for container terminals, trucking companies, and government regulators [10].

Truck turnaround time is derived from the sum of the truck waiting time and the truck service time. Waiting time is the idle time of the truck before being serviced; service time is the time required to move containers. Increased waiting time reduces the operational efficiency of the terminal's stacking yard [13]. The depiction of the activity flow considered in truck turnaround time can be seen in Figure 1.

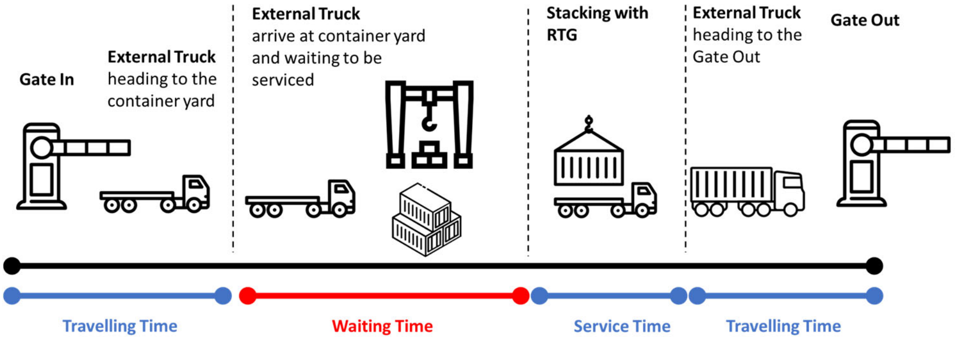

Figure 1. External truck turnaround time in container terminal.

Due to the limited land area available for expansion around most ports, terminal operators must find ways to enhance productivity using existing resources [11]. Two potential solutions are as follows: (1) expediting container service times and (2) regulating the arrival times of external trucks. Numerous studies have examined these methods to reduce average truck turnaround times. The container service time can be reduced by deploying more yard cranes and minimizing the frequency of container relocations [14,15]. Huynn et al. [14] employed a simulation to assess how many additional yard cranes would be needed to meet the desired turnaround time. Their findings demonstrated that increasing the number of cranes can substantially decrease the average turnaround time. Additionally, container relocations affect service times; when trucks arrive, containers may need to be shifted if stacked underneath others. Boysen and Emde [15] explore solutions to these challenges using operational research techniques to speed up the service time for external trucks. They suggest that implementing a truck appointment system is an efficient way to manage and control truck arrival times. This system allows for more efficient scheduling of container pick-up activities.

It is important to recognize that the truck arrival process and container handling operations are interconnected. Minimizing the truck waiting time in the yard, which consumes the largest share of turnaround time, is essential for reducing overall turnaround time [16]. Reducing turnaround time can be beneficial for alleviating congestion, optimizing freight traffic, and reducing pollution, which ultimately contributes to achieving the SDG targets for 2030, particularly SDG 6, 9, 11, and 12. Therefore, it is valuable to study a coordinating approach to optimize yard crane working time with truck appointments [17]. Trucks queue at terminal gates until yard cranes are available to serve them, and, once in the yard, turnaround time depends on both the truck-to-crane ratio and the yard crane service strategy [18]. Effective synchronization between the gate and yard is essential for designing an efficient truck appointment system [19].

External truck congestion at ports primarily stems from issues related to resource allocation and gate scheduling. Although tracking real-time queue lengths at gates can help in developing appointment systems, the actual port operations involve a complex interplay of three main subsystems: (1) berth, (2) yard, and (3) gate system [19]. In this study, we concentrate on these interrelationships and thoroughly investigate the synchronization of truck arrival scheduling with the yard crane scheduling strategy in the container terminal yard. The authors examined yard scheduling strategies in combination with both centralized and decentralized truck appointment procedures, assessing how these combinations impact terminal performance. To clarify the specific contributions of this study, the following key areas were addressed:

1. Comparison of yard scheduling strategies: compared existing yard crane scheduling strategies, specifically focusing on FCFS (first-come-first-served) and the proposed

NTFS (nearest-truck-first-served) and nearest-truck longest-waiting-time first-served (NLFS), to assess operational efficiencies.

2. Comparison of centralized and decentralized truck appointment procedures: evaluated the impact of centralized vs. decentralized procedures on truck turnaround times and yard efficiency.
3. Performance assessment of combined strategies: assessed the effect of combining different yard scheduling strategies with both appointment systems to understand their influence on terminal performance.
4. Carbon emissions analysis: measured carbon emissions across different combinations of yard scheduling and truck appointment strategies to identify environmentally efficient practices.

2. Related Works

This study investigated the interrelationship between the procedures used in the truck appointment system and the yard scheduling strategy. Therefore, this literature review examines extant research into yard scheduling strategy and truck appointment systems, and research that combines these two methods, namely the integrated truck appointment system with yard crane scheduling strategy.

2.1. Yard Scheduling Strategy

Enhancing container service times can be accomplished by augmenting the quantity of cranes deployed within the storage yard and minimizing the need for container relocations [14,15]. In [14], simulation methods were employed to determine how many extra yard cranes would be required to reach the target average turnaround time for external trucks. Their research indicated that increasing the number of cranes significantly reduces the average turnaround time for external trucks. Adding more yard cranes to reduce truck turn times may appear to be a straightforward solution for terminals that stack containers. However, the significant initial investment required to install additional cranes, along with the increased ongoing maintenance and operating expenses, poses significant barriers to this seemingly obvious solution. Seeking alternative solutions, Kim et al. [16] tested various sequencing methods to deploy yard cranes more effectively, thereby reducing the in-terminal wait time of trucks. Huynh and Vidal [18] employed an agent-based simulation to examine a specific aspect of the issue: the service strategies of yard cranes. Their goal was to identify the optimal strategies for minimizing truck wait times, considering the random arrival of trucks.

One issue that prolongs service time for external trucks is container relocation. When picking up or dropping off containers, external trucks often encounter containers that are stacked beneath others, necessitating the relocation of the upper containers first. Boysen and Emde [15] addressed this problem using operational research methods to expedite service times for external trucks. Wasesa et al. [20] proposed a synchronization policy that assigns the requests of the incoming trucks to the topmost container. They found that achieving a 100% utilization rate of the synchronization policy will reduce the probability of relocation to less than 1%.

Diverging from the approach in [18], this study instead synchronizes yard scheduling and truck appointment systems, focusing on the yard scheduling model that aims to minimize truck turnaround time, that is, the shared performance indicator for each problem involved, instead of other performance indicators for yard scheduling problems.

2.2. Truck Appointment System

In the operational decision-making process, a truck appointment system considers the available time for container terminal resources and trucking company resources (such as trucks and drivers) as well as the terminal's capacity in terms of truck density and storage space [6]. The review study written by the author in [19] describes the truck appointment system as a two-factor decision-making framework focused on time and space. Its objective is to balance the flow of trucks arriving at the gate throughout the day, thereby reducing the strain on the terminal's physical capacity.

Relevant truck appointment systems can be categorized based on various methods, such as (1) determining reservation quotas, (2) scheduling and optimizing truck arrivals, (3) scheduling and optimizing truck arrivals with collaboration, and (4) minimizing empty truck trips. Research studies can also be organized based on the approaches they utilize, such as queuing theory, mathematical modeling, simulations, or a mix of these techniques, as demonstrated in a variety of the academic literature.

The first method, vessel-dependent time windows (VDTWs), sets a limit on the volume of trucks permitted to arrive within each designated time window. Chen et al. [21] introduced the VDTW method to control truck arrivals by categorizing trucks and allocating them to different time windows. Gracia et al. [22] analyzed the effects of gradually introducing a truck appointment system and a dedicated entry lane approach for external trucks on waiting times through simulations. Their findings indicated that increasing the number of trucks using the appointment system led to a reduction in average waiting times. Huynh [23] investigated the effect of truck quotas on average turnaround times, and showed that optimal truck quotas can significantly lower turnaround times. Torkjazi et al. [24] proposed a method to evenly spread truck arrivals across the day to prevent congestion at gates and yards, while also taking into account drayage truck routes.

The second approach focuses on coordinating truck arrivals by balancing the objectives and constraints of the trucking companies and the container terminal. This system considers the available resources and terminal capacity regarding truck density and storage space [6]. Huiyun et al. [19] described this method as a two-dimensional decision-making system that balances truck arrivals over time to reduce spatial pressure at the terminal. Truck scheduling entails selecting time slots for truck arrivals, which can be determined by the trucking company and the port [25–27].

The third approach involves cooperation and negotiation between trucking companies and terminal operators to determine vehicle arrival timings and manage operations during high-demand periods [25]. Phan and Kim [28] introduced a decentralized decision-making model to facilitate these negotiations. Azab et al. [12] proposed a dynamic collaboration model integrating discrete-event simulation with mixed integer programming. Wasesa et al. [29] proposed an overbooking reservation mechanism (ORM) and conducted agent-based simulations to evaluate the ORM's performance. Research indicates that using ORMs can result in high productivity and service levels while minimizing negative externalities such as long queues, overtime, and greenhouse gas emissions.

The fourth method focuses on minimizing empty trips by grouping the delivery of export containers and the pick-up of import containers. Islam et al. [30] were among the pioneers in addressing the issue of empty container trucks, proposing a dynamic truck-sharing system to allocate export containers to vacant slots in empty trucks. Schulte et al. [31] developed a truck appointment model that considers the impact of empty trips on carbon emissions and costs, using an optimization model based on multiple traveling salesman problems with time windows. Caballini et al. [32] combined optimization techniques and data analysis methods to minimize the occurrence of empty truck journeys and improve service levels using a truck appointment system. Dekker et al. [33] investigated the idea of a chassis exchange terminal, an off-dock facility where truck drivers can swap chassis to alleviate congestion.

Research on truck appointment systems often uses mathematical modeling, queuing theory, simulations, or a combination of these approaches. Phan and Kim [25,28] employed mathematical modeling to tackle the issues in their studies; Huynh [23] and Murty et al. [34] relied on simulation techniques; Zhang et al. [10] and Chen et al. [4] addressed the problem through the queuing theory; and Azab et al. [12] introduced a method that combines a mixed-integer programming (MIP) model with a simulation model to minimize turnaround times for external trucks and mitigate disruptions caused by adjusting truck arrivals away from the preferred times of the trucking companies.

Considering the goals of this study, the scheduling problem for truck arrivals can focus on maximizing resource utilization while minimizing transportation costs, truck turnaround times, waiting times, empty trips, and emissions, among other factors. Huynh and Walton [5] investigated how restricting truck arrivals affects both truck turnaround times and crane usage. Chen and Yang [27] developed an optimization model for managing export container truck operations, aiming to minimize the overall cost of export container activities. Zhang et al. [10] proposed a stationary-based queuing optimization model for truck appointments to alleviate severe congestion in container terminals; their method demonstrated high accuracy in predicting queue lengths at both the gates and the yard, and effectively reduced truck turnaround times. Azab et al. [12] use the average turnaround time of external trucks to estimate congestion costs; this approach is considered more realistic and comprehensive because it considers both waiting and service times at the gate.

As shown in Table 1, previous research has commonly utilized mathematical modeling, operational research, or discrete-event simulation approaches. However, these methods often neglect the communication and operational sequence aspects of the appointment reservation process in their formulation and evaluation of improvement proposals or models. In contrast, this study employs business process analysis and agent-based simulation techniques to analyze, propose, and evaluate the proposed solution. Unlike prior research conducted by authors in [29], which used agent-based modeling for the truck appointment system, this research investigates various configurations of the truck appointment system and yard scheduling strategies to assess how those factors affect average truck turnaround time.

Table 1. Truck appointment system literature review.

Author(s)	Controlling Arrival Times				Methodology			
	Quota	Truck Scheduling	Collaboration Scheduling	Combine Export Import Container	Mathematical Modeling		Simulation Model	Queueing System
					Exact	Approximation		
Huynh et al. (2004) [14]							✓	
Huynh (2009) [23]	✓						✓	✓
Chen and Yang (2010) [27]		✓				✓	✓	
Chen et al. (2013) [21]	✓					✓		✓
Islam et al. (2013) [30]				✓	Business Process Re-engineering			
Phan and Kim (2015) [28]			✓		✓			✓
Boysen and Emde (2016) [15]						✓		
Phan and Kim (2016) [25]			✓		✓			✓
Gracia et al. (2017) [22]	✓						✓	
Schulte et al. (2017) [31]				✓	✓			
Torkjazi et al. (2018) [24]	✓				✓			
Riaventin and Kim (2019) [26]		✓				✓		
Yi et al. (2019) [35]		✓				✓		
Azab et al. (2020) [12]			✓		✓		✓	
Caballini et al. (2020) [32]				✓	✓			
Wasesa et al. (2021) [29]			✓				✓	

2.3. Synchronization of Truck Appointment System with Yard Crane Scheduling Strategy

A few studies on the design of container terminal operations that address both the yard and gate areas in parallel are presented in Table 2. Guo et al. [36] aims to improve the efficiency of yard crane operations by using predicted vehicle arrival information to dynamically dispatch the crane. Hwang et al. [37] and Wasesa et al. [20] utilize the container arrival information to improve container terminal's performance in terms of truck waiting time. Zhou et al. [38] proposed an integrated optimization method for simultaneously determining yard crane schedules and vehicle parking positions, utilizing Chebyshev's movement to allow for the concurrent movement of the yard crane's gantry and trolley. Azab and Morita [17] presented a decision support system designed to schedule optimized truck appointments, truck service orders, and container relocations within the yard. They developed a bi-objective optimization model that considers container relocation (terminal perspective) and appointment shifting (trucking company perspective). Gao and Ge [39] proposed a model that addresses both the truck assignment and yard crane routing problems simultaneously to optimize each yard crane's servicing of the trucks and to establish the ideal sequence for yard cranes' handling of containers for each truck. Talaat et al. [40] proposed a mixed-integer programming model to optimize the scheduling of external trucks and yard cranes. The primary goals are to minimize CO_2 emissions, reduce truck turnaround time, close the gap between trucking companies' preferred and appointed arrival times, and lower the energy consumption of yard cranes. Finally, Huang et al. [41] proposed a unified model that addresses both the scheduling of trucks and empty containers in container drayage operations, along with the appointment problem.

Table 2. Synchronization of truck appointment system and yard crane scheduling literature review.

Author	Operation Area			Truck App. System		Yard Scheduling		Method			
	Yard	Gate	Drayage	Decentralized	Centralized	Seq.	Strategy	Opt.	Heuristic	DES	ABS
Guo et al. (2011) [36]	✓	✓			✓	✓		✓	✓		
Wasesa et al. (2012) [20]	✓	✓			✓		✓				✓
Hwang et al. (2019) [37]	✓	✓			✓	✓		✓		✓	
Zhou et al. (2020) [38]	✓	✓			✓	✓		✓	✓		
Azab and Morita (2022) [17]	✓	✓			✓	✓		✓			
Ma et al. (2022) [42]	✓	✓			✓	✓		✓	✓		
Gao and Ge (2023) [39]	✓	✓			✓		✓	✓	✓		
Talaat et al. (2023) [40]	✓	✓			✓	✓		✓			
Huang et al. (2024) [41]	✓		✓		✓				✓		
This research	✓	✓		✓	✓		✓				✓

Seq.—sequence, Opt.—optimization, DES—discrete-event simulation, ABS—agent-based simulation.

Based on the previous research in Table 2, this research makes several important contributions that position it distinctly within the body of prior work on yard crane scheduling and truck appointment systems. This research significantly contributes to the field by exploring the simultaneous synchronization of yard crane scheduling and external truck appointment systems. Unlike prior studies, such as Talaat et al. [40] and Ma et al. [42], which approached yard crane and truck scheduling using multi-stage programming methods, this study investigates how the combination of yard crane scheduling and truck appointments jointly influences truck turnaround time, offering a more comprehensive solution to optimize terminal operations. Additionally, this research introduces and compares both centralized and decentralized truck appointment systems, distinguishing itself from previous studies like Wasesa et al. [20], Hwang et al. [37], Gao and Ge [39], and Huang et al. [41], which primarily focused on centralized systems. By evaluating decentralized systems—where trucking companies have more control over appointment schedules—alongside centralized systems, this study highlights the increased flexibility of decentralized approaches while maintaining or enhancing key performance metrics such as truck turnaround time and yard crane utilization.

Furthermore, this research emphasizes the integration of yard crane scheduling strategies with both centralized and decentralized truck appointment systems. While many studies have addressed truck scheduling and yard crane sequencing, such as those by Guo et al. [36], Zhou et al. [38], and Azab and Morita [17], this study focuses on sequencing rules or strategies for yard crane scheduling, with a focus on feasibility in real-world systems. Unlike the works of Wasesa et al. [20] and Gao and Ge [39], which also considered scheduling strategies, this research evaluates the combination of these strategies with both decentralized and centralized truck appointment systems, offering a more comprehensive analysis of how these elements interact to improve terminal efficiency.

To achieve this, this study employs agent-based simulation (ABS), in contrast with the optimization models, heuristics, and discrete-event simulation (DES) methods used by previous researchers such as Guo et al. [36], Zhou et al. [38], Gao and Ge [39], and Hwang et al. [37]. ABS is particularly well suited for modeling dynamic interactions between agents, such as trucking companies and terminal operators, in yard crane operations where each RTG operator works independently within specific blocks. This often creates conflicts, as minimizing truck waiting times may lead to longer crane travel distances, slowing down overall service. ABS captures these complexities, allowing for flexible modeling of individual agent objectives—balancing truck waiting times with crane movement efficiency—while addressing the broader goal of minimizing truck turnaround times. Compared with static models or optimization techniques, ABS provides a more adaptable simulation environment, especially for decentralized systems where agent interactions significantly impact performance.

In summary, this research contributes significantly by synchronizing yard crane scheduling strategy and truck appointment systems—both centralized and decentralized—using agent-based simulation. It advances the field by addressing the critical gap in the literature where previous studies either focused on one system at a time or lacked integration between yard crane and truck scheduling. This holistic approach provides a new understanding of how to optimize terminal operations, reduce truck waiting times, improve yard crane utilization, and reduce CO_2 emission, distinguishing it from prior research.

3. Agent-Based Modeling Container Pick-Up

This research used the methodology of agent-based modeling (ABM) developed by Wilensky and Rand [43]. Phenomena in the container terminal, especially yard scheduling and truck appointment, can be effectively modeled with agents, an environment (yard and gate system), and a description of agent–agent and agent–environment interaction.

Each truck agent aims to minimize waiting time as a part of turnaround time so that the trucks that arrive first can be served first. However, with the objective of external trucks, the RTG transport time may increase due to activities such as back-and-forth movements and reshuffling of containers. Therefore, the objective function of the system is to minimize the average truck turnaround time at the container yard. With this shared objective function, the overall container handling activities can be minimized. To achieve the common goal while considering the independence of each agent, a utility is needed to regulate the conflict between trucks and RTG.

3.1. Yard Crane Scheduling Strategy

When external trucks arrive in the yard, they wait for an available yard crane to service them; crane operators must decide which truck to service first because multiple trucks may arrive at the same block. Various sequencing methods can be used to deploy the yard crane to the trucks, with the most common method being first-come-first-served (FCFS). However, simulation results by Huynh and Vidal [18] indicated that if crane operators select the trucks closest to them (nearest-truck-first-served, or NTFS), minimizing the need for cranes to turn frequently (a time-consuming process) and reverse direction, the overall system performance improves. The NTFS approach reduces both the average waiting time and the maximum waiting time for any truck compared with selecting trucks based on their waiting times. For comparison, we also include the merging of time-based utility (FCFS) and distance-based utility, nearest-truck longest-waiting-time first-served (NLFS). In this study, we evaluate three rules: FCFS, NTFS, and NLFS. This research models the yard scheduling strategy based on the work of Hyunh and Vidal [18] as follows.

3.1.1. First-Come-First-Served (FCFS)

Yard cranes will give higher priority to external trucks that have the longest waiting time [18]. The utility function will calculate the waiting time of external trucks as in (1).

$$u_c(t)_{FCFS} = \left[u_o(t) - u_a(t) - \sum_{i=1}^{2} M.o_{i[p(c,j)]}\right] \tag{1}$$

where $u_c\ (t)$ is RTG c utilization at event-time t. $u_o(t)$ is container handling service time at event-time t. $u_a(t)$ is external truck arrival time at event-time t. o_1 is the presence of another RTG on the RTG and external truck path. o_2 is RTG block change. $P(c,j)$ is fastest path between RTG c and target external truck j. M is a large constant number.

3.1.2. Nearest-Truck-First-Served (NTFS)

Yard cranes will prioritize service to external trucks that are closest to the yard crane. The utility function will calculate the distance between the yard crane and external trucks as in (2).

$$u_c(t)_{NTFS} = -\left[T.\ D(c,j) + \sum_{i=1}^{2} M.o_{i[p(c,j)]}\right] \tag{2}$$

where $u_c\ (t)$ is RTG c utilization at event-time t. T is time required to move to the nearest container. $D(c,j)$ is distance between RTG c and the target external truck j. o_1 is the presence of another RTG on the RTG and external truck path. o_2 is RTG block change. $P(c,j)$ is fastest path between RTG c and target external truck j. M is a large constant number.

3.1.3. Nearest-Truck Longest-Waiting-Time First-Served (NLFS)

Vidal and Hyunh [44] define the time-based (FCFS) and distance-based (NTFS) into one such as in (3).

$$u_c(t)_{NLFS} = -[T.\ D(c,j)] + u_c(t)_{FCFS} \tag{3}$$

where T is time required to move to the nearest container. $D(c,j)$ is distance between RTG c and the target external truck j. $u_c(t)_{FCFS}$ is time-based (FCFS) utility function.

3.2. Truck Appointment System Approaches

Phan and Kim [28] identify two approaches for adjusting truck arrival times in an appointment system for multiple trucking companies: (1) a centralized decision-making model (CDM) and (2) a decentralized decision-making model (DDM). CDM involves a single decision maker, typically the container terminal, making all decisions. This model is effective when the terminal has significant bargaining power over trucking companies. However, because trucking companies and terminal operators are often independent entities with their specific conditions, DDM is generally used to facilitate negotiations between trucking companies and the terminal operator.

In this study, the truck appointment system is generally operated by port operators who set a maximum quota of trucks allowed to enter a block during a specified period. From the truck company's perspective, when the quota for a particular period is reached, trucks will arrive at another period; in this study, that process is referred to as the centralized truck appointment system (CTAS). Another approach in truck appointment systems involves collaboration between trucking companies and terminals to coordinate operational activities and truck arrival schedules [28]. The mechanism used involves negotiation between several trucking companies and container terminal operators to schedule truck arrivals at the port during peak hours; in this study, that process is referred to as the decentralized truck appointment system (DTAS).

3.2.1. Centralized Truck Appointment System (CTAS)

CTAS is a truck arrival scheduling system wherein container terminal operators can manage container pick-up activities based on resource availability in the field. Truck arrivals are evenly distributed over a specific time horizon and divided into several time windows to achieve ideal conditions. The detailed process of CTAS in this research is described in Figure 2.

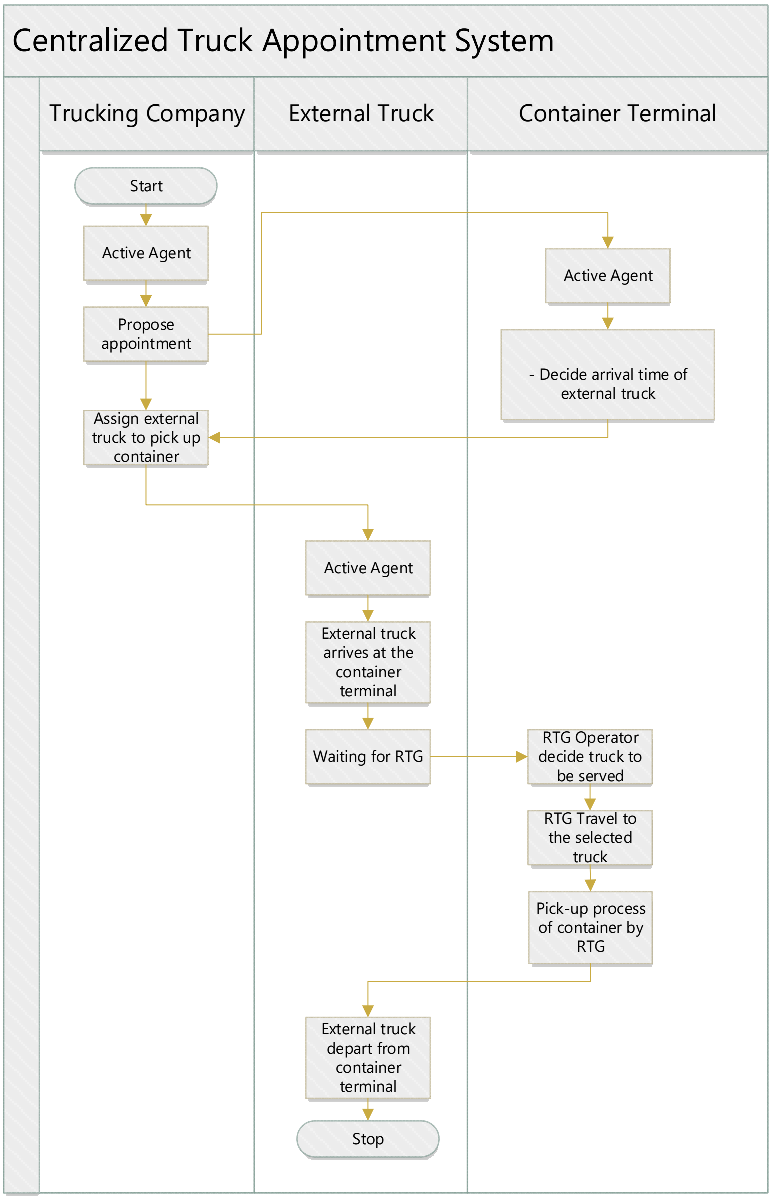

Figure 2. Centralized truck appointment system (CTAS).

3.2.2. Decentralized Truck Appointment System (DTAS)

DTAS involves determining truck arrival schedules through negotiations between container terminals and trucking companies. The decentralized negotiation model, based on an agent-based mechanism within DTAS, considers the projected waiting times that trucks are expected to experience within the container terminal zone. The essence of implementing the truck reservation system lies in scheduling truck arrival times. A negotiated truck appointment system refers to a DTAS with negotiation protocols that allow trucking companies to make changes to their arrival times at the terminal according to their preferred truck arrival schedule. Decisions are made independently by each trucking company and terminal. The detailed process of DTAS in this research is described in Figure 3.

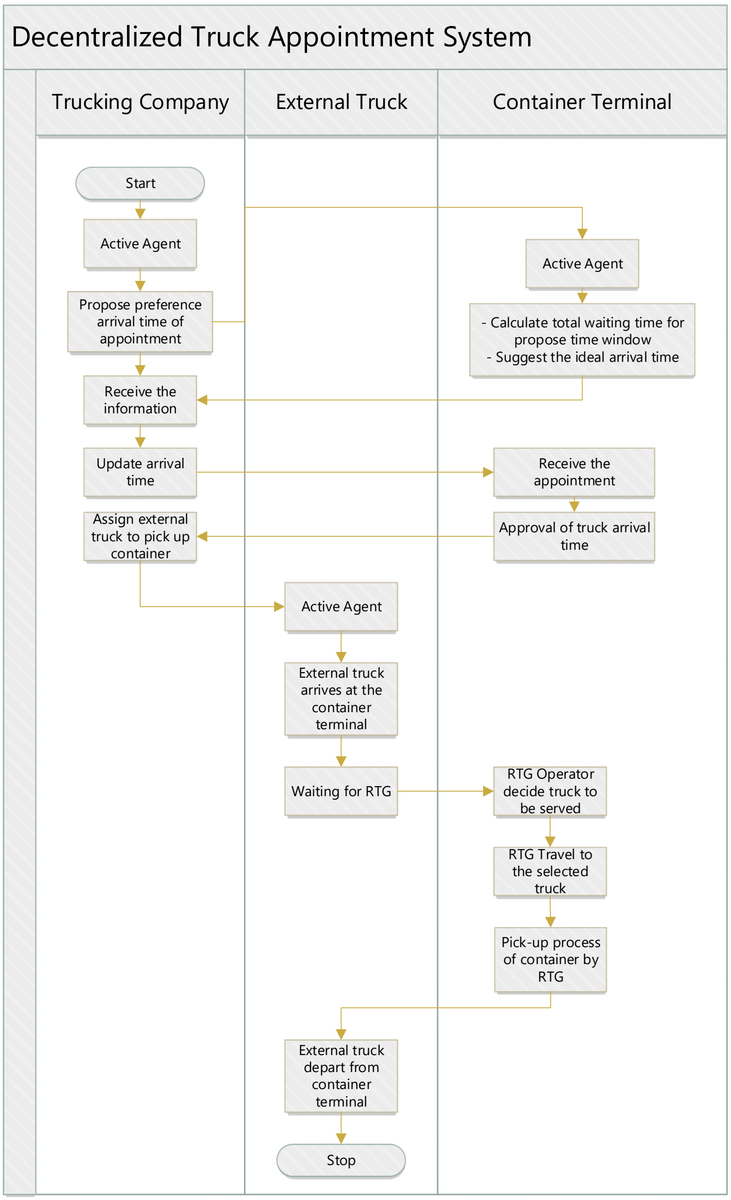

Figure 3. Decentralized truck appointment system (DTAS).

4. Agent-Based Simulation Model

4.1. Conceptual Model

To develop an agent-based simulation model, NetLogo 6.3.0 software, a simulation platform and programming language, is used [43]. The evaluation of integrating a yard crane scheduling strategy and centralized/decentralized truck appointment system is based on an agent-based simulation model that was developed in prior research [18,29]. The steps in the simulation using an agent-based model are as follows.

1. Determine the research questions that serve as the foundation for choosing an agent-based model.

The research question related to the simulation being developed is as follows: how does the external truck turnaround time change by considering the yard crane scheduling strategy and the truck appointment system mechanism?

2. Determine the type of agent.

In this simulation, there are four types of agents: (1) external trucks, (2) containers, (3) yard cranes, and (4) trucking companies. The detail of each agent is described in Table 3.

Table 3. Type of agent.

Type of Agent	Index	Task
Container(s)	$n = \{1, 2, 3, \ldots. N\}$	Containers that arrive at the stacking yard
Crane(s)	$c = \{1, 2, 3,\ \ldots 10\}$	RTG (rubber-tired gantry) crane that serves container pick-up
Truck(s)	$j = \{1, 2, 3, \ldots. N\}$	Trucks that arrive to pick up containers
Client(s)	$i = \{1, 2, 3, \ldots. N\}$	Trucking company that assigns external truck to pick up container

3. Specify agent properties.
    - Agent status: Indicates the availability of an agent acting as a resource (available or not). An agent with status is an agent providing port services and logistics such as yard cranes and trucks.
    - Agent position: Indicates the geographic location of an agent placed. An agent with a position is mobile (mobile agent) in the process, such as containers, yard cranes, and external trucks.
    - Preference: Indicates the timing of retrieval containers. An agent with preference is a trucking company.
    - Service time: Indicates the duration of service of the agent. An agent with service time is a yard crane.

The details of agent properties are listed in Table 4.

Table 4. Agent properties.

Truck(s)	
Variable	**Description**
cargo	Truck destination container
my-crane	RTG that will or is currently serving the truck
my-utility	Utility value of existing trucks
my-group	Group where the destination container is located
my-stack	Column where the destination container is located
my-start-time	Time the truck arrives in the stacking yard
waiting	True if the truck is waiting outside the port to enter because there is another truck in the same stack
on-service	True if the truck is being served by the RTG
current-idle	Current time spent idling (waiting to be serviced in the stack)
service-time	Starting ticks when truck is being serviced
my-block	Block where the destination container is located
my-terminal-time	Time when the truck arrives inside the terminal
my-queue-time	Total time truck spends queueing outside terminal
my-client	Company that owns the truck
booked-truck	Binary booking status of truck (true/false)
my-arrival-time	Time when the truck booked its slot

Table 4. *Cont.*

Crane(s)	
Variable	**Description**
goal	Destination of an RTG (external truck that will be served)
travel-distance	Distance traveled by crane
my-block	Block where the destination container is located
crane-idle	Number of idle cranes
crane-service	Number of cranes in service
state?	State of crane
t-gantry	Time needed for current gantry operation
t-liftnl	Time needed for current lift without load operation
t-lift	Time needed for current lift with load operation
t-gantry-back	Time needed for current gantry operation to the truck
gantry-position	Location of the gantry in the row
Container(s)	
Variable	**Description**
z-cor	Z-coordinate of the container
my-group	Group where the container is located
my-stack	Column where the container is located
my-row	Row where the container is located
my-truck	Truck that will or is currently picking up the container
my-crane	RTG that will or is currently serving the container
my-block	Block where the destination container is located
pick-me	False if the container's truck is not yet in the stack
Client(s)	
Variable	**Description**
my-preference	Preferred arrival time
my-bound	Time flexibility bound
my-ewt	Expected waiting time
my-wait-time	Actual waiting time for the client
my-arrival-time	Final arriving time
my-truck	External truck belongs to client
cargo	Truck destination container
my-start-time	Time the truck arrives in the stacking yard
booked-client	Binary booking status of trucking company (true/false)

4. Determine the environment and stationery agent.

The agent that becomes the environment in this simulation is the main agent. This main agent is the place where other agents are generated. Specifically, the main agent in this simulation is the container terminal, especially the landside area where the receiving and delivery takes place.

5. Determine agent behavior.

The behavior of each agent for the simulated study system is described along with the time steps.

6. Designing time step.

In the design of the time steps, the behavior of each involved agent is also described.

7. Determine the parameters and performance indicators of the model.

The performance measure in this study system is truck waiting time at the container terminal. The desired performance measure is the minimization of average truck waiting time at the container terminal. Truck waiting time at the container terminal affects the truck turnaround time. Truck turnaround time also become an important indicator of container terminals [6].

The conceptual model of the agent-based simulation is illustrated in Figure 4.

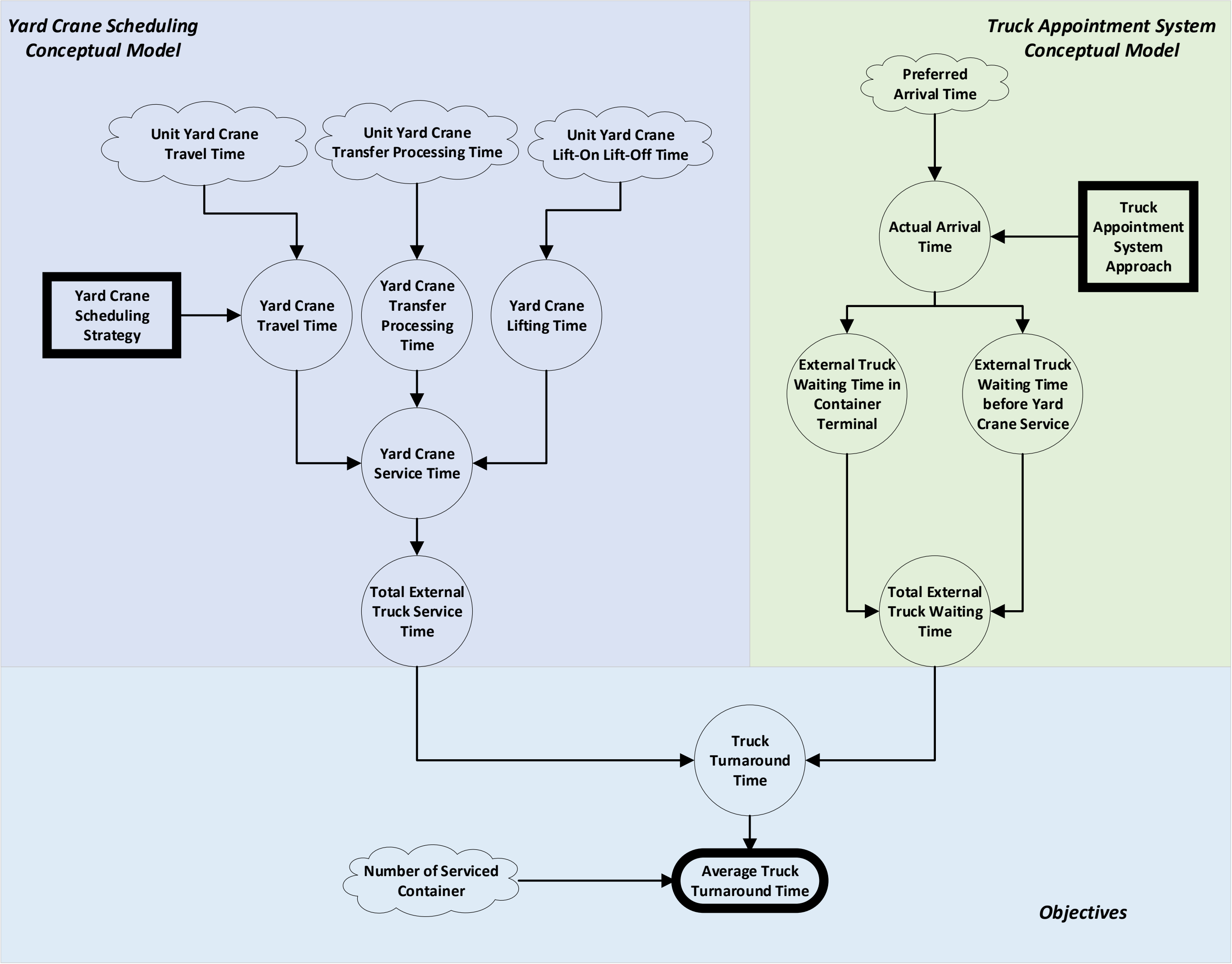

Figure 4. Conceptual model.

4.2. Agent-Based Simulation

Based on the conceptual model that has been constructed, and the method used, which is agent-based modeling that is distributed in nature, an agent-based simulation model is built. The simulation begins with the initialization of the global parameters, simulation environment, container agent, crane agent, and trucking company agent. The pseudocode of the agent-based simulation model is as follows.

```
Setup:
    Initialize agents, world, crane, and containers

Go:
    For each session:
        Initialize containers
        Initialize clients
        Perform appointments

        Appointments are made at the beginning of each session
        Reset current expected wait time
        Reset current estimation at the beginning of each session

        Set x to 1
        Calculate new appointments count
        Repeat for each new appointment:
            Choose a client with booking not yet done
            Set cargo's stack
            Update client's expected wait time
            Book cargo for client

            If decentralized procedure is enabled:
                Decentralized procedure time

Do-Arrive:
    Assign clients to create their trucks if they haven't already
    Create trucks for clients who have arrived and have cargo assigned

Appointment-Arrival:
    Handle appointment arrivals

Do-Move:
    Count trucks threshold inside the terminal
    Move the chosen truck to the container's position

Go-Crane:
    Check if it's time to perform crane operations
    If it's time and there's a goal position:
        Move towards the goal position
        Perform gantry, lift-no-load, and lift-load operations as necessary
        Deliver the container if it's at the designated position
```

The first stage of the agent-based simulation involves making appointments. During the appointment process, the performance indicator to be calculated is the truck turnaround time, which is calculated as shown in (4).

$$\overline{TT_t} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} Td_{ij} - Ta_{ij}}{s_t} \tag{4}$$

where

- i: index for trucking company;
- j : index for container pick-up appointment by external truck;
- m: number of trucking company;
- n: number of containers pick-up;
- $\overline{TT_t}$: average truck turnaround time at event time t;
- Td_{ij}: departure time for container pick-up appointment by external truck j owned by trucking company i;

- Ta_{ij}: arrival time for container pick-up appointment by external truck j owned by trucking company i;
- s_t: number of serviced trucks at event time t.

To simulate the variability in the estimated waiting times or arrival times for each external truck agent, the variable for individual external truck turnaround time is designed to introduce a level of randomness that mimics real-world uncertainties, as in (5).

$$w_{ijk} = \overline{TT_t}.RVF \tag{5}$$

where

- k: index for session;
- RVF: random variation factor;
- w_{ijk}: expected waiting time for container pick-up appointment by external truck j owned by trucking company i at session k.

For the decentralized procedure, the container terminal will calculate the estimated waiting time that considers both the current average truck turnaround time and the number of appointments scheduled in the session to forecast the waiting time for the next hour, as formulated in (6).

$$\overline{TT_k} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} Td_{ij} - Ta_{ij} + \sum_{i\epsilon k} \sum_{j\epsilon k} w_{ijk}}{s_t + a_k} \tag{6}$$

where $\overline{TT_k}$ is the average truck turnaround time at session k. a_k is the number of appointments at session k.

The estimated waiting time for external trucks is communicated to the trucking company in response to their appointment application, whereupon the trucking company determines the optimal arrival time (adjusted pick-up time) based on their lower and upper bounds, as shown in (7). This adjusted pick-up time is then submitted to the container terminal. The appointment process concludes once the terminal operator sends an appointment confirmation.

$$\begin{gathered} Tadj_{ij} = \overline{TT_k} - w_{ijk} + Ta_{ij}\ ; \\ lb_i \leq Tadj_{ij} \leq ub_i \end{gathered} \tag{7}$$

where $Tadj_{ij}$ is the adjusted arrival time for container pick-up appointment by external truck j owned by trucking company i. lb_i is the earliest possible time (lower bound) of trucking company i. ub_i is the latest possible time (upper bound) of trucking company i.

To measure the performance indicator for each agent, trucking company (agent client) and container terminal (agent crane), we propose the inconvenience cost (IC_{ij}) in (8) and yard crane utilization (uc) in (9).

$$IC_{ij} = Tadj_{ij} - Ta_{ij} \tag{8}$$

$$uc = 1 - \frac{time\_crane\_idle}{number\ of\ ticks} \tag{9}$$

4.3. System and Simulation Setup

The model parameterization refers to one of a container terminal in Indonesia, which primarily uses one yard crane per block. The simulation model is adopted from the reference models by Wasesa et al. [29]. The stacking yard consists of 40 container bays, with 6 rows and a maximum height of 4 container tiers. Each time window (1 time window: 60 min) has 300 containers in the stacking yard awaiting the delivery process. In modeling and setting parameters for yard crane gantry speed and handling times, this study references Huynh and Vidal [18], who identify a typical yard crane gantry speed of 135 m per minute. Consequently, it takes approximately 6 ticks for the crane to move from one 40-foot bay to the next. We tested four constant truck arrival rates—6, 7, 8, and 9 trucks per hour—using a single yard block and one yard crane. The details of the system parameters are described in Table 5.

Table 5. System parameters.

Parameter	Value
Number of containers	300 TEU
Number of bays	40
Number of rows	6
Number of tiers	4
Number of yard cranes	1 unit
Yard crane travel time	6 s/unit container
Yard crane transfer processing time	50 s/unit container
Yard crane lifting constant time	15 s/unit container
Yard crane lifting elevation time	5 s/unit container
Gantry movement time	1 s/unit container
Truck arrival rate per hour	6, 7, 8, 9 trucks/hour

This research evaluated alternative truck appointment system models in terms of the performance measure of the truck turnaround time in the container terminal. In developing the simulation model, it is essential to determine simulation inputs that correspond to decision variables (controllable inputs). Based on the simulation scenarios, three yard crane scheduling strategies and two truck appointment system procedures are simulated. The inputs are represented by *chooser* as input strategies for yard crane scheduling and *switch* as input strategies for truck appointment system procedure, as follows in Figure 5.

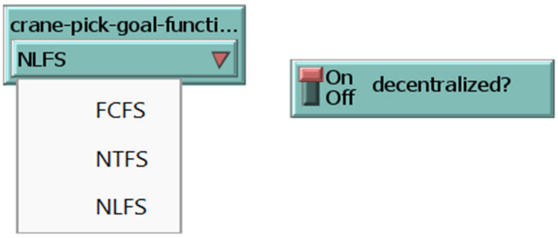

Figure 5. Controllable inputs for yard crane scheduling strategy (**left**) and truck appointment system procedure (**right**).

A total of 3 × 2 × 4 scenarios are conducted, and each scenario is replicated 30 times. The appointment process is performed at the beginning of each time window, with 10 time windows in total, where each time window, as commonly used in container terminals, is 1 h long. The scenario designs for the simulation are described in Table 6.

Table 6. Simulation parameters.

Component	Value	Status
Truck appointment system mechanism	Centralized, Decentralized	Decision Variable
Yard scheduling strategy	FCFS, NTFS, NLFS	Decision Variable
Simulation duration	36,000 s	Simulation Parameter
Number of time windows	10	Simulation Parameter
Duration of each time window	3600 s/time window	Simulation Parameter
Warm-up duration	2 time windows (7200 s)	Simulation Parameter
Replication	30	Simulation Parameter

The simulation model verification is conducted by ensuring that each entity in the simulation model follows the process flow outlined in Figures 2 and 3. Verification involves checking the code and logic of the simulation model. Code inspection in NetLogo is used to confirm that no errors are present. In NetLogo, verification is performed by selecting the “Check” option. Based on Figure 6, it is confirmed that the syntax created could be executed, thereby verifying the model developed using NetLogo.

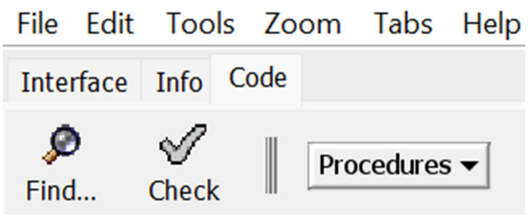

Figure 6. Syntax verification conducted using the “Check”’ feature.

The simulation model is validated by first testing the simulation model with the parameters used in the reference model and comparing the results obtained. In the model, the higher the truck arrival rate, the higher the average turnaround time for external trucks, as observed in the reference model results. Second, the model validation is conducted by comparing performance measures. Validation is performed for the CTAS simulation and the FCFS yard scheduling strategy by comparing the performance metrics from the reference study with those from the developed model, specifically focusing on the average turnaround time. The data tested uses a truck arrival rate parameter of 6 trucks per hour. Validation is carried out using a *t*-test with a 95% confidence interval. The comparison between the reference study results and the simulation run with 30 replications shows a significant value of 0.139, indicating that the model can be considered valid.

5. Experimental Results and Discussion

This research phase tests an agent-based truck appointment system model by comparing alternative configuration scenarios for the truck appointment system approach and yard crane scheduling strategy. Tables 7 and 8 list the results of simulations conducted for varying rates of external truck arrivals (in trucks per hour), along with the turnaround time of external trucks (in seconds) for two different reservation scenarios: centralized (CTAS) and decentralized (DTAS) procedures. Each procedure is simulated for three yard crane scheduling strategies, FCFS, NTFS, and NFLS. For each rate of external truck arrival, there are minimum, average, and maximum values for the turnaround time of external trucks in both reservation scenarios. This information provides an overview of the variation in external truck turnaround times that may occur in different situations.

In both scenarios of the truck appointment system mechanism and yard crane scheduling strategy, i.e., FCFS, NTFS, NFLS, an increase in the turnaround time of external trucks is observed to accompany an increase in the rate of external truck arrivals. This can be seen from the significantly increased average turnaround times, with the increase in truck arrival rates from six to nine trucks per hour.

Table 7. Results of the centralized truck appointment system (CTAS)’s turnaround time.

External Truck Arrival Rate (Trucks/Hour)	**Turnaround Time (s)**								
	FCFS			**NTFS**			**NLFS**		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
6	247	351	498	218	254	288	241	347	474
7	308	512	730	246	275	308	357	485	357
8	679	1197	2453	262	307	354	540	1225	2458
9	1203	2380	3198	300	342	380	1011	2443	3606

Table 8. Results of the decentralized truck appointment system (DTAS)'s turnaround time.

External Truck Arrival Rate (Trucks/Hour)	**Turnaround Time (s)**								
	FCFS			**NTFS**			**NLFS**		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
6	251	335	439	209	248	276	274	351	488
7	339	488	724	231	275	323	352	492	783
8	659	1127	2141	269	303	331	523	1113	1882
9	1216	2301	3318	306	344	377	1519	2321	3086

At all truck arrival rate levels, the NTFS scenario consistently shows lower external truck turnaround times than the FCFS scenario. The average turnaround times in the NTFS scenario (254–342 s) are significantly lower than those in the FCFS scenario (351–2380 s), indicating that NTFS is more efficient in optimizing external truck turnaround times.

The NLFS scenario presents average turnaround times ranging from 347 to 2443 s, generally performing better than FCFS but not surpassing NTFS, especially at higher arrival rates.

External truck turnaround times vary considerably across all three strategies and at each arrival rate, as indicated by the difference between the minimum and maximum times. The NTFS scenario demonstrates the smallest range of variation, suggesting it is more consistent at providing predictable turnaround times. In contrast, the FCFS strategy exhibits the widest range, with turnaround times varying from 247 to as high as 3198 s.

The NLFS strategy is more consistent than FCFS at lower arrival rates but shows greater variability at higher rates, particularly with maximum turnaround times exceeding 3600 s. NTFS remains the most reliable and efficient strategy, particularly under higher traffic conditions.

In the DTAS, each agent has the authority to make reservations, whereas in the CTAS, truck appointments are made through a single central entity: the container terminal. Decentralization provides greater flexibility to agents (in this case, trucking companies) to manage reservations according to their arrival preferences. Furthermore, in the decentralized approach, the main consideration is how to align truck arrival schedules as closely as possible with trucking companies' preferred times. This yields outcomes that are not significantly different from those of the centralized system in terms of the performance indicator, i.e., external truck turnaround time. The results of various configurations of truck appointment approaches and yard scheduling strategies in terms of truck turnaround time are described in Figure 7.

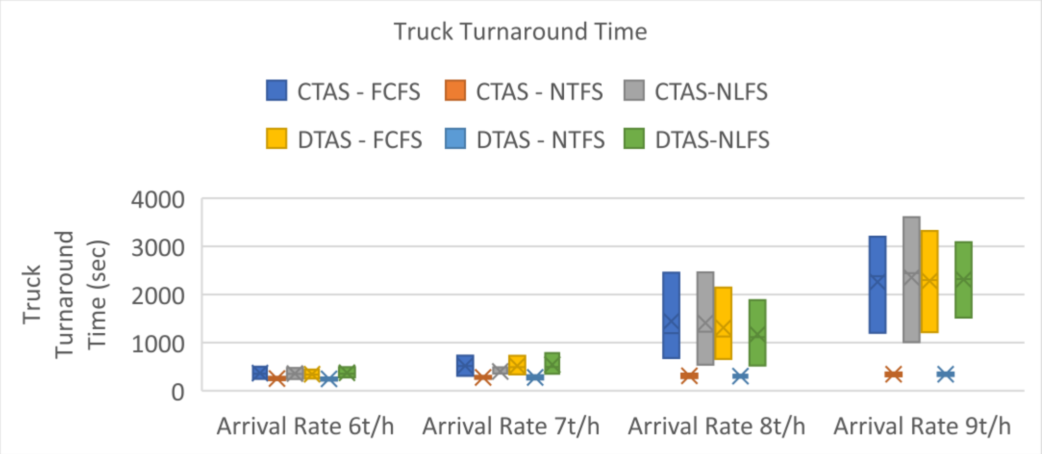

Figure 7. Comparison of truck turnaround time.

Based on yard crane utilization, NTFS consistently shows lower utilization rates compared with FCFS in both the centralized and decentralized truck appointment system approaches, as presented in Tables 9 and 10. This indicates that yard crane operation time under NTFS is lower than under FCFS, aligning with the truck turnaround time results. In other words, with NTFS, the yard crane remains available to service more external trucks due to its more efficient operation.

Table 9. Results of the centralized truck appointment system (CTAS)'s yard crane utilization.

External Truck Arrival Rate (Trucks/Hour)	Yard Crane Utilization								
	FCFS			NTFS			NLFS		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
6	69%	76%	82%	65%	70%	77%	71%	76%	83%
7	79%	88%	94%	76%	78%	83%	82%	88%	82%
8	94%	97%	99%	81%	85%	88%	94%	98%	99%
9	97%	99%	100%	86%	90%	93%	98%	99%	100%

Table 10. Results of the decentralized truck appointment system (DTAS)'s yard crane utilization.

External Truck Arrival Rate (Trucks/Hour)	Yard Crane Utilization								
	FCFS			NTFS			NLFS		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
6	71%	75%	81%	64%	70%	73%	71%	76%	84%
7	80%	87%	92%	72%	78%	82%	84%	88%	93%
8	93%	97%	100%	82%	85%	90%	93%	98%	100%
9	96%	99%	100%	88%	91%	95%	96%	99%	100%

The results of various truck appointment system configurations and yard scheduling strategies regarding yard crane utilization are shown in Figure 8.

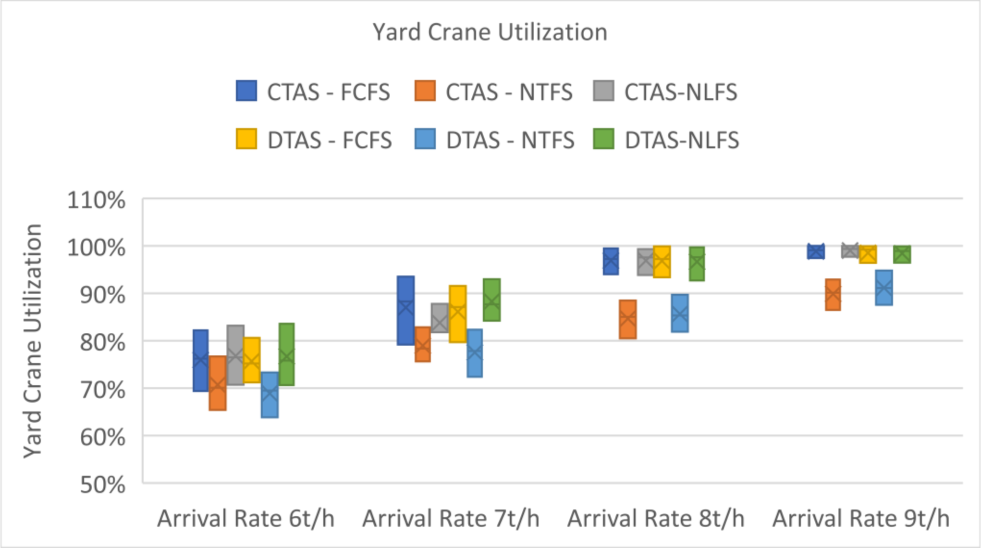

Figure 8. Comparison of yard crane utilization.

From the data on yard crane utilization across different external truck arrival rates, FCFS has the highest utilization, peaking at 100%, while NTFS maintains lower average utilization rates (70–90%), indicating better availability of yard cranes. The NLFS strategy exhibits similar utilization trends to FCFS at lower arrival rates but approaches NTFS utilization levels as the truck arrival rate increases, with utilization reaching up to 100% at higher rates.

Given the significant difference in inconvenience costs, NTFS is more effective than FCFS in minimizing inconvenience for truck drivers, leading to higher overall satisfaction and smoother operations, especially under higher traffic conditions, as shown in Table 11 and Figure 9. Therefore, if the goal is to reduce inconvenience for truck drivers and ensure more consistent operations, NTFS would be the superior strategy.

Table 11. Results of the decentralized truck appointment system (DTAS)'s inconvenience.

External Truck Arrival Rate (Trucks/Hour)	Average Inconvenience								
	FCFS			NTFS			NLFS		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
6	10	14	25	9	11	14	11	14	20
7	15	20	32	10	12	15	15	21	37
8	23	35	69	11	13	16	23	38	72
9	35	56	94	12	15	18	32	54	82

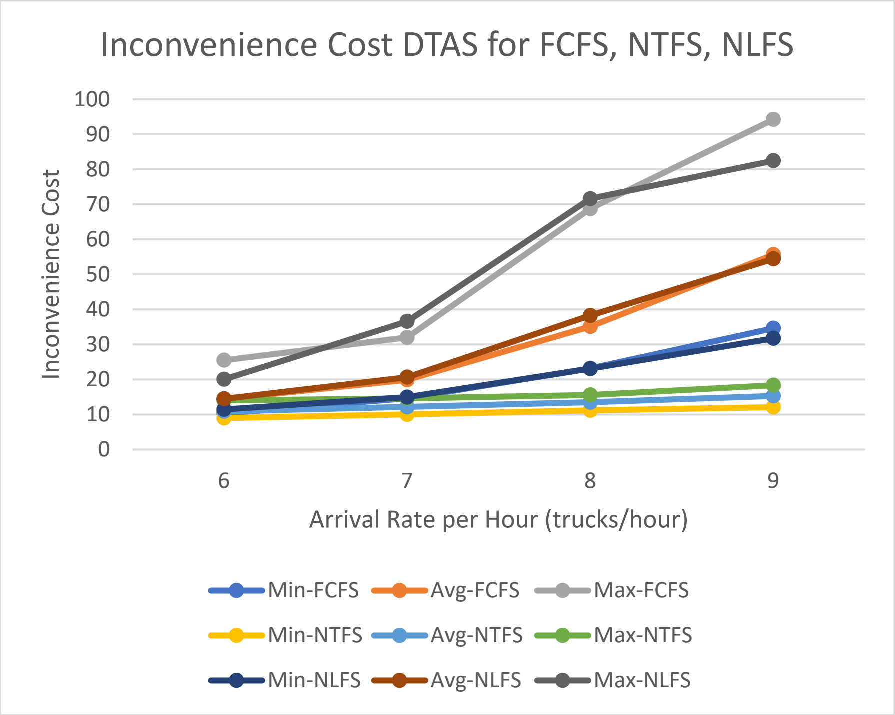

Figure 9. Results of inconvenience cost for decentralized truck appointment system (DTAS).

NLFS shows inconvenient levels comparable to FCFS, particularly as truck arrival rates increase. Both NLFS and FCFS tend to exhibit higher inconvenience compared with NTFS at medium to high arrival rates. For instance, at eight–nine trucks per hour, NLFS's average inconvenience (38–54) aligns closely with that of FCFS (35–56), indicating that NLFS and FCFS perform similarly in minimizing inconvenience under heavier traffic, while NTFS remains more effective.

Based on the experimental results of turnaround time in Tables 7 and 8, the CO_2 emissions are calculated using the following parameters:

(1) Average fuel consumption of trucks: 10 liters per hour;

(2) Carbon emission factor: 2.68 kg CO_2 per liter of diesel.

The results from Tables 12 and 13 demonstrate a clear comparison of CO_2 emissions across the different yard crane scheduling strategies in both centralized (CTAS) and decentralized (DTAS) truck appointment systems. In Table 12, the NTFS strategy shows the lowest average CO_2 emissions at 2193.68 kg compared with FCFS (8264.61 kg) and NLFS (8376.10 kg). This suggests that NTFS is more effective in reducing carbon emissions in centralized systems. Similarly, in Table 13, the NTFS strategy once again results in the lowest average emissions at 2178.28 kg, while FCFS shows 7910.83 kg and NLFS produces 7959.01 kg. In general, DTAS shows higher efficiency in emission reduction compared with CTAS, especially at moderate to high truck arrival rates, as evidenced by slightly lower average emissions across strategies.

Table 12. Results of the centralized truck appointment system (CTAS)'s CO_2 emissions.

External Truck Arrival Rate (Trucks/Hour)	CO_2 Emissions (Gram)								
	FCFS			NTFS			NLFS		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
6	1835.80	2615.51	3707.25	1626.22	1893.85	2146.82	1792.12	2585.79	3527.24
7	2292.63	3812.22	5431.53	1831.89	2045.67	2295.31	2654.06	3611.80	2654.06
8	5052.13	8912.16	18,262.03	1951.59	2288.27	2637.96	4022.50	9121.55	18,299.01
9	8957.88	17,718.54	23,806.94	2231.11	2546.93	2830.71	7523.08	18,185.25	26,842.66
Average	4534.61	8264.61	12,801.93	1910.20	2193.68	2477.70	3997.94	8376.10	12,830.74

Table 13. Results of the decentralized truck appointment system (DTAS)'s CO_2 emissions.

External Truck Arrival Rate (Trucks/Hour)	CO_2 Emissions (Gram)								
	FCFS			NTFS			NLFS		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
6	1871.36	2497.40	3271.34	1554.87	1849.24	2057.15	2040.39	2611.73	3632.51
7	2526.79	3630.20	5390.95	1722.07	2046.79	2401.81	2622.38	3659.63	5826.99
8	4903.62	8388.79	15,939.34	2003.00	2253.00	2462.70	3892.20	8289.18	14,012.13
9	9051.80	17,126.92	24,699.44	2280.67	2564.09	2809.52	11,310.78	17,275.50	22,971.15
Average	4588.39	7910.83	12,325.27	1890.16	2178.28	2432.79	4966.44	7959.01	11,610.70

6. Conclusions and Future Work

In analyzing both CTAS and DTAS alongside the yard crane scheduling strategies of FCFS, NTFS, and NLFS, several key insights are derived. An increase in the rate of external truck arrivals leads to a significant rise in external truck turnaround times, a trend consistent across all strategies. The NTFS strategy consistently produces lower average turnaround times compared with FCFS, indicating that NTFS is more efficient in optimizing truck turnaround times. Furthermore, the NTFS strategy demonstrates superior consistency, with a smaller range between minimum and maximum turnaround times, suggesting greater reliability over FCFS. In terms of CO_2 emissions, NTFS consistently achieves the lowest average emissions across both CTAS and DTAS, as seen in Tables 12 and 13. DTAS generally shows slightly higher efficiency in emission reduction compared with CTAS, especially at moderate to high truck arrival rates. This makes DTAS more suitable for scenarios where emissions reduction is a priority, as it provides better alignment with truck company preferences by accommodating truck arrivals according to their schedules. While DTAS offers increased flexibility, allowing each trucking company to manage reservations according to their preferred schedules, the difference in external truck turnaround time performance between DTAS and CTAS is minimal. However, the decentralized approach can still enhance satisfaction from the perspective of truck companies, as it provides greater autonomy and flexibility than the centralized system, which is controlled by a single central entity.

To optimize key performance indicators—such as external truck turnaround time, yard crane utilization, and trucking company inconvenience—DTAS should be implemented in conjunction with an effective yard scheduling strategy like NTFS. This combined approach can better accommodate varying truck arrival rates, improve operational efficiency, and support more sustainable terminal operations.

Future work can build upon the contributions of this research by incorporating additional yard crane scheduling strategies, such as uni-directional travel and shortest processing time rule. Additionally, there is potential for further improvement of the decentralized approach algorithm, along with exploring the impact of varying truck arrival rates under different operational scenarios. Finally, incorporating real-time data integration for more dynamic appointment scheduling could enhance the flexibility and responsiveness of the system. These additions provide a clearer pathway for future research and potential improvements to the current model.

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