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RESEARCH ARTICLE

Advancing Smart Sustainable Seaports: Auction-Based Truck Appointment System for Automated Container Terminal

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ABSTRACT This study proposes alternative solutions to the container pick-up reservation problem involving container terminals and drayage operators by introducing two variations of a modified auction mechanism—cost-based and service-oriented—into the terminal's truck appointment system, with the First Come First Served (FCFS) scheme as a baseline. Each scheme is evaluated using key performance indicators relevant to terminals, drayage operators, and the environment, such as yard crane utilization, container retrieval/service time, storage cost/dwelling time, reservation costs, appointment tardiness, truck turnaround time, congestion, and CO_2 emissions. Results indicate that retrieval-cost-based schemes achieve the lowest container retrieval costs, while storage-cost-based schemes maintain consistent container dwelling times; service-based schemes excel in minimizing appointment tardiness but require more reservation communication cycles. All proposed mechanisms significantly enhance environmental outcomes, improving truck turnaround time, queue length, and CO_2 emissions by at least 85% compared to FCFS. This study highlights the critical need for decentralized coordination to effectively integrate the interests of business actors, emphasizing the importance of aligning stakeholder objectives for overall system enhancement.

INDEX TERMS Truck appointment systems, auctions, container terminals, drayage operators, port, logistics information systems, multi-agent systems, agent-based modeling, simulation, prescriptive analytics.

I. INTRODUCTION

The transportation of commodities across the hinterland is an important component of intermodal logistics [1]. Although the distance traveled overland constitutes less than 5% of the total logistics cost, the cost of hinterland transportation can be as high as 80% [2]. In competitive global commerce landscape, traders seek high performing hinterland logistics partners that enable fast, efficient, and economical commodities delivery [3].

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Road connections remain the most commonly used means of transportation for reaching inland destinations, as they provide higher speed and flexibility [4]. Although other options such as trains and inland waterway carriers exist, they involve more complex operations such as additional handling and bundling, as well as inflexible schedules [2]. Due to the advantages of road connections, utilizing the road logistics network in the hinterland stands out as the most preferred means for global trade actors to reach these regions.

Congestion issues near seaports affect many hinterland regions [5], [6], resulting in adverse effects on direct coordinating business actors like container terminals and drayage operators, as well as on indirect stakeholders such as port authorities, business communities, and local residents. The congestion's negative impacts encompass uneven resource distribution at container terminals, unproductive waiting periods for drayage trucks, and the overflow of truck queues, resulting in road congestion, pollution, and low quality of life for communities in the vicinity [7], [8].

Strategies to alleviate road congestion can be categorized into two types: diversion and non-diversion initiatives [1]. The primary objective of diversion initiatives is to reroute freight traffic from roads to alternative transportation modes. One example is extended gateway initiatives, which aim to transfer some of the seaport container terminal's loading and unloading activities to alternative inland terminals [4]. This approach requires terminal operators to use trains or barges to transport goods to inland terminals [1]. Another example of a traffic diversion initiative is the dry port initiative [9]. Dry ports are inland terminals with direct connections to seaports, facilitating the pickup and delivery of cargo via trains, drayage trucks, or barges.

The implementation of diversion initiatives may face several challenges, including financing, market viability, support from both public and private sectors, the stability of political situation, and the adequacy of barge and railway connections [9]. Instead, non-diversion initiatives such as extending container terminals' service hours and developing truck appointment systems can be considered [10]. Extending the service hours of container terminals aims to alleviate congestion during peak periods by providing additional off-peak service hours. Nevertheless, incentivizing drayage operators to utilize these new service options remains a challenge. Other instance of a non-diversion initiative is the truck appointment system, tailored to align reservation requirements for drayage operators handling container pick-up operations. From the perspective of capital investment and land procurement, the appointment system initiative may offer greater benefits compared to extending terminal service hours, establishing dry ports, or extended gateway initiatives.

Truck appointment systems have been implemented in many hinterland areas, including the ports of Long Beach, Los Angeles, and Vancouver, among others [10], [11], [12]. However, several reports have found minimal evidence of these systems' effectiveness in reducing congestion and air pollution [10], [11]. In many cases, the systems struggled to attract a substantial number of drayage operators due to design flaws and the voluntary participation terms [10], [11]. Moreover, many appointment systems were initially designed and implemented to comply with regulations rather than to improve the coordination of container pick-up operations.

Previous studies have primarily focused on improving the design and implementation of appointment systems from the perspective of specific business actors, such as drayage operators or container terminal operators [12], [13]. However, appointment systems should ideally serve as interorganizational information systems that accommodate the concerns of all involved business actors [14], [15]. Therefore, incorporating the concerns and objectives of multiple actors is crucial for designing better appointment systems.

In response, this study proposes a modified auction mechanism for the reservation process of container pick-up operations between container terminals and drayage operators. The study aims to make the following contributions:

- *Accommodative Decentralized Solution:* This mechanism considers the self-interests of both drayage operators and container terminals. Unlike previous studies that improved the truck appointment system from the perspective of a single actor, this study addresses the design impact on the interests of multiple actors simultaneously (i.e., container terminals, drayage operators, and the port region), an aspect that has been previously neglected [12], [13].
- *Holistic Evaluation*: The evaluation includes key performance indicators for container terminals (e.g., utilization, service rate, dwelling time) and drayage operators (e.g., appointment tardiness, reservation cost, truck turnaround time), as well as port surrounding concerns such as road congestion and CO_2 pollution.
- *Agent-Based Simulation*: To evaluate the feasibility and impact of the proposed solution on the operational performance of container terminals, drayage operators, and port surroundings agent-based simulations are conducted [16], [17].

II. RELATED LITERATURE

As mentioned before, previous studies have mostly focused on improving the design appointment systems from a particular actor's perspective [12], [13]. Earlier research analyzed scheduling aspects that affect the turnaround time of trucks or the operational efficiency of terminals, such as limiting truck arrivals or controlling their arrival times [18], [19]. More recent research focus on the container terminals' perspective. These include propositions such as integrated resource assignment optimization, complex task scheduling algorithm, multi-period coordinated optimization, and hybrid data mining and optimization approaches [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30].

Meanwhile, other studies consider the drayage operators' perspective. Earlier studies assess how scheduling parameters, such as the number of available appointments, the duration of appointment time windows, and access capacity, influence the operational efficiency of inland carriers [31], [32]. More recently, drayage tours concerns incorporation and data-driven methods are starting to gain attention [25], [33], [34].

Another body of literature examines how coordinating actors can optimize their own performance within existing appointment systems settings. Unlike the previous stream, this study focuses on container operational approaches such as container stacking, storage space allocation, and yard crane movements, rather than enhancing the appointment system's design [35], [36]. A study adopts a governance perspective, highlighting congestion externalities of container terminals and inefficiencies in drayage truck appointments [37].

Appointment systems ideally serve as interorganizational information systems that accommodate the concerns of involved self-interested business actors [14]. Therefore, incorporating multiple actors' interests is crucial to designing better appointment systems. Thus, we utilize the agent-based approach, which provides a way to analyze complex and decentralized coordination problems [16], [17]. This approach considers a system's behavior to be an emerging result of the interactions among the autonomous actors involved in the system. Each actor is represented as having limited authority, access to information, and influence on the entire system's behavior. This approach differs from the centralized methods used in most previous studies, such as discrete-event simulation or mathematical programming, which assume that decision-makers have the authority and information necessary to govern the behavior of the entire system [13].

The agent-based modeling has been applied in numerous logistics contexts [45], [46], [47], with many studies focusing on coordination challenges between container terminals and drayage operators. However, there is a shortage of studies that specifically target enhancing the design of truck appointment systems using a decentralized approach. To our knowledge, few articles have applied a decentralized approach to designing truck appointment systems (see Table 1).

Recent studies propose a decentralized negotiation mechanism to set pick-up appointment times [41], [42]. However, the solutions assume that the terminal operator knows the detailed cost parameters of each drayage operator and has the authority to compel the drayage operators to adhere to the proposed schedule. This is contrary to the actual situation, where each drayage operator is an autonomous entity with its own interests. If the proposed system does not accommodate the operators' interests, it is unlikely to be used. Conversely, it is essential to consider the interests of both the drayage operators and the container terminals. In response, this study proposes a modified auction coordination mechanism that accommodates the interests of both drayage operators and container terminals, while also considering congestion and CO_2 emissions in the port region.

TABLE 1. Related literature on appointment systems.

Ref	KPI	Interest			Method	
		CT	DO	PR	Centralized	Decentralized
[20]	CT Operational Time	✓	✗	✗	✓	✗
[21]	CT Equipment Utilization; Waiting Time	✓	✗	✗	✗	✓
[38]	CT Operational Time	✓	✗	✗	✓	✗
[23]	Truck Travel Distance	✓	✗	✗	✓	✗
[39]	Resource; CT Systems Capacity; YC Service Rate	✓	✗	✗	✓	✗
[40]	CT Productivity; Gross QC Rate	✓	✗	✗	✓	✗
[26]	CT operation completion time (YC)	✓	✗	✗	✓	✗
[27]	CT Service Time; Truck Waiting Time	✓	✗	✗	✓	✗
[28]	CT Lay Time; Container Throughput	✓	✗	✗	✓	✗
[29]	Yard and Access Road Occupancy; Container Throughput	✓	✗	✗	✓	✗
[30]	Truck Turnaround Time, Congestion,	✓	✗	✗	✓	✗
[33]	Truck Turnaround Time, Truck Preferred Appointment	✗	✓	✗	✓	✗
[25]	Truck Operation Time	✗	✓	✗	✓	✗
[37]	Congestion,	✗	✗	✓	✓	✗
[34]	Yard Congestion, Preferred Appointment	✓	✗	✗	✓	✗
[41]	Waiting Time, Penalty Cost	✓	✓	✗	✗	✓
[42]	Truck Turnaround Time, Pickup Cost	✓	✓	✗	✗	✓
[43]	Relocations, Appointment Shift	✓	✓	✗	✓	✗
[44]	Road Congestion	✗	✓	✓	✓	✗
This Study	Container Storage Cost; Retrieval Cost; Reservation Cost; Appointment Tardiness	✓	✓	✓	✗	✓

III. ANALYSIS

A. EXISTING CONTAINER PICK-UP OPERATION

The truck appointment system facilitates the coordination of container pickup reservations, linking container terminals with drayage operators. The pick-up operation consists of two primary processes: pre-arrival and on-arrival procedures. The pre-arrival process entails fulfilling requirements prior to a drayage operator dispatching its truck for container retrieval, whereas the on-arrival process concerns the actual operation of the pick-up. The appointment system focuses on the information exchange pertaining to the pre-arrival process.

To pick-up a container, drayage operators must first complete the pre-arrival procedure. This step involves a transaction screening and verification process that is crucial to prevent long terminal turn times resulting from incomplete administrative clearance [48]. The United Nations Committee for Electronic Data Interchange for Administration, Commerce, and Transport (i.e., UNECE) [49] regulates the information exchange standards for this procedure. Figure 1 shows the drayage operator initiating the process by sending a pick-up permission request in the Container Pre-notification Message (i.e., COPINO) format. This request includes details like the drayage operator's identity (SenderID), the container's identity (ContainerID), the assigned truck's identity (TruckID), and the proposed pick-up date.

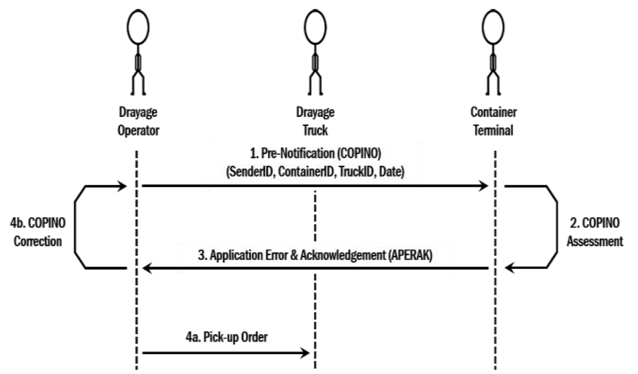

FIGURE 1. The pre-arrival procedure.

After the terminal receives the COPINO request, three primary checks are conducted to ensure that the information details are complete, the container is present in the yard, and customs clearance has been obtained for the proposed pick-up date. Afterward, the container terminal sends an Application Error and Acknowledgement (i.e., APERAK) message to the drayage operator, who can then dispatch its truck for the pick-up operation. Should the COPINO request be declined, the pick-up assignment cannot proceed. The drayage operator needs to examine the cause of rejection, resolve any issues, and resubmit the COPINO request.

The on-arrival procedure can only be performed once the pre-arrival procedure is complete. The on-arrival procedure from the container terminal's perspective begins when a drayage truck arrives at the gate-in area. During peak hours, trucks queue for service. Upon reaching the front, the gate-in officer verifies documentation and authorizes the pick-up if pre-registered. Then, the truck waits for the container to be delivered to the designated location in the terminal yard by the quay/stacker crane. Finally, the truck completes administrative formalities at the gate-out before departure.

B. PROBLEM IDENTIFICATION

This study aims to address five central issues. Firstly, the appointment system involves two independent actors, i.e., container terminals and drayage operators, each with their objectives and no dominant power to influence each other's decisions. Secondly, the current appointment system mainly deals with administrative issues, such as truck and container details, customs clearance, and documentation, with the only scheduling-related information exchanged being the drayage operator's preferred pick-up date [10], [11].

Thirdly, most previous studies have adopted a centralized perspective while formulating improvements to the appointment system, ignoring that container terminals and drayage operators are independent actors with their interests [13]. Fourth, existing study implementing a decentralized coordination mechanism in the truck appointment system [41], [50] could benefit from improvements, including enabling concurrent reservation options and resolving actors' conflicting interests. Finally, the growing demand for horizontal supply chain collaboration and the rapid advancement of Industry 4.0 technologies such as internet of things require solutions suitable for smaller-scale computing devices [38], [51], [52], [53], [54].

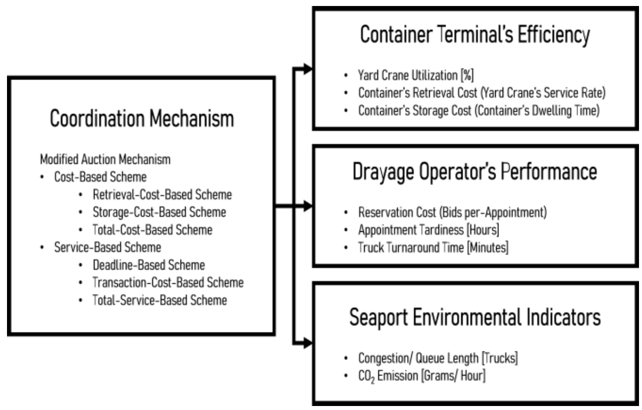

FIGURE 2. The research conceptual model.

Figure 2 illustrates the conceptual model of this study, showcasing how the proposed modified auction-based mechanism can benefit not only the interests of coordinating actors, such as drayage operators and container terminals, but also the seaport region. Two variants of the modified auction mechanism will be evaluated: the cost-based scheme and the service-oriented scheme. Each scheme will be assessed based on the operational efficiency of the container terminal, the reservation performance of drayage operators, and seaport region environmental indicators.

From the container terminal's perspective, the evaluation will focus on yard crane utilization, yard crane service rate, and container dwelling time. From the drayage operator's standpoint, the analysis will examine how well each scheme accommodates their interest in securing preferred appointment time slots and minimizing reservation costs. Lastly, from the seaport region environmental impact perspective, we will evaluate each scheme based on congestion due to queuing and the CO_2 emissions generated by container pickup activities.

C. MODIFIED AUCTION MECHANISMS

The modified auction mechanism draws inspiration from two well-known resource allocation approaches, namely the Contract Net (CNET) and the auction mechanisms [55], [56], [57]. The implementation of the proposed modified auction mechanism will require only minor adjustments to the current container pick-up pre-arrival process, as we deliberately avoid making significant alterations to the pre-arrival procedure regulated by the UNECE.

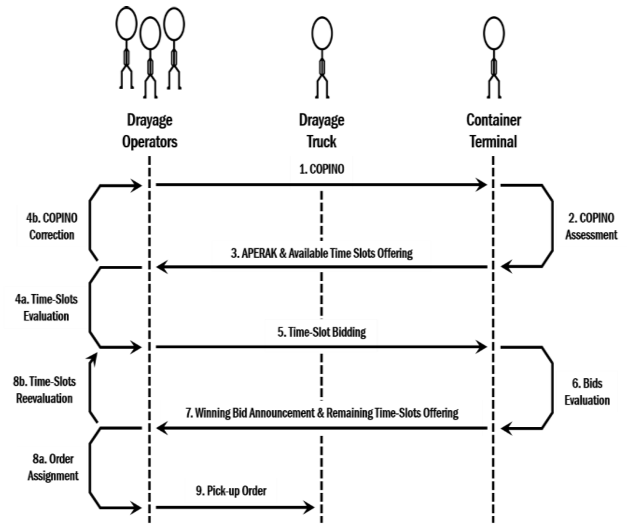

FIGURE 3. Modified auction mechanism based pre-arrival procedure.

Figure 3 portrays an overview of the modified auction mechanism, which consists of nine steps. The first two steps resemble the current pre-arrival procedure (see Existing Container Pick-up Operation Section). In the first step, the reservation cycle commences as the drayage operators send their COPINO request. In the second step, the container terminal evaluates the COPINO request for the completeness of the drayage operator's information, container availability, customs clearance status, and the proposed pick-up date.

Step three marks the beginning of customization. The container terminal transmits a standard APERAK message and announces the time slots that are available for the requested date. In the fourth step, upon approval of the COPINO request, the associated drayage operator evaluates the available time slot options and chooses the most appropriate one. Subsequently, in the fifth step, the drayage operator initiates a reservation for the selected time slot, while the container terminal remains open to receiving reservation requests from other operators for that same time slot until a designated deadline. When the deadline approaches, the container terminal assesses all incoming reservations and selects the winner. Next, the container terminal notifies the successful reservation and presents the remaining time slots to the unsuccessful operators. The winning operator proceeds to dispatch its truck for the pick-up operation, while the unsuccessful operators review the remaining time slot options and begin the reservation cycle again.

An auction is a market mechanism that utilizes an explicit set of rules to allocate resources and establish prices through bids submitted by participants [57]. This is relevant because many pick-up reservation systems for trucks lack transparency and standardization [12]. In response, we have opted to incorporate the first-price sealed-bid auction mechanism into our revised auction system. In this auction format, prospective buyers submit sealed bids, and the highest bidder secures the item at the price they offered [57]. Sealed-bid auctions prevent bidders from observing their competitors' bids and only allow them to submit a single bid. As a result, the mechanism requires minimal communication overhead and is easy to determine the winner.

In this study, the auction functions under an independent-private-values model, where each bidder knows their valuation but is unaware of their competitors' valuations [57]. Additionally, all bidders are symmetric, risk-neutral, and share the same goal of reducing their waiting and turnaround time at the container terminal. To formalize the auction mechanism, we adopt the approach of Shoham and Leyton-Brown [58] as follows:

- The set $O = \{o_1, \ldots o_n\}$ consists of n drayage operators,
- $T = \{t_1^1, \ldots t_m^s\}$ represents a collection of m available time slots in a day. Here, the index s represents the container terminal's capacity i.e., the number of active yard cranes/ servers. In this study, the time slot length is set to $l_t = 30$ minutes. If there is a single server container terminal $s = (1)$ that operates 24 hours a day, the first time slot, t_1^1, begins at 00:00 and end at 00:30. Similarly, the final timeslot, $m =$ (24 hours/30 minute= 48), t_{48}^1, starts at 23:30 and end at 24:00.
- d represents the booking deadline period, and $t_{d\to j}$ denotes the deadline for reserving a time slot t_j^x, where $t_{d\to j} = t_j^x - (d.l_t)$. Suppose the container terminal sets $d = 4$ and $l_t = 30$ minutes, reservation requests for time slot t_j^x will not be accepted after $d.l_t = 4 * 30\ minutes = 2$ hours. At $t_{d\to j}$, the container terminal evaluates of all incoming reservations for time slot t_j^x.
- A drayage operator o_i has a set of daily pick-up and delivery orders, represented as $\Theta_i = \{\Phi_{i\to 1}, \ldots \Phi_{i\to z}\}$. The z index in $\Phi_{i\to z}$ indicates the order fulfillment deadline. For instance, $\Phi_{i\to 7}$ indicates that the drayage operator, o_i, must complete $\Phi_{i\to 7}$ no later than t_7^s.
- $\overline{T}, \overline{T} \subseteq T$ represents available, unreserved time slots (see Steps 3 and 7 in Figure 3).
- To identify the most profitable time slot $\overline{t_{i\to j}^x}$ for carrying $\Phi_{i\to z}$ (see Steps 4a and 8b in Figure 3), the drayage operator's valuation, $v_{i-z}(\overline{T})$, is used. The $v_{i-z}(\overline{T})$ assesses the value of each $t_j^x \in \overline{T}$, defined as follows:

$$v_{i-z}(t_j^x) = \begin{cases} r_i - \propto_{\Phi_{i-z}} .q_i, & j \leq z \\ r_i - \propto_{\Phi_{i-z}} .q_i - p_i.(j - z), & j > z \end{cases} \quad (1)$$

A drayage operator's valuation for a time slot, $v_{i-z}(t_j^x)$, includes the revenue r_i from the container pick-up fee, the reservation cost $\propto_{\Phi_{i-z}} .q_i$ for submitting a reservation bid, and the penalty cost $p_i.(j-z)$ incurred for delayed pick-up operatio $\Phi_{i\rightarrow z}$, where $j > z$.

- The optimal time slot selected by the drayage operator o_i for executing $\Phi_{i\rightarrow z}$ is represented by $\overline{t^x_{i\rightarrow j}}$. After determining $\overline{t^x_{i\rightarrow j}}$ using $v_{i-z}\left(\overline{T}\right)$ (Equation 1), operator o_i will proceed to place a reservation for t^x_j (see Step 5 in Figure 3).
- The container terminal's reasoning behind selecting the winning reservation for t^x_j is represented by $c(\overline{T^x_j})$ (see Step 6 in Figure 3). $c\left(\overline{T^x_j}\right)$ lists the value of each reservation request $\overline{t^x_{i\rightarrow j}}$ from all drayage operators O_j interested in t^x_j, where $O_j \in O$.
- Two primary schemes are under consideration for determining the winning bid: the cost-based scheme and the service-based scheme.
  - In the cost-based scheme, the winning reservation bid is the order requiring the least operational cost $c\ (\overline{t^x_{i\rightarrow j}})$ from the container terminal side. Where $c(\overline{t^x_{i\rightarrow j}})$ is formalized as follows:

$$c(\overline{t^x_{i\rightarrow j}}) = c_\alpha(\overline{t^x_{i\rightarrow j}}) + c_\beta((\overline{t^x_{i\rightarrow j}}) \tag{2a}$$

When it comes to container pick-up, the container termina's operational cost $c(\overline{t^x_{i\rightarrow j}})$ involves the container's storage cos $c_\alpha(\overline{t^x_{i\rightarrow j}})$ and retrieval cost $c_\beta(\overline{t^x_{i\rightarrow j}})$ The storage cost $c_\alpha(\overline{t^x_{i\rightarrow j}})$ represents the expenses to store the container $\Phi_{i\rightarrow z}$ in its yard, and is directly proportional to the container's duration of stay (container dwelling time). Meanwhile, the container's retrieval cos $c_\beta(\overline{t^x_{i\rightarrow j}})$, refers to the crane's operational effort to move the container in and out of its yard, and is estimated based on the cran's occupancy in handling the order $\Phi_{i\rightarrow z}$.

- In the service-based scheme, the terminal prioritizes better service for the drayage operators, who aim to optimize their schedules to pick up and drop off containers cost-effectively. Therefore, we take into account the drayage operator's objective of minimizing reservation costs $\propto_{\Phi_{i-z}}\ .q_i$ and late pick-up penaltie $p_i.(z-j)$, and define the service-based cost as follows:

$$c\left(\overline{t^x_{i\rightarrow j}}\right) = \propto_{\Phi_{i-z}} .q_i + p_i.(z-j) \tag{2b}$$

- The winning reservation bid for orde $\Phi_{i\rightarrow z}$ is denoted as $t^x_{i\rightarrow j}$ (see Equation 2). It is important to note that $t^x_{i\rightarrow j}$ is not identical to $\overline{t^x_{i\rightarrow j}}$, as $t^x_{i\rightarrow j}$ refers to a confirmed appointment (see Step 7 in Figure 3) while $\overline{t^x_{i\rightarrow j}}$ refers to an appointment request (see Step 5 in Figure 3).
- The process of updating the list of unreserved time-slots is shown by $\overline{T} \leftarrow \overline{T} - \{t^x_{i\rightarrow j}\}$. This updating occurs at the end of each reservation cycle (see Step 7 in Figure 3).

IV. SIMULATION SETUP

The proposed auction mechanisms are evaluated through agent-based simulations, which provide a natural and effective way to model, experiment, and analyze their performance [16], [17]. Agent-based simulation employs a bottom-up modeling approach that focuses on agents, their behavior, the environment, and the resulting emergent behavior from their interactions. This approach is well-suited for analyzing complex systems in terms of their components' interactions and interdependencies, as opposed to the top-down perspective employed by the discrete-event and system dynamics approaches [20], [37], [59], [60].

We adopt the standard procedure of agent-based simulation [16], [17]. The method consists of (1) the identification of the agents, (2) the definition of the interactions rules among agents and environment, (3) the selection of the simulation platform and development strategy, (4) data collection, (5) simulation model validation, (6) experiment scenario definition, and (7) simulation run and analyses of the simulation results.

Discussing the first step, we define two active agent types: the drayage operator and the container terminal. In our simulation, we assume that each truck has the autonomy to reserve an appointment slot so that the authority distinction between the drayage operator and truck is non-existent. In addition, we also define reservation time slots as passive agents to the two active agents. Moving on to the second stage, we select the Port of Rotterdam as a case study, and confirmed that the pre-arrival procedure analyzed is similar to the one utilized in Rotterdam [35], [61], [62].

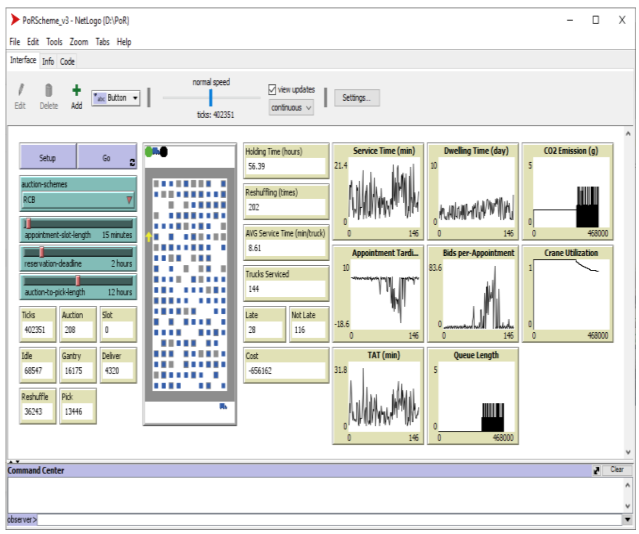

FIGURE 4. The graphical user interface of the agent-based simulation.

We implemented the modified auction mechanisms in the NetLogo agent-based simulation environment [17]. This simulation platform has been used in many prior studies on container terminal operations [45], [46], [47]. The simulation interface is visualized in Figure 4. The reservation processes are modeled as a single-server queuing system [18] to concentrate on the impact of the coordination mechanisms studied and reduce the interference effects associated with multi-server queuing system models. To gather and validate data, we utilized the technical specifications of the respondent container terminal from prior research [35], [61]. The simulation settings are portrayed in Table 2.

TABLE 2. The simulation settings.

Variable	Values
Agents Type	Container Terminal, Drayage Operator, Reservation Time Slot
Containers' Arrival Rate	Poisson, λ = 5.44 containers/ hour
Reservation Rate	Normal, μ = 15.9 reservations/ hour, σ = 10.0 reservation/ hour
Auction Schemes	retrieval-cost-based (RCB), storage-cost-based (SCB), total-cost-based (TCB), reservation-service-based (RSB), deadline-service-based (DSB), total-service-based (TSB), schemes
Reservation Deadline Scenario, d	$d = 0$, $d = 2$ hours, $d = 6$ hours, $d = 12$ hours
Appointment Slot Length, l_t	$l_t = 15$ minutes
Dependent Variables	Container's retrieval cost/ service time (minutes), container's storage cost/ dwelling time (days), yard crane utilization (%), reservation cost (number of bids), lateness cost (appointment tardiness), trucks' turnaround time (minutes), queue length (trucks), CO_2 Emission (grams/ hr)
Warmup Period	3 days (3*24 hours)
Simulation Length	7 days (7*24 hours)
Simulation Replications	10

In the simulation studies, the evaluation focuses on the performance of two main modified auction schemes: cost-based and service-based. Each scheme encompasses three variants, each with distinct criteria for determining the winning reservation request. The cost-based scheme includes the retrieval-cost-based (RCB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [c_\beta(\overline{t^x_{i\to j}})]$), storage-cost-based (SCB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [c_\beta(\overline{t^x_{i\to j}})]$), and total-cost-based (TCB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [c_\alpha(\overline{t^x_{i\to j}})+ c_\beta((\overline{t^x_{i\to j}})]$). On the other hand, the service-based scheme comprises the reservation-service-based (RSB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [\propto_{\Phi_{i-z}} .\, q_i]$), deadline-service-based (DSB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [p_i.\, (z-j)]$), and total-service-based (TSB, where $t^x_{i\to j} \leftarrow \text{arg.min}\, [\propto_{\Phi_{i-z}} .\, q_i + p_i.\, (z-j)]$) variants.

We analyze how adjusting the reservation deadline d affects the performance of each scheme through various reservation deadline configurations. We consider four reservation deadline conditions: $= 0$, $d = 4$ (2 hours), $d = 12$ (6 hours), and, $d = 24$ (12 hours) for each scheme. The duration of each appointment time slot is set at 30 minutes. We conduct ten simulation runs for each experiment (coordination scheme-deadline pairs), with a warm-up period of three days (3*24 hours) and a simulated period of seven days (7*24 hours).

V. RESULTS AND ANALYSIS

Table 3 and 4 present simulation experiments' results in detail. Each scheme is assessed based on several key performance indicators (KPIs) relevant to the container terminal, drayage operators, and the surrounding environment. For the container terminal, the KPIs include yard crane utilization (%), container retrieval cost/ service time (minutes), and container storage cost/ dwelling time (days). For drayage operators, the analysis examines how well each scheme minimizes reservation costs (number of bids), appointment tardiness (hours), and truck turnaround time (minutes). From the port region environmental perspective, the evaluation considers congestion (trucks queue) and CO_2 emissions (grams/ hour) from container pickup activities.

Additionally, we evaluate the First Come First Served (FCFS) mechanism as a baseline to compare the proposed auction mechanisms. The proposed mechanisms evaluated are retrieval-cost-based (RCB), storage-cost-based (SCB), total-cost-based (TCB), reservation-service-based (RSB), deadline-service-based (DSB), and total-service-based (TSB). This comparison highlights the performance of the proposed modified auction mechanisms against a purely reactive pickup delivery operation without any reservation mechanism.

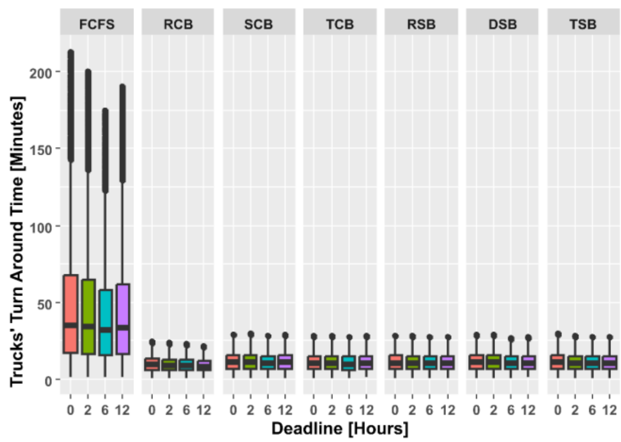

FIGURE 5. Truck turnaround time performance.

As shown in Figure 5, it is evident that the FCFS scheme performs poorly in terms of truck turnaround time. Truck turnaround time is measured from the moment a truck arrives at the container terminal, including waiting for service, receiving service, and until it leaves. This scheme allows trucks to arrive without reservations, resulting in long waiting times. The mean truck turnaround time value for FCFS is 52.11 minutes, with a standard deviation of 47.99 minutes. In contrast, the auction-based schemes have an average truck turnaround time of around 11 minutes, with a standard deviation of approximately 5 minutes. The RCB scheme is the best-performing auction-based scheme, achieving a turnaround time of only 8.91 minutes. By prioritizing the nearest containers, the turnaround time for trucks is reduced, as they do not have to wait long to pick up containers. This indicates that the auction-based scheme has the potential to improve customer satisfaction from the drayage operators' point of view by more than 90% in terms of truck turnaround time, compared to the FCFS scheme.

TABLE 3. The simulation results.

Appointment Scenario	Crane's Utilization [%]		Trucks' Turn Around Time [Minutes]		Queue Length [Trucks]		CO_2 Emission [Grams/Hour]	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
First Come First Served [FCFS]								
d = 0	86	3	52.11	47.99	7.59	7.71	601.44	50.05
d = 2	86	4	49.47	45.11	6.82	7.14	580.45	52.70
d = 6	86	4	44.41	39.21	6.38	6.59	562.95	50.77
d = 12	87	4	47.46	42.58	7.21	7.43	558.41	50.36
Retrieval-Cost Based								
d = 0 [RCB]	78	7	10.09	4.91	1.67	0.57	1.38	0.06
d = 2	78	7	9.78	4.76	1.65	0.57	1.37	0.05
d = 6	79	8	9.45	4.63	1.61	0.59	1.37	0.05
d = 12	77	8	8.91	4.26	1.56	0.59	1.36	0.04
Storage-Cost Based [SCB]								
d = 0	81	5	11.69	5.95	1.80	0.59	1.39	0.06
d = 2	82	5	11.86	6.13	1.82	0.60	1.40	0.06
d = 6	83	6	11.31	5.73	1.76	0.59	1.40	0.05
d = 12	83	6	11.56	5.77	1.79	0.61	1.40	0.05
Total-Cost Based [TCB]								
d = 0	79	6	11.15	5.77	1.77	0.57	1.39	0.06
d = 2	80	6	11.05	5.69	1.76	0.58	1.39	0.06
d = 6	81	7	10.84	5.66	1.74	0.60	1.39	0.05
d = 12	82	7	11.12	5.83	1.76	0.60	1.39	0.05
Reservation Service Based [RSB]								
d = 0	80	6	11.47	5.76	1.77	0.59	1.39	0.06
d = 2	81	6	11.49	5.83	1.79	0.59	1.39	0.06
d = 6	82	6	11.24	5.59	1.75	0.59	1.40	0.05
d = 12	82	6	11.15	5.54	1.76	0.60	1.39	0.05
Deadline Service Based [DSB]								
d = 0	81	5	11.66	5.82	1.80	0.59	1.39	0.06
d = 2	81	6	11.69	5.85	1.81	0.59	1.40	0.06
d = 6	82	6	11.14	5.46	1.74	0.60	1.39	0.05
d = 12	82	6	11.12	5.48	1.73	0.61	1.39	0.05
Total Service Based [TSB]								
d = 0	81	5	11.70	5.94	1.80	0.59	1.40	0.06
d = 2	81	6	11.39	5.65	1.76	0.57	1.39	0.06
d = 6	82	6	11.20	5.57	1.75	0.58	1.39	0.05
d = 12	82	6	11.27	5.58	1.77	0.59	1.39	0.05

In the FCFS scheme, high truck turnaround time is not supported by efficient operations. Figure 6 shows the yard crane utilization performance, measured as the percentage of time a crane handles containers during its active time. Inefficiencies are evident in the FCFS scheme, with an average utilization of 87%, indicating many unproductive crane moves. In contrast, the auction-based schemes have lower utilization rates, ranging from 78% to 83%, with the RCB scheme having the lowest average rate of 78% (see Table 3).

The inefficiencies of the FCFS mechanism are confirmed by the average queue length and CO_2 emissions metrics. As portrayed in Figure 7, the FCFS can lead to a queue length as high as 7.59 trucks, with a standard deviation of 7.71 trucks. In contrast, the worst-performing auction-based mechanism, the Storage Cost-Based (SCB) scheme, is able to reduce the queue to an average of 1.82 trucks, with a standard deviation of 0.6 trucks (see Table 3). This indicates that the auction-based schemes have an advantage over the FCFS strategy, potentially reducing queue length by more than 85%.

TABLE 4. The simulation results.

Appointment Scenario	Retrieval Cost [Minutes]		Storage Cost [Days]		Reservation Cost [Number of Bids]		Appointment Tardiness [Hours]	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
d = 0	9.55	4.66	2.93	1.32	-	-	1.18	1.69
d = 2	9.38	4.55	2.90	1.30	-	-	1.41	1.83
d = 6	9.19	4.51	2.86	1.31	-	-	1.57	1.71
d = 12	9.30	4.52	2.76	1.26	-	-	1.76	1.87
Retrieval-Cost Based								
d = 0 [RCB]	8.96	4.27	3.45	1.88	13.25	21.17	26.42	38.47
d = 2	8.71	4.11	3.43	1.95	13.37	21.20	33.85	40.63
d = 6	8.48	3.99	3.19	1.88	13.53	21.42	40.47	42.68
d = 12	8.08	3.73	3.30	2.23	18.65	31.91	58.05	45.54
Storage-Cost Based [SCB]								
d = 0	9.91	5.02	3.40	0.73	66.41	79.47	23.00	19.84
d = 2	9.98	5.08	3.29	0.76	66.46	80.37	26.45	18.53
d = 6	9.73	4.89	3.11	0.68	68.46	80.03	26.37	16.22
d = 12	9.88	4.95	3.11	0.55	91.87	91.98	28.23	15.85
Total-Cost Based [TCB]								
d = 0	9.55	4.83	3.55	1.31	47.76	69.39	20.34	25.50
d = 2	9.52	4.83	3.45	1.27	50.36	72.43	24.85	25.53
d = 6	9.36	4.84	3.29	1.29	54.65	78.22	28.69	24.98
d = 12	9.54	4.95	3.35	1.24	86.76	104.60	32.24	24.99
Reservation Service Based [RSB]								
d = 0	9.78	4.80	3.42	1.41	66.44	38.59	14.94	9.98
d = 2	9.82	4.83	3.36	1.44	66.46	38.58	14.43	9.15
d = 6	9.69	4.72	3.20	1.42	68.46	38.59	13.35	7.69
d = 12	9.60	4.69	3.18	1.41	91.87	39.69	13.55	7.57
Deadline Service Based [DSB]								
d = 0	9.92	4.88	3.44	1.43	66.42	38.61	13.57	10.25
d = 2	9.89	4.90	3.36	1.43	66.46	38.58	13.56	9.36
d = 6	9.65	4.61	3.23	1.44	68.46	38.59	13.06	7.74
d = 12	9.64	4.62	3.20	1.43	91.87	39.69	13.72	7.60
Total Service Based [TSB]								
d = 0	9.91	4.97	3.46	1.43	66.43	38.60	15.08	9.81
d = 2	9.82	4.83	3.37	1.43	66.46	38.58	14.44	9.07
d = 6	9.66	4.71	3.16	1.37	68.46	38.59	13.49	7.56
d = 12	9.66	4.69	3.20	1.42	91.87	39.69	13.59	7.50

Figure 8 portrays the CO_2 emission KPI of each scheme. Note that in this study, CO_2 emission is the sum of CO_2 produced the drayage trucks within the container terminal vicinity and by the yard cranes. We calculate the emission by multiplying the active time of both agent types with a specific emission constant [47]. The FCFS scheme leads to high average CO_2 rate of 601.44 grams/ hour with a standard deviation of 50.05 grams. This emission level starkly contrasts with the significantly lower carbon footprints of all proposed auction schemes, aligning with sustainable practices in logistics operations. Among them, the RCB scheme stands out for its effectiveness in minimizing CO_2 emissions compared to alternative schemes. This also indicates that the auction-based schemes have an advantage over the FCFS strategy, potentially reducing CO_2 emissions by more than 90%

Figure 9 reveals that the RCB performs the best retrieval cost performance. Under this scheme, the average yard crane's occupancy can drop below 8.08 minutes per single retrieval operation (see Table 4). This outcome corresponds with the RCB scheme's design, which prioritizes the container's retrieval cost in determining the winning reservation.

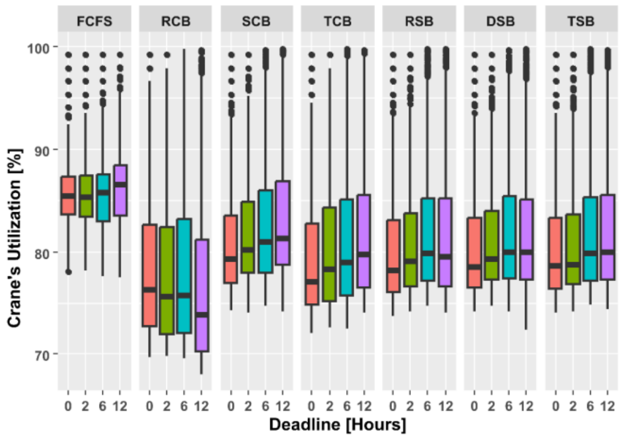

FIGURE 6. Crane utilization performance.

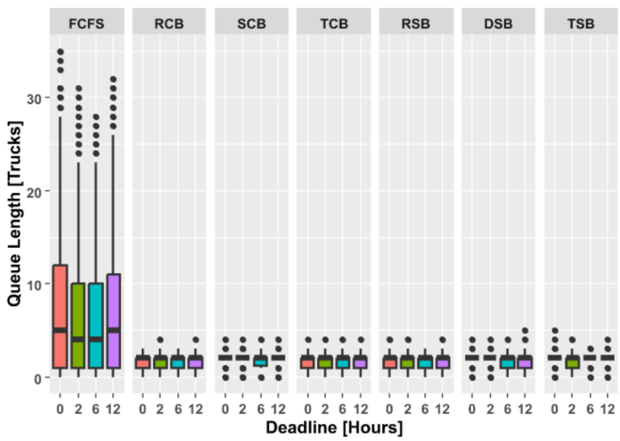

FIGURE 7. Queue length performance.

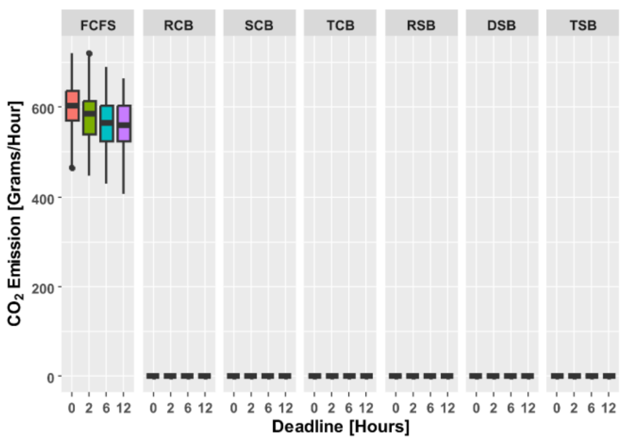

FIGURE 8. CO_2 performance.

In contrast, with other auction schemes, the yard crane's occupancy may exceed 9.98 minutes per single service.

All auction schemes have comparable container storage cost performance, with average dwelling time between 3.11 and 3.55 days (see Table 4). Nonetheless, the SCB

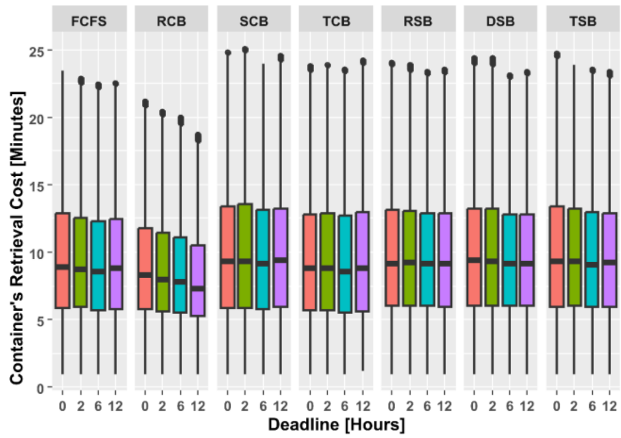

FIGURE 9. The retrieval cost (Service Time) performance.

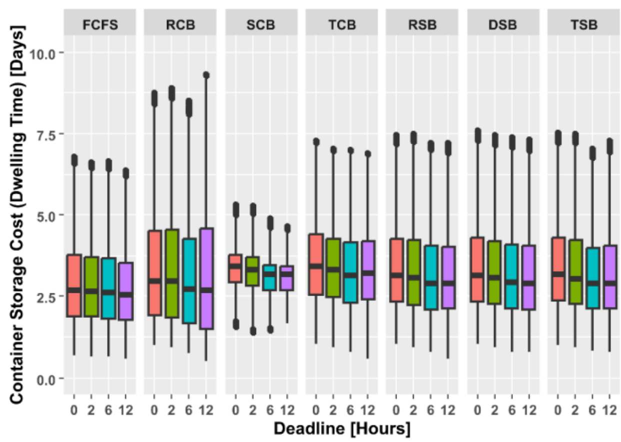

FIGURE 10. The storage cost (Dwelling Time) performance.

scheme demonstrates the most stable container dwelling time, with a standard deviation as low as 0.55 days. Conversely, the RCB scheme shows greater fluctuation in storage cost, with a standard deviation up to 2.23 days. Furthermore, the reservation deadline parameter positively influences the dwelling time of the TCB and TSB schemes, resulting in decreased dwelling times (see Figure 10).

In terms of service performance, all three service-oriented schemes (RSB, DSB, and TSB) excel in minimizing appointment tardiness (see Figure 11). In contrast, the cost-focused schemes (RCB, SCB, and TCB) tend to exhibit poorer and more unpredictable performance. Additionally, we notice a discrepancy in how the reservation deadline parameter affects these schemes. Specifically, for the cost-oriented schemes, higher deadline values lead to increased tardiness, whereas for the service-oriented schemes, higher deadline values result in reduced tardiness.

Achieving minimal appointment reservation delays is most effective with service-oriented schemes, but it requires frequent reservation cycles. As illustrated in Figure 12, service-based schemes require a significantly greater number of bids to secure the desired time slot, unlike the fewer

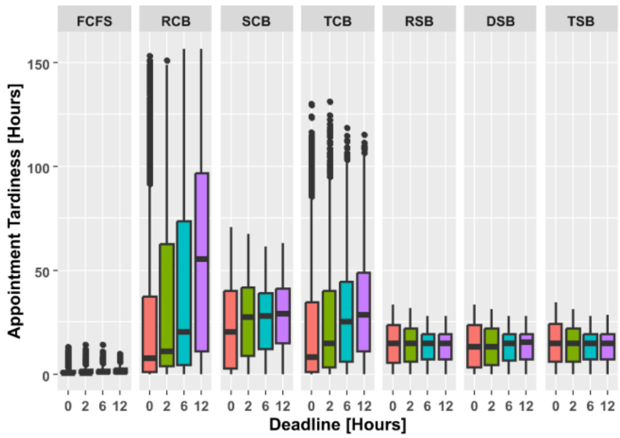

FIGURE 11. The appointment tardiness performance.

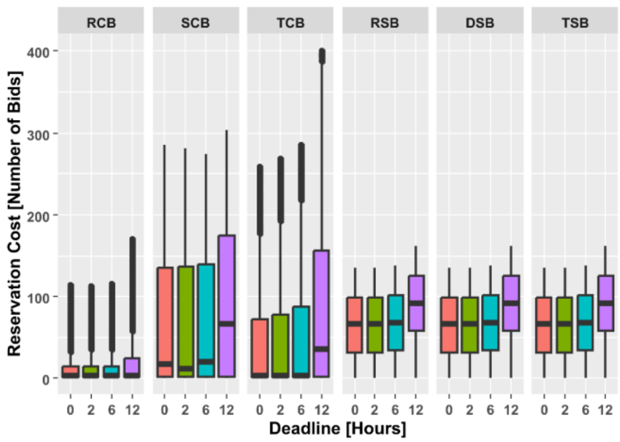

FIGURE 12. The reservation cost (Number of Bids) performance.

reservation iteration cycles required in cost-based schemes for drayage operators. The reservation costs across all schemes are impacted by the reservation deadline parameter. A higher deadline parameter provides drayage operators with additional time to adapt and iterate their reservation requests to secure the preferred pick-up time slot.

VI. CONCLUSION

This study proposes alternative solutions to the container pick-up reservation problem involving container terminals and drayage operators. Two variations of a modified auction mechanism (cost-based and service-oriented) are introduced for integration into the terminal's truck appointment system. The First Come First Served (FCFS) scheme is used as a baseline for comparison. Each scheme is assessed using KPIs relevant to terminals, drayage operators, and the environment, including yard crane utilization, container retrieval/service time, storage cost/dwelling time, reservation costs, appointment tardiness, truck turnaround time, congestion, and CO_2 emissions.

The retrieval-cost-based scheme results in the lowest container retrieval costs, while the storage-cost-based scheme maintains consistent container dwelling times. In contrast, the service-based schemes excel in minimizing appointment tardiness but require more reservation communication cycles. Furthermore, all proposed auction mechanisms positively impact the port region's environment, potentially improving truck turnaround time, queue length, and CO_2 emissions by at least 85% compared to the FCFS scheme.

From a practical view, this paper emphasizes the importance of adopting a decentralized approach to develop more effective coordination mechanisms for self-interested business actors, such as drayage operators and container terminals. The observed low participation in existing appointment systems is largely due to the neglect of the concerns of participating actors. successful implementation depends not only on technical feasibility but also on adapting existing interorganizational settings—such as coordination, information sharing, and stakeholder alignment. These factors significantly impact business performance, informational efficiency, agility, and environmental outcomes [15], [53]. Understanding and aligning stakeholder interests is essential for improving systems that involve multiple parties [63]. Moreover, in a decentralized coordination framework, the ability to communicate, iterate, and make quick decisions is crucial for maintaining a competitive edge. Thus, there is an increasing need for intelligent software agents and their supporting infrastructures to help users manage high-frequency transactions in the reservation processes.

From a research perspective, this study addresses the gap in designing decentralized truck appointment systems, offering a solution that allows concurrent reservations and aligns with the interests of both container terminals and drayage operators. Not less importantly, appointment systems should function as interorganizational information systems that address the concerns of all involved business actors. Thus, we employ an agent-based approach to analyze complex, decentralized coordination problems. This method views system behavior as emerging from interactions among autonomous actors, each with limited authority, information, and influence, differing from centralized methods like discrete-event simulation or mathematical programming, which assume comprehensive control by decision-makers. Additionally, as environmental sustainability gains prominence, we include environmental impact assessments, such as CO_2 emissions and queue length, alongside business KPIs in evaluating the propositions.

However, this study does have certain limitations that open up avenues for further research. Firstly, we design container terminals as "auctioneers" with the authority to determine the winning reservation, potentially leading to exploitation for their own benefit. Therefore, additional investigations are necessary to identify the optimal corresponding mechanism that ensures a mutually beneficial outcome for all parties. Secondly, we utilize a single-unit auction model for allocating appointment reservations, which could be enhanced by employing more sophisticated models such as multi-unit auctions or combinatorial auctions. Thirdly, our service-based schemes require the disclosure of the pick-up operation deadline by drayage operators. Addressing the challenge of safeguarding the reservation mechanism from dishonest disclosure of deadline information urges further exploration. Fourthly, the proposed solutions are modeled as a single-server queuing system to focus on the impact of the coordination mechanisms and minimize interference effects typical in multi-server models. However, since multi-server container terminals are common worldwide, the findings of this study are optimistic. Therefore, the proposed mechanisms would need further adjustment to be applicable in a multi-server context. Lastly, this study is limited by its focus on a specific case study, the Port of Rotterdam, and its reliance on data from previous research. While this approach provides valuable insights, the generalizability of the findings to other container terminals with different operational characteristics and constraints may be restricted.

SUMMARY OF ABBREVIATIONS

Abbreviation	Description.
KPI	Key Performance Indicator(s).
CT	Container Terminal.
YC	Yard Crane.
DO	Drayage Operator.
PR	Port Region.
UNECE	United Nations Committee for Electronic Data Interchange for Administration, Commerce, and Transport.
COPINO	Container Pre-notification Message.
APERAK	Application Error and Acknowledgement Message.
SenderID	Drayage Operator Unique Identification.
ContainerID	Container Unique Identification.
TruckID	Truck Unique Identification.
CNET	Contract Net Mechanism.
FCFS	First Come First Served Scheme.
RCB	Retrieval Cost Based Scheme.
SCB	Storage Cost Based Scheme.
TCB	Total Cost Based Scheme.
RSB	Reservation Service Based Scheme.
DSB	Deadline Service Based Scheme.
TSB	Total Service Based Scheme.

SUMMARY OF NOTATIONS

Notation	Description.
$O = \{o_1, \ldots o_n\}$	Set n of drayage operators.
o_i	A drayage operator with index i.
$T = \{t_1^1, \ldots t_m^s\}$	A collection of m available time slots in a day.
s	A server/ yard crane's index.
m	A time slo's index.
l_t	A time slot's length.
d	Reservation deadline parameter.
$t_{d\to j}$	The deadline for reserving a time slot t_j^x, where $t_{d\to j}= t_j^x - (d.l_t)$.
o_i	A Drayage operator with an index i.
i	A drayage operator's index.
z	The deadline for fulfilling the order.
$\overline{T} \subseteq T$	Available unreserved time slots.
$v_{i-z}(\overline{T})$	Valuation of unreserved time slots T.
$\overline{t^x_{i\to j}}$	The optimal time slot selected by the drayage executing order $\Phi_{i\to z}$.
$t^x_{i\to j}$	The winning bid for the appointment time slot, as confirmed by the container terminal.
$\overline{T}$	Unreserved time slots, where $\overline{T} \leftarrow \overline{T} - \{t^x_{i\to j}\}$.
$c(\overline{T_j^x})$	The container terminal's valuation of incoming reservation to determine the winning bid.
$(c\,\overline{t^x_{i\to j}})$	Container terminal's total cost to execute the pickup service for container $\Phi_{i\to z}$.
$c_\alpha(\overline{t^x_{i\to j}})$	Container terminal's storage cost/ dwelling time for container $\Phi_{i\to z}$.
$c_\beta(\overline{t^x_{i\to j}})$	Container terminal's retrieval cost to execute the retrieve container $\Phi_{i\to z}$.
r_i	Drayage operator's revenue.
$\propto_{\Phi_{i-z}} .q_i$	Drayage operator's reservation cost for submitting a bid.
$p_i.(j-z)$	Drayage operator's penalty cost incurred for delayed pick-up operation of orde $\Phi_{i\to z}$.

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