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Greening container terminals through optimization: a systematic review on recent advances

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Container terminals are essential nodes in global trade, facilitating worldwide cargo flows between various transport modes. However, their operations contribute significantly to global emissions, producing greenhouse gases like CO_2 and pollutants such as nitrogen oxide. Mitigating that impact requires integrating green technologies and goals as well as exploiting renewable energy sources into terminal planning and decision support systems. Optimization techniques are key for driving terminals into this green transformation. In recent years, there has been a relevant increase in research and attention to greening ports. This growing interest includes the development of effective strategies and optimization approaches to reduce the terminal's environmental impact. This systematic literature review examines relevant studies in optimization and greening terminals from the past two years, highlighting examples such as implementing microgrids, cold ironing, autonomous electric vehicles, retrofitting yard machinery, or promoting truck platooning. We propose a research agenda to guide future efforts in this direction.

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Introduction

As the backbone of global trade, maritime transport and container terminals are essential for efficient freight shipping and handling activities [33]. They serve as critical interfaces between vessels and the shore for cargo transfer. Beyond their conventional transshipment role, terminals have grown into sophisticated logistics hubs, concentrating economic activities related to freight transfers [29]. Nevertheless, this growth comes with an environmental impact, as terminals and vessels contribute to greenhouse gas emissions due to their dependency on and use of fossil fuels.

Given this context, the maritime industry is progressing toward decarbonization, and the role of container terminals is becoming increasingly important in this transition [17]. To support this swift, green container terminals have emerged as an effective response to cope with the increasing concern over maritime transport's environmental impact. These terminals are defined as transport facilities that maintain a healthy ecological environment, use resources efficiently, consume low energy levels, and produce minimal pollution [38]. Greening terminals requires optimization, which is essential in aiding decision-makers and enforcing terminal systems to fully integrate and exploit green technologies and related innovations such as the electrification of crane and yard vehicles, implementation of cold ironing, adoption of energy-efficient strategies, and so on.

Recent literature in this area is rapidly expanding, reflecting the increasing interest from practitioners, industry, and researchers in green container terminal planning. This highlights the need for a focused review of the most recent advances in optimization techniques for promoting green container terminals. In response to this journal's invitation to review the literature from the last two years (i.e., 2022–2024), we concentrated our analysis on this period. Despite the short time frame, we identified a significant increase in research contributions, demonstrating the growing interest and the importance of analyzing this topic. Optimization techniques in this context refer to a broad set of approaches to solving optimization problems, including mathematical models, exact algorithms, heuristic and metaheuristic methods, and hybrid algorithms. This article presents a systematic literature review to capture these recent advancements and outline a future research agenda. It is important to note that this review does not address the economic or social implications of green terminals, as our focus is strictly on environmental sustainability and optimization methodologies.

Review methodology

This study employs a systematic review and bibliometric analysis to better understand the use of optimization techniques to enhance terminals' environmental sustainability. This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a comprehensive and transparent process [28].

The search, conducted in June 2024, was carried out using the Web of Science (WoS) database selected for its comprehensive indexing and data quality [9]. The search formula was defined considering keywords from three different components: (1) maritime logistics and port operations, (2) optimization techniques (e.g., mathematical models, algorithms, etc.), and (3) sustainability (e.g., green energy, alternative fuels, etc.). The search formula, divided into keyword categories, can be found in Table 1.

The search was limited to journal articles published in English between 2022 and 2024, resulting in 391 articles. Eligibility was assessed by three coders, who independently coded a random sample of 10% (40 papers) to ensure consistency [51]. The inclusion (✓) and exclusion (✘) criteria applied during the eligibility stage are listed below:

✓ The paper addresses at least one of the following working areas: seaside, landside, yard, automated guided vehicles (AGVs), or overall.
✓ The paper addresses at least one of the following topics: waste, energy consumption, or emissions.
✓ The paper includes optimization methods.

✘ The paper is a review of the literature.
✘ The paper is about dry ports or bulk ports.
✘ The paper is not about operations planning.

The coding process achieved an inter-rater reliability of k = 0.848, calculated using Fleiss' Kappa [11], indicating an almost perfect agreement among the coders [22]. Following calibration, the remaining papers were divided among the coders, identifying 109 relevant papers. Bibliometrix for R was used for bibliometric analysis [1], including productivity analysis and co-word analysis to map current research trends and guide the discussion.

Container terminal operations

A container terminal is a dedicated facility at a seaport designed to link sea and land cargo flows using specialized equipment for handling, transporting, and stacking containers. Typically, container terminals are split into three distinct areas, that is, seaside, yard, and landside. These areas are interconnected through internal vehicles, such as AGVs. Figure 1 illustrates a container terminal layout divided into its operational areas. The figure also includes relevant green port elements discussed in the following subsections.

Seaside

The seaside area of a terminal is where container vessels are berthed for unloading and loading operations through quay cranes (QCs). The resources in this area primarily consist of berths and QCs. Berths are designated spaces along the

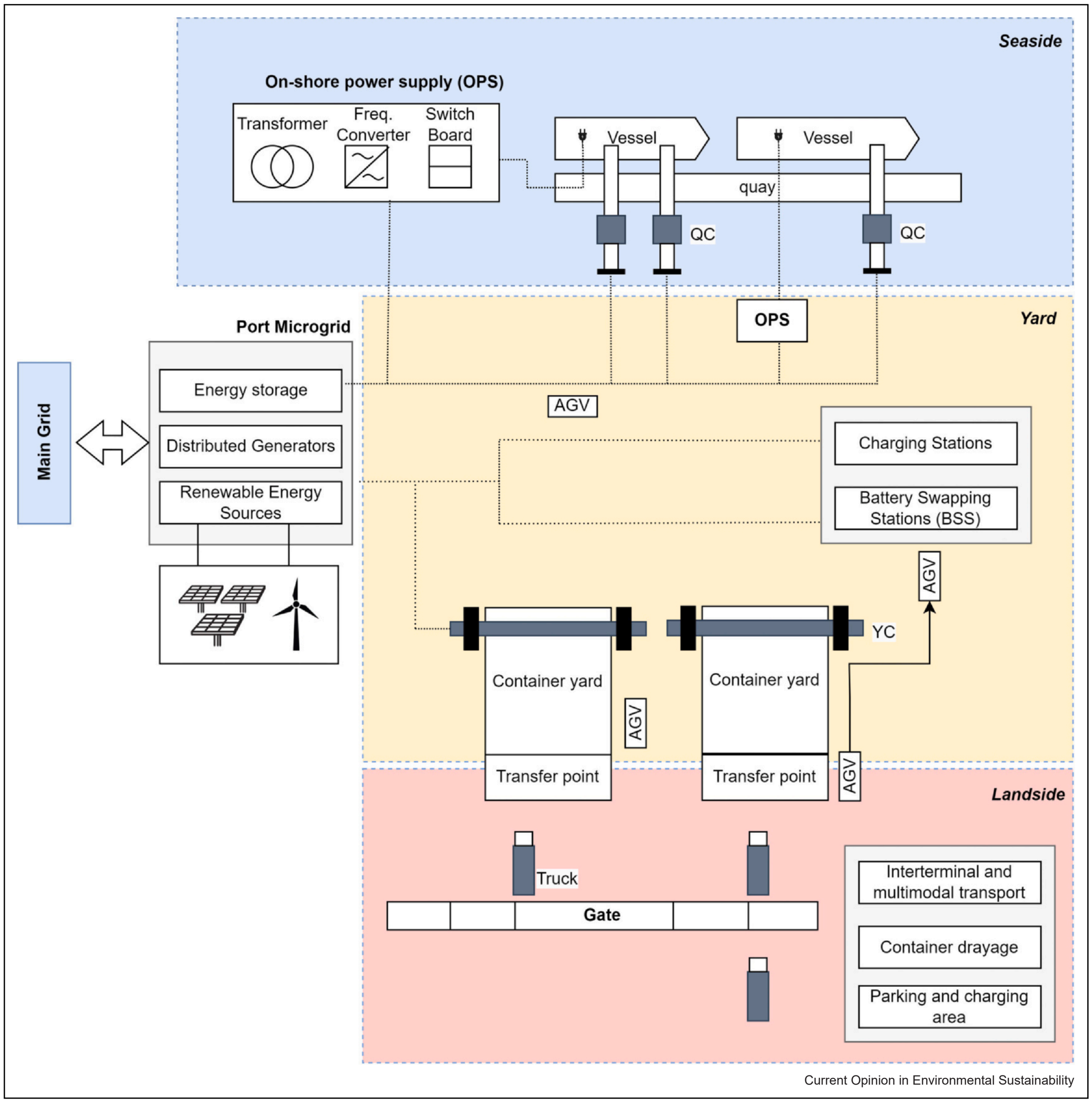
Table 1

Search categories and formulas used in this review.[a]

Category	Search formula
Maritime logistics and port operations	(((“maritime” AND (“logistic*” OR “transport*” OR “port”)) OR ((“container” OR “cargo” OR “roro”) AND (“terminal” OR “port” OR “harbor” OR “yard” OR “staking” OR “dispatching” OR “drayage” OR “truck” OR “interchange area” OR “freight station”)) OR (“yard” AND (“terminal” OR “operations” OR “storage” OR “truck” OR “management” OR “area”)) OR ((“port” OR “terminal” OR “operations” OR “planning” OR “scheduling” OR “allocation” OR “crane” OR “container*” OR “storage”) AND (“seaport” OR “sea port” OR “sea-port” OR “seaside” OR “sea-side” OR “landside” OR “land-side” OR “yard*” OR “berth*” OR “quay” OR “hinterland”)) OR “vehicles” AND “container*” AND (“port” OR “terminal” OR “automated guided”)) OR ((“straddle” OR “gantry”) AND “carrier”) OR ((“gate” OR “transport” OR “truck” OR “train”) AND “area” AND (“port” OR “maritime terminal” OR “seaport”)) OR ((“container*” OR “intermodal”) AND “drayage”) OR “inter-terminal transport” OR “stowage planning”)
Optimization techniques	(((“model*” OR “algorithm*”) AND (“math*” OR “optimi*” OR “simulation*”) OR ((“meta*” OR “mat*” OR “hyper*”) AND “heuristic*”) OR “heuristic*” OR ((“decision-support” OR “decision support”) AND “system*”) OR “Reinforcement learning”)
Environmental sustainability	(((“green” OR “renewable” OR “efficien*” OR “clean” OR “alternative” OR “electr*”) AND (“energ*” OR “fuel*”)) OR “sustainab*” OR “waste” OR “pollution” OR “air quality” OR “decarbonisation” OR “greenhouse” OR “recycle” OR “contamination” OR “ cology*” OR “climate change” OR “circular economy” OR “sustainable development” OR “footprint” OR “low-carbon” OR “carbon reduction” OR “emission*” OR “battery” OR “smart grid*” OR “environment*”)

[a] Note that to use this search formula in the WoS (Web of Science) database, you must (i) add the prefix ‘TS=’ at the beginning of the search formula and (ii) combine the three formula blocks using the ’AND’ operator, ensuring that each block is enclosed in parentheses.

Figure 1



Container terminal integrating traditional and green technologies.

quay where vessels are berthed to carry out their related cargo-handling operations. QCs are specialized equipment dedicated to loading and unloading containers from vessels to and from the yard according to the vessel stowage plan.

The main source of seaside emissions comes from berthed vessels using auxiliary engines to generate electricity to sustain onboard activities such as ventilation, lighting, and cargo operations. In this regard, the International Maritime Organization (IMO) recommends using on-shore power supply (OPS) technology to power vessels while berthed [18]. This means that diesel fuel is replaced by electricity, with vessels switching from their diesel engines to the OPS. This practice, known as *cold ironing*, can be effectively managed using a microgrid. A *microgrid* is a localized network featuring energy resources (e.g., renewable energy, storage devices, or controllable loads) that can operate independently from the primary grid. Implementing cold ironing and microgrids is challenging when considering variable energy prices or using renewable sources. Chargui et al. [2,3] address such issues through robust optimization to provide the best worst-case berth and QC deployment. To cope with demand peaks, Fan et al. [10] propose an incentive-based cooperative coordination framework between the port microgrid and vessels. Under that incentive scheme, vessels alter their power demands to relieve the port's peak burden. Zhen et al. [48] investigate berthing-priority-based incentive policies for vessels with onboard ship-side shore power modules and optimize the shipborne power system, berth allocation, and ship service order. Zhang et al. [47] consider the costs of allocating vessels and microgrid operations into a two-stage approach. Wang et al. [39] address the joint berth and QC assignment together with the OPS allocation to simultaneously reduce energy consumption and carbon emission costs. Results show that OPS allocation is more effective in reducing emissions than implementing carbon taxation.

Besides energy management, contemplating the emission reduction when generating berth and QC planning is relevant. Several papers consider carbon tax costs due to QCs and vessel emissions as performance metrics in their optimization models and solve them using heuristic approaches. Jauhar et al. [19] tackle the berth allocation and yard assignment problem, integrating emissions from the nearshore, port side, and handling operations into the objective through carbon taxes. In addition to carbon taxes, Kenan et al. [21] develop optimization models for QC scheduling considering the carbon cap-and-trade policy where a cap on the amount of emissions is set. They show that emissions are slightly lower using a cap-and-trade policy and that considering penalties or having more QCs to reduce late departure times reduces vessel emissions. Moreover, recent contributions highlight the importance of jointly considering planning uncertainties while tackling emissions. Jiang et al. [20] address berth and QC scheduling considering multiple uncertainties such as vessel arrival time, QC efficiency, or maintenance. Carbon emissions during the vessels' turnaround time were considered carbon tax costs. The use of heuristics resulted in planning with significant carbon emission reductions. Qu et al. [32] consider vessel emissions due to waiting, service time, and the deviation from berth preference. They propose a robust two-stage programming model to cope with uncertain arrival times.

Yard

The yard is a designated area where cargo is stored, organized, and managed by yard cranes (YCs) before and after being loaded onto or unloaded from vessels. This space is essential for storing and handling cargo, as it allows for systematically stacking and categorizing containers based on their destination, type, and priority.

One research line is dedicated to integrating and analyzing the use of advanced technologies in the yard, such as automated cranes and electric or hybrid handling equipment [5]. In this context, *retrofitting* yard machinery arises as a compelling strategy. It involves updating and modifying existing equipment with new technology and parts to improve performance and efficiency. A common approach is to replace internal combustion engines with cleaner propulsion alternatives. A representative example of this can be found in the paper by Lombardi et al. [26], where they study how to minimize consumption in a fuel cell/battery hybrid engine and design an adaptive energy management strategy that optimizes the power distribution between the fuel cell and the battery. Zhang et al. [46] consider retrofitting and deploying machinery strategically to minimize the costs associated with purchasing, retrofitting, and chartering yard trucks, from diesel to electricity or liquefied natural gas.

A relevant research line focuses on the efficient scheduling and coordination of yard equipment. Zheng et al. [49] propose a mixed-integer linear programming model and a genetic algorithm to coordinate the container operations of QCs, yard trucks, and YCs. Similarly, Duan et al. [7] consider the coordination of AGVs and automatic stacking cranes, considering buffer zones that connect the yard with the other terminal areas. This coordination between cranes and vehicles promotes the reduction of total energy consumption associated with stacking cranes by avoiding long round trips. Li et al. [24] developed a conflict-free operation strategy to coordinate the YCs when moving containers with trucks. This strategy ensures that the operations of multiple gantry cranes are coordinated effectively, reducing conflicts and unnecessary movements. Talaat et al. [36] focus on coordinating YCs and external vehicles. They introduce a mixed-integer programming model to schedule external trucks and YCs. This reduces the number of necessary truck trips for container handling, thus achieving a substantial daily reduction in CO_2 emissions.

Moreover, mathematical models, heuristics, and metaheuristics contribute to assigning yard storage spaces to cargo so that transport distances and unproductive movements are minimized. Unproductive movements occur, for instance, when a container blocks another container from being retrieved, resulting in additional rehandling. Thus, reducing the unnecessary movement of goods within the yard contributes to energy savings. A representative example of this research line can be found in the paper by Durasević et al. [8]. The authors, through heuristic methods, find efficient sequences of container relocation movements to retrieve containers in a predetermined order. Hsu et al. [16] propose a simulation-optimization approach that considers yard stacking operations jointly with other terminal operations (e.g., stowage and internal transport) at automated container terminals. They take into account energy consumption rates, transport speed, and crane moving distance, among others. Computational results demonstrate the benefits derived from using metaheuristics and suggest that a distributed container policy among multiple blocks helps smooth bottlenecks.

Lastly, digital twins, virtual replicas of physical systems, leverage advanced simulation and modeling technologies to create accurate digital representations of real-world objects and processes. By simulating real-world crane operations, digital twins provide insights into energy usage patterns, identifying inefficiencies and areas for improvement. Gao et al. [12] describe a virtual replica of the physical container yard that synchronizes with real-world operations, allowing for real-time observation and validation. This replica provides data to minimize the total energy consumption of automated stacking cranes during container handling operations.

Automated guided vehicles

The movement of containers between the different port areas, that is, seaside, landside, and yard, is known as internal transport and is typically carried out by a fleet of AGVs. Optimizing these fleets is one of the main challenges in improving a port's overall performance. Terminals are transitioning to electric AGVs with batteries to increase sustainability. This change has advantages, such as reducing costs and gas emissions. However, managing the limited capacity of the batteries arises as a challenge.

One line of research to reduce AGVs' energy consumption is to optimize their operational planning. Improving collaboration between AGVs and other port equipment is crucial. For example, Sun et al. [35] propose a genetic algorithm to optimize AGVs' energy consumption in collaborative scheduling with YCs and QCs. Similarly, Zhong et al. [50] optimize the integrated scheduling of AGVs and YCs with conflict-free routes using a genetic algorithm. Additionally, machine learning techniques have been explored to enhance AGV management. Gao et al. [14] present a Q-learning algorithm to improve AGV dispatching at terminals, while Drungilas et al. [6] aim to reduce energy consumption by adjusting vehicle speed using deep reinforcement learning. Xing et al. [40] propose a three-phase algorithm that adjusts AGVs' speed to minimize the makespan of port crane operations and reduces vehicle energy consumption.

Because of the limited battery capacity of AGVs, their energy levels must be monitored. When energy levels reach a certain threshold, vehicles must recharge their batteries to continue operating. Terminals offer different systems for energy recovery: *charging stations* and *battery swapping*. Charging stations are specific facilities where vehicles can connect to the electric network and recharge their batteries. Battery swapping involves replacing a nearly empty battery with a fully charged one at Battery Swapping Stations (BSS). Generally, BSS are more prevalent in terminals than charging stations due to their higher operational efficiency. In both systems, the vehicle must interrupt its tasks, move to the corresponding station, and wait until the battery is recharged.

Recent research has studied factors affecting AGV scheduling performance when using charging stations, such as vehicle conflicts, failures, and battery constraints. Gao et al. [13] propose a decision support system based on a digital twin to maintain the efficiency of AGV scheduling from real-time changes. In the same line, Song et al. [34] employ a large-adaptive neighborhood metaheuristic to create AGV schedules that can handle emergent uncertainties, such as emergency jobs. Some terminals are updating their charging stations to use fast charging technologies to reduce charging time and, consequently, improve the operating efficiency of their vehicle planning. Li et al. [25] investigate the use of this technology and create integrated plans for AGVs, YCs, and QCs using fast charging facilities. It proposes a decomposition-iteration algorithm to minimize the makespan of the planning process and reduce the vehicles' charging costs.

For terminals utilizing battery swapping, Yang et al. [43] propose a set-partitioning method for scheduling AGVs using BSS to minimize energy consumption. In addition to battery swapping, controlling AGVs' speed can improve energy efficiency. The combination of both factors is treated in the paper by Yang et al. [42], proposing a genetic algorithm that combines efficient AGV planning with a speed control strategy based on traffic conditions, using BSS as needed. Finally, Li et al. [23] consider AGV planning with battery swapping with uncertainty due to the arrival of new transportation tasks using a simulation-optimization approach.

Landside

The landside of a container terminal encompasses the infrastructure and equipment necessary to support cargo handling and transportation between the yard and truck gates, that is, horizontal transport, between other container terminals, empty container depots, bonded warehouses, or dry ports (i.e., inter-terminal), and transportation to the hinterland. Coordinating cargo pickup and delivery by external trucks is crucial to guarantee efficient hinterland transport operations, also known as *container port drayage* [4].

Truck appointment systems (TAS) have been implemented in many ports to reduce truck congestion by coordinating the pickup and delivery of cargo. Several papers have proposed optimization approaches to aid in designing TAS and allocating service gates [27]. These approaches consider the uncertainty of truck arrivals and the need to reschedule appointments [41] or model the TAS as a multiplayer optimization problem, with the port terminal as the leader and several drayage firms as followers [37]. Balancing the arrival of trucks throughout the port's operating hours and reducing truck turnaround times helps decrease congestion and emissions [27,41]. Other strategies include limiting truck arrival hours and defining pricing mechanisms to avoid peak-time arrivals. For instance, Yildirim [44] copes with a policy in which the government restricts truck circulation at peak hours, utilizing a buffer zone that processes peak truck traffic as a pre-terminal. The use of such buffer zones, together with a cost model, showed significant truck delays and congestion reduction.

Electric vehicles and *truck platooning* have been studied in the literature to enhance sustainable hinterland and inter-terminal transport or container drayage operations. In truck platooning, a lead human-operated truck is followed by a convoy of trucks with automated longitudinal control. You et al. [45] propose a multi-trip container drayage problem incorporating truck platooning. They assume load-dependent costs and a piecewise linear fuel cost function of the number of trucks in the platoon. In this case, rather than the traditional operation mode, *stay-with mode*, in which a driver is assigned to a single trip, multiple trips are allowed, facilitated by the platooning technology to perform transport services while containers are unpacked. Regarding inter-terminal transport, Han et al. [15] consider container transport within a port consisting of multiple container terminals with a fleet of electric trucks (ETs). Because of the limited battery capacity, ETs have a restricted driving range requiring charging activities. They proposed an adaptive large neighborhood metaheuristic and conducted a sensitivity analysis. Their results highlight the importance of including the battery mileage and charging power of ETs for the allocation of fleets, as well as both fixed and operational fleet costs.

Pourmohammad-Zia et al. [31] assess the benefits of shifting to automated transport outside terminal areas by utilizing AGV platoons for direct inbound container delivery to pre-terminals or dry ports. They consider two case studies that examine the cost, dwell time, and emissions reduction to transport freight between the seaport and a pre-terminal or dry port, representing short- and long-distance traveling, respectively. Their results show that dwell time reduction is achieved similarly for both cases, but cost savings are higher for long traveling distances. Peng and Xue [30] investigate truck platooning for local container drayage, evaluating the effects of a laden-or-empty state of trucks on platoon fuel consumption, a factor often neglected. They conducted numerical experiments, demonstrating that considering the truck-laden-or-empty state reduces fuel consumption and costs for both small- and large-scale instances in contrast to when this state is ignored and that optimal routes also change.

Future agenda

The future agenda for advancing to green ports through optimization should focus on progressing the integration of technological developments into terminal planning systems. This includes enhancing and leveraging existing decision support systems and algorithms to incorporate sustainability-related objectives in planning to provide a competitive trade-off between energy consumption, emissions, and terminal performance indicators. Those approaches must acknowledge the container terminal's stochastic and dynamic nature, where additional sustainability-related aspects must be considered, such as energy peaks, renewable energy provision, or price variability. In this context, real-time monitoring combined with stochastic optimization is relevant in providing more accurate operation planning for preparing and responding to disruptions and uncertainty. Integrated optimization frameworks incorporating real-time information and machine learning approaches can improve planning multiobjective operations.

On the seaside of container terminals, we observed a transition to electrification and the use of renewable energies. Terminals increasingly incorporate microgrids, integrating renewable energy sources (e.g., wind and solar). Looking ahead, the agenda should involve exploiting this direction while deepening the integration of the terminal's energy management with operations planning to dynamically and intelligently balance supply and demand. In this way, studies should focus on real-time scheduling algorithms that consider the energy balance and the management of berths and QCs. Studies related to evaluating the incorporation of storage solutions for the excess renewable energy and using machine learning to forecast energy needs are relevant future direction lines.

Future research in yard management should consider combining digital twins with optimization algorithms and simulation models to enhance predictive accuracy and operational efficiency. By enabling predictive maintenance, digital twins allow for predicting yard machinery conditions and facilitating repair scheduling before yard machinery fails, thus avoiding energy waste caused by malfunctioning equipment. Operational efficiency is another area where digital twins can make a significant impact. They can be jointly used within hybrid simulation-based optimization frameworks to determine the most efficient routes for transporting containers within the yard. Lastly, this technology can be used to evaluate energy-efficient equipment, such as battery-operated forklifts or hybrid rubber-tired gantry cranes, among others, before making major investments.

For battery-powered AGVs, technological trends in this area must guide future studies, whether in the field of navigation and control or in improving battery charging efficiency. Digitalization and sensorization have been implemented in AGVs in recent years. Correctly using these technologies and optimization algorithms allows for creating energy-efficient plans that can also avoid possible problems such as path conflicts or vehicle congestion. Additionally, increased sensorization allows for dynamic algorithms that provide real-time reactions to possible planning issues. On the other hand, new charging technologies such as renewable charging stations or hydrogen engines must be studied to increase the efficiency and sustainability of the charging process.

In landside operations, adopting greener transport modes, such as electric vehicles and truck platooning, is expected to continue its expansion. The future agenda should focus on deepening their integration with energy management. For example, more precise energy consumption modeling of truck platooning can be used to determine the number of trucks in a platoon and their traveling speed for multi-truck trips. Regarding coordination mechanisms like a TAS, more research is needed to integrate machine learning schemes to estimate truck arrivals and service times to optimize workload assignment and truck quotas, including green metrics such as CO_2 emissions or terminal energy efficiency. Lastly, further research should consider integrating energy management and horizontal transport decisions with yard equipment assignment within interterminal transport, as it allows better coordination across various operations, reducing peak energy demands and operational schedules.

In addition to the previous opportunities, there is a need to broaden the review focus from academic perspectives to a more comprehensive analysis of practical applications. Most existing reviews on environmental sustainability in container terminals are focused primarily on academic research. However, a significant gap exists in examining and analyzing real-world projects and initiatives. A review that collects and consolidates lessons learned from past and ongoing practical implementations in greening terminals would enhance the synergy between research and industry practices, driving further advancements toward greener operations at container terminals.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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