Maritime Economics & Logistics
https://doi.org/10.1057/s41278-024-00307-y

ORIGINAL ARTICLE

Handling modular containers in a physical internet environment

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Accepted: 3 November 2024

Abstract

The shipping industry is currently the sixth largest source of global emissions, generating one billion tons of greenhouse gases annually. Physical Internet is a leading solution to enhance the efficiency of shipping operations and reduce CO_2 emissions. In a physical internet framework, this research compares and simulates two sequencing strategies, based on the Dijkstra algorithm, designed to optimize the routing of terminal vehicles in managing modular containers at terminals. Our results indicate that the proposed method could save the total travel time of Automated Guided Vehicles by 1.2% and lead to a 0.5% reduction in global CO_2 emissions if implemented in the top 100 container ports in the world. We show that the physical internet contributes positively to mitigating climate change in maritime transport, towards eventually achieving cargo neutrality. Furthermore, our proposed mathematical model provides decision aid for handling modular containers in terminals.

Keywords Physical internet · Modular containers · Container sequencing strategies · Dijkstra algorithm · Climate change

1 Introduction

The logistics industry is now challenged by high levels of greenhouse gas (GHG) emissions, among others due to inefficiencies in its operations, such as poorly planned routes, inefficient warehouse and stacking layouts, and poor inventory placement. Physical Internet (PI) is seen by many as one of the most efficient solutions to address such challenges while achieving sustainability and resilience in global logistics (Yang et al. 2017).

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Published online: 05 December 2024

PI is a worldwide logistics system that operates by connecting various logistics networks using a standardized set of collaboration protocols, modular containers, and intelligent interfaces. Modular containers (also known as PI containers) come in a variety of standardized sizes (cf. Figure 3; Montreuil et al. (2014) proposed 18 different sizes) and can be assembled and disassembled, in smaller or larger units, based on cargo volume and needs. This allows for greater flexibility, interoperability and efficiency in loading, transportation, and storage. In the PI paradigm, container terminals are expected to be able to handle all sizes of modular containers. This integration aims to increase efficiency and promote sustainability in logistics (Ballot et al. 2014; more details on modular containers are provided in Sect. 2.2).

Since Montreuil (2011) introduced the concept of PI as a new research area, there has been an explosion of studies in the scientific literature. A Google Scholar search using the keyword "Physical Internet" retrieves more than 1.5 million articles as of January 17, 2024. By reviewing a large number of them, we find that there is a lack of research on handling strategies of modular containers. Given that the EU and Japan are poised to implement PI by 2040 (ALICE 2020; METI and MLIT 2022) research on the practices of terminal operations, such as modular container handling in a PI paradigm, not only provides a scientific foundation but it is also offering new insights to the shipping industry, as modular containers are one of the central pillars of PI.

Motivated by the lack of relevant studies, in this research we propose two sequencing strategies based on the Dijkstra algorithm, designed to optimize the routing of vehicles, in particular Automated Guided Vehicles (AGVs), in managing modular containers at terminals. Our results indicate that the proposed method could save the total travel time of AGVs by 1.2% and lead to a 0.5% reduction in global CO_2 emissions if implemented in the top 100 container ports worldwide.

The contribution of our research is twofold. First, it proposes an efficient strategy for handling modular containers in a PI environment; a first research attempt in this area. Second, we offer insights into the decarbonization efforts in shipping towards the goal of IMO) to achieve carbon neutrality by 2050.

The remaining sections are organized as follows. Section 2 outlines the research progress on PI, modular containers, and research on container handling in terminals. In Sect. 3, we propose a strategy to be applied to a medium-sized container terminal, suCortes-Murciach as Tokyo, of approximately 3.5 million TEUs per annum, handling different types of modular containers. Section 4 presents the simulation environments and results. Section 5 discusses terminal performance measures and the benefits of the proposed strategy. Section 6 concludes.

2 Previous studies

2.1 Physical Internet and its developments

The term "Physical Internet" (PI) first appeared in 2006 in a cover story of the British publication The Economist. The article featured a logistics survey and a series of mainstream articles on supply chains (Markillie 2006). In the years that followed,

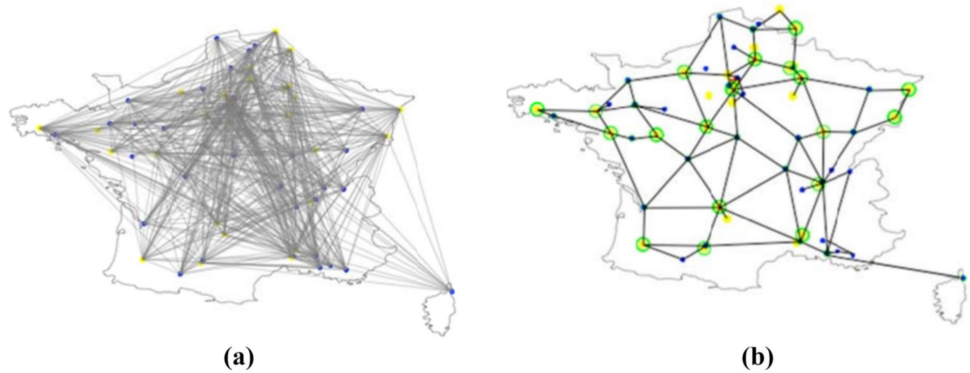
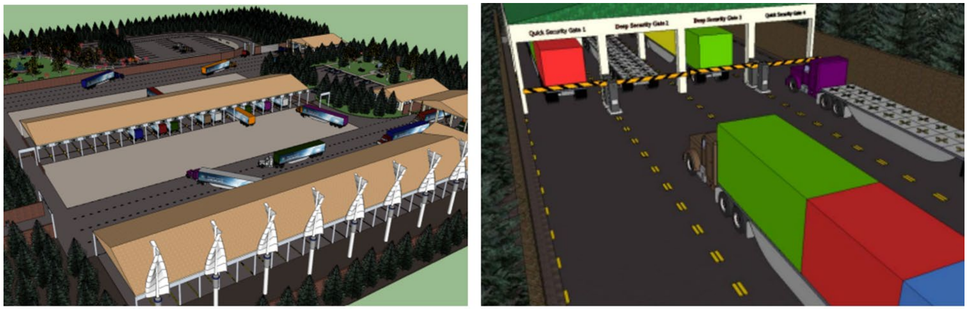


Fig. 1 **a** Example of conventional logistics networks, **b**. Example of structured logistics network in PI environment. Source: Adopted from (Ballot and Montreuil 2012)



(a) (b)

Fig. 2 **a**. An example of road-road hub, b. An example of rail-road hub. Source: adopted from Meller et al. (2012). **b**. An example of rail-road hub. Source: adopted from Ballot and Montreuil (2012) this topic sparked the interest of a group of researchers who explored how the distribution of physical goods could be structured in a manner analogous to data traffic on the digital internet (Montreuil 2011). PI is a futuristic concept yet to be implemented in the real world. Montreuil (2011) gave examples such as cross border long haul trailers between the US and Canada, delivered by multiple drivers in a shift mode. The shift concerned distributed multi-segment travel of modular containers through PI with an open market of transport service providers and users.

Over the years, systematic literature reviews by Münch et al. (2023) were conducted to understand trends, summarize the status of the literature, and identify gaps and areas for future research to advance this area. From the synthesis of these review papers, we conceptualize the development of PI in six phases, each marked by specific advances and milestones. The following outline provides a general overview of these phases in the development of the PI.

2.1.1 Phase 1: Conceptualization (early to mid-2000s)

The early phase involves the conceptualization of the PI, drawing parallels between the movement of physical goods and the principles of the digital internet. One example is decentralized warehousing, where multiple small warehouses (nodes) are distributed throughout a city, much like data on the digital internet stored on multiple servers around the world. Storing goods in different strategically located warehouses could reduce the distance between products and end users while speeding up delivery. Researchers lay the theoretical foundations by exploring the key principles, benefits, and challenges associated with creating an interconnected and open system for global logistics (Ballot et al. 2014).

2.1.2 Phase 2: Research and feasibility (mid-2000s to early 2010s)

In this phase, researchers and industry stakeholders conducted feasibility studies to assess the practicality and viability of implementing the principles of the PI in real-world logistics. Figure 1a, b. illustrate a conventional logistics network and a PI-enabled logistics network.

Scientists worked to model and validate PI-hubs (Fig. 2a,b) in road-road (Meller et al. 2012) and rail-road (Ballot and Montreuil 2012) transport, and mass distribution (Hakimi et al. 2012). A PI-hub is a logistics facility that provides a mechanism for transferring modular containers from one mode of transport to another.

2.1.3 Phase 3: Pilots and demonstrations (2012 to 2016)

Pilot projects such as MODULUSHCA (EU 2012) were conducted. These served as test beds to evaluate the effectiveness of the approach in real-world scenarios. Several industry players worked together to demonstrate connected supply chains, highlighting the benefits of information sharing, collaborative logistics, and modular systems (Sarraj et al. 2014). Increased integration of advanced technologies into logistics processes was tested, with a focus on improving efficiency, visibility, and responsiveness.

2.1.4 Phase 4: Standardization and infrastructure development (2014 to 2019)

Here, the focus is on identifying and developing technologies that can serve as enablers for the PI, such as IoT, blockchain, and autonomous vehicles, as well as developing early prototypes of modular containers (e.g., Montreuil et al. 2014; Landschützer et al. 2015) and simulations to test the feasibility of modular logistics, standardization, and information sharing mechanisms.

2.1.5 Phase 5: Scaling and global adoption (late 2010s to present)

Expanding successful pilots and initiatives to broader regions and industries, demonstrating the scalability of the PI model. In this phase, industry stakeholders and international organizations work to develop standards for containers (Montreuil et al. 2014), communication protocols, and modular logistics systems to ensure interoperability. Attention to regulatory frameworks that facilitate the development and deployment of PI, while addressing privacy, security, and interoperability issues (EU 2017). Initiatives emerge to design the roadmaps of PI implementation in specific sectors or regions. Commercial applications and solutions based on PI principles become more widespread as businesses recognize the economic and operational benefits. Seven PI themes are identified, namely business models, cooperation models, modular containers, seamless, secure, and confidential data exchange, transit centers, vehicle use optimization, and legal models (Treiblmaier et al. 2020).

2.1.6 Phase 6: Continuous optimization and evolution (Ongoing)

Ongoing efforts to optimize logistics processes, incorporate new technologies, and adapt to changing economic and environmental factors. Integrating evolving technologies such as artificial intelligence, machine learning, and advanced analytics to further enhance the efficiency and adaptability of the PI. Research on route optimization in PI is on the rise; Ancele et al. (2021) develop a meta-heuristic based on simulated annealing method to solve VRP with pickup and delivery, aligning with the PI concept.

The phases outlined above provide a general roadmap for the development of the PI, illustrating the progression from conceptualization to widespread deployment and continuous optimization.

The work presented by Ballot and Montreuil (2012) and Meller et al. (2012) has made it possible to model and validate the normal operation of PI hubs in road-road and road-rail transport. However, no modeling of container terminal operations in a PI environment has been specified. In particular, very little research has addressed the stacking problems and handling of modular containers in a PI-enabled container terminal. We aim to fill this research gap.

2.2 Modular containers

Modular containers are used to encapsulate goods in intelligent, standardized, modular units, designed for logistics operations (Montreuil et al. 2014). They can

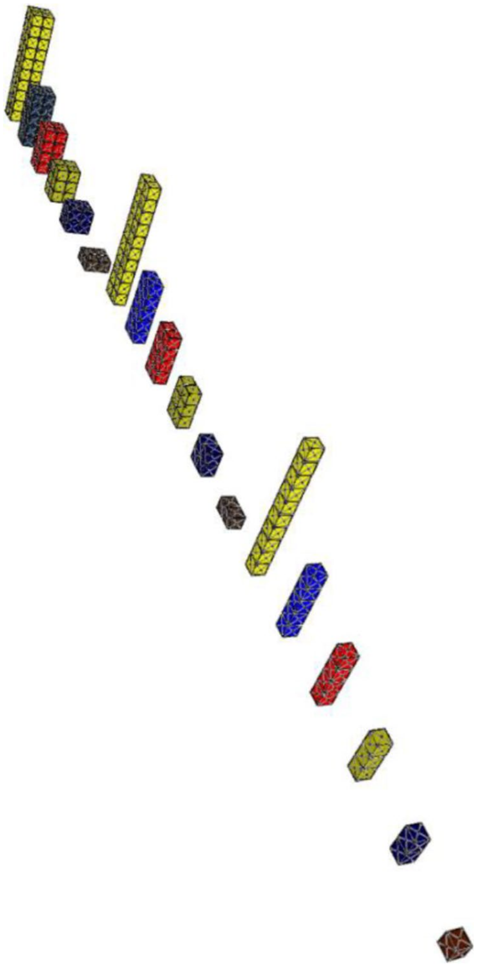


Fig. 3 Different sizes of modular containers (adopted from Montreuil et al. 2014)

Table 1 Comparison of the dimensions of modular containers and M-box

Modular container Variation of dimensions			M-box Variation of dimensions		
Length	Width	Height	Length	Width	Height
1.2 m	1.2	1.2	0.10 m	0.10 m	0.80
2.4 m	2.4	2.4	0.12 m	0.12 m	
3.6 m			0.20 m	0.20 m	
4.8 m			0.24 m	0.24 m	
6 m			0.30 m	0.30 m	
12 m			0.40 m	0.40 m	
			0.48 m	0.60 m	
			0.60 m	1.20 m	
			0.80 m		
			1.20 m		
			2.40 m		

Sources: authors, compiled based on information in Montreuil et al. (2014) and Landschützer et al. (2015)

incorporate smart technologies for tracking and monitoring, such as IoT sensors, RFID tags, and GPS, to improve visibility and control along the supply chain. The system is also designed to easily scale up or down to efficiently handle varying volumes of goods based on demand.

In the design of modular containers, Montreuil et al. (2014) propose a three-level characterization, i.e., packaging containers, handling containers, and transport containers. The authors further introduce the 18 types of modular containers illustrated in Fig. 3.

Landschützer et al. (2015) present a systematic engineering approach for the design of a modular and multifunctional load unit, called M-box. The M-box is specifically designed for applications in the fast-moving consumer goods sector in a PI scenario. The authors propose the M-box with folding, collapsing, stacking, interlocking, product-box interaction, strength, durability, cleaning, identification, and handling capabilities. A comparison of the dimensions of the modular container and M-box is shown in Table 1. The M-box is designed to be compatible with current logistics standards.

Although there are discussions on modular container designs, there is a lack of studies on how they should be handled, especially in marine terminals. This is another gap that our research aims to fill. The transport, port and logistics industries are generally cautious about adopting new technologies and concepts until these have been thoroughly tested and proven. The industry is beginning to recognize the benefits of modular containers, particularly in terms of sustainability and adaptability. However, widespread adoption may take time as companies evaluate the long-term benefits and overcome logistical hurdles. Modular containers offer great potential in terms of flexibility and efficiency, but there are challenges related to standardization, compatibility, and initial investment costs. Empirical studies are needed to prove the effectiveness of PI and modular container handling. This has been the motivation behind our research.

2.3 Container handling in the terminal

2.3.1 Terminal layout and automated guided vehicle in container terminal

Container terminal layouts come in two types, parallel and perpendicular, depending on the orientation of the berths and stacking (container storage) yards relative to the shoreline. In a parallel layout, berths (quay wall) run parallel to the shoreline. Vessels berth along the land–water interface. Container storage yards are located directly behind the berths, also parallel to the waterfront. Cargo handling equipment, such as Ship-to-Shore (StS) cranes, can move along the length of the quay loading and unloading containers from various berthed ships. Terminal vehicles (AGV, straddle carriers, etc.) move containers from ship to yard and vice versa.

Alternatively, in the perpendicular layout, container storage areas are organized perpendicular to the waterfront, while the berthing area is parallel to the shoreline. Ships dock along the sides of these piers, and containers are unloaded across the piers into storage yards perpendicular to the berths. This layout maximizes berth space by using both sides of the piers for docking, but it generally requires more sophisticated logistics systems to move containers from the berths to storage and handling areas further inside the terminal.

Zhang et al. (2023) compared the two layouts, pointing out that the two different vehicle travel routes affect differently terminal efficiency. The authors found that a perpendicular layout results in shorter travel distances for vehicles but in some cases results in longer travel distances for yard cranes. The overall efficiency of the terminal varies depending on the size of the yard.

Improvement in terminal operations efficiency and optimization of new terminal layouts can contribute to GHG emissions. Abu Aisha et al. (2020) conducted a case study of a container terminal at the Port of Montreal and proposed a layout that achieves a 46.5% reduction in total container transportation costs and a 21.6% reduction in CO_2 emissions.

AGV is an essential component in container terminals as it offers efficient transport of cargo between different parts of the facility. Considering the advancements in technology and the pressures for terminal efficiency, the future generation of

AGVs will be more intelligent,[1] efficient, and integrated, playing a crucial role in automated terminals and smart logistics ecosystems. Liu et al. (2004) use multiple attribute decision-making (MADM) to simulate the performance of AGVs in different terminal layouts. The authors suggest that while yard layout inevitably affects terminal performance, the use of AGVs significantly increases terminal throughput compared to manual operations.

In this paper, we study two scenarios within a PI framework, where modular containers are handled in two different scenarios using AGVs. The aim is to quantitatively evaluate the efficiency achieved in terminal operations and the reduction of GHG emissions. The setup of the two scenarios is described in Sect. 4.1.

2.3.2 Solving vehicle routing problem using Dijkstra algorithm

The use of the *vehicle routing problem* (VRP)[2] in city logistics problems has been implemented in previous studies (Firdausiyah et al. 2019; Teo et al. 2015). VRP is often applied to minimize the distance traveled, which contributes positively to the reduction of carbon emissions (Eglese and Black 2010).

The Dijkstra algorithm is a technique that is widely applied in path planning in container terminals. It is an approach that calculates the shortest path from the starting point to the destination, taking into account the minimum weight, i.e., the smallest cumulative cost or distance between two nodes along a path (Hartomo et al. 2019), making it a straightforward yet powerful technique. Some examples include Zaghdoud et al. (2016) applying Dijkstra and genetic algorithms to the assignment of containers to AGVs; Yue and Fan (2022) integrating Dijkstra and Q-learning algorithms to optimize AGV scheduling and path schemes; and Lou et al. (2023) proposing an artificial fish swarm algorithm Dijkstra for AGV scheduling and routing solutions in container terminals.

In addition to path planning in container terminals, Dijkstra is also used to identify the shortest route in transport and logistics areas. An et al. (2020) apply the Dijkstra algorithm with varying time frames to provide a methodological framework for network-level autonomous vehicle control. De Nunzio et al. (2021) compare Dijkstra and other search algorithms to identify the shortest path for hybrid electric vehicles. Chen et al. (2019) apply a timetable-based Dijkstra algorithm to compute the origin–destination accessibility in urban rail networks. Yu (2020) uses a modified Dijkstra shortest path algorithm to simulate the routing of pedestrian crowds. Chen et al. (2022a, b) apply the Dijkstra algorithm for trajectory planning in airspace operations.

These studies prove that Dijkstra is a useful technique in searching for shortest path. For this reason, we propose a Dijkstra algorithm-based model to find all

[1] An example of a more intelligent AGV is presented by Tai (2024). This is a system combined with a robotic arm for flexible operations. The system integrates advanced computer and sensor technology. This enhances the AGV's ability to navigate and perform tasks autonomously in a dynamic environment.

[2] VRP is a method for determining the most efficient routes for a fleet of vehicles to deliver goods to different locations while minimizing factors such as cost, time, and distance. Its objective is to ensure that vehicles use as few resources as possible while meeting delivery requirements, including capacity, delivery windows, and route constraints.

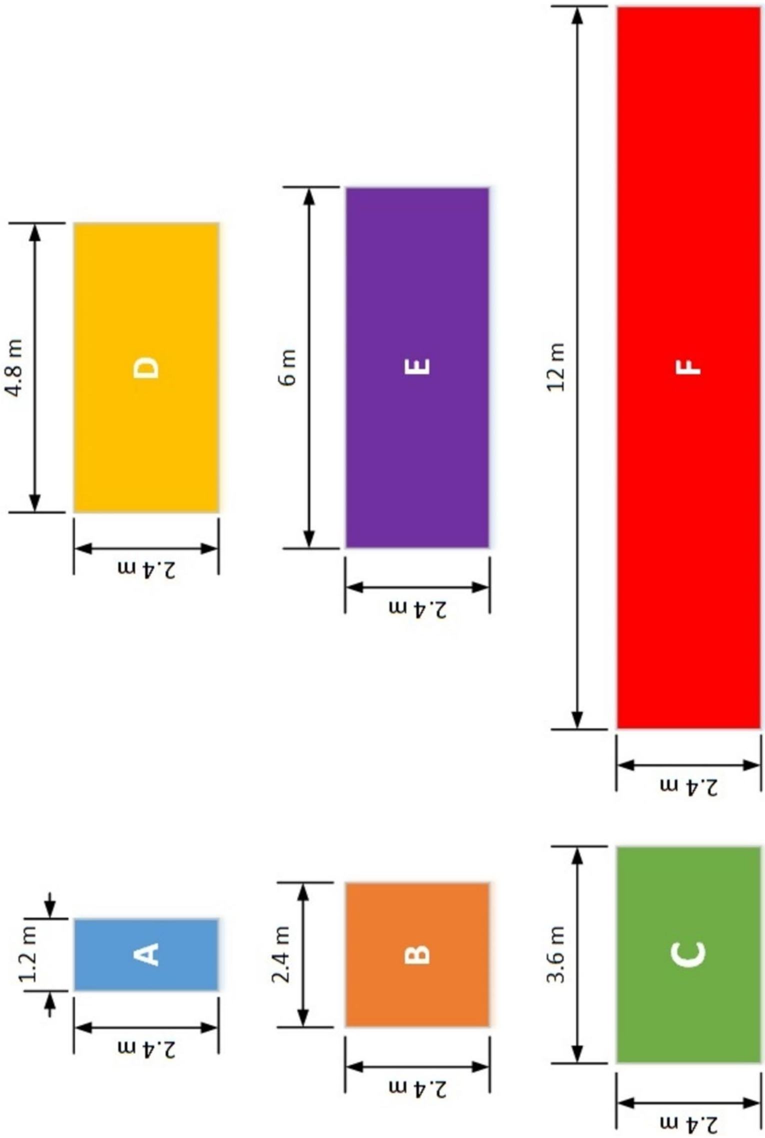


Fig. 4 Modular container types and dimensions

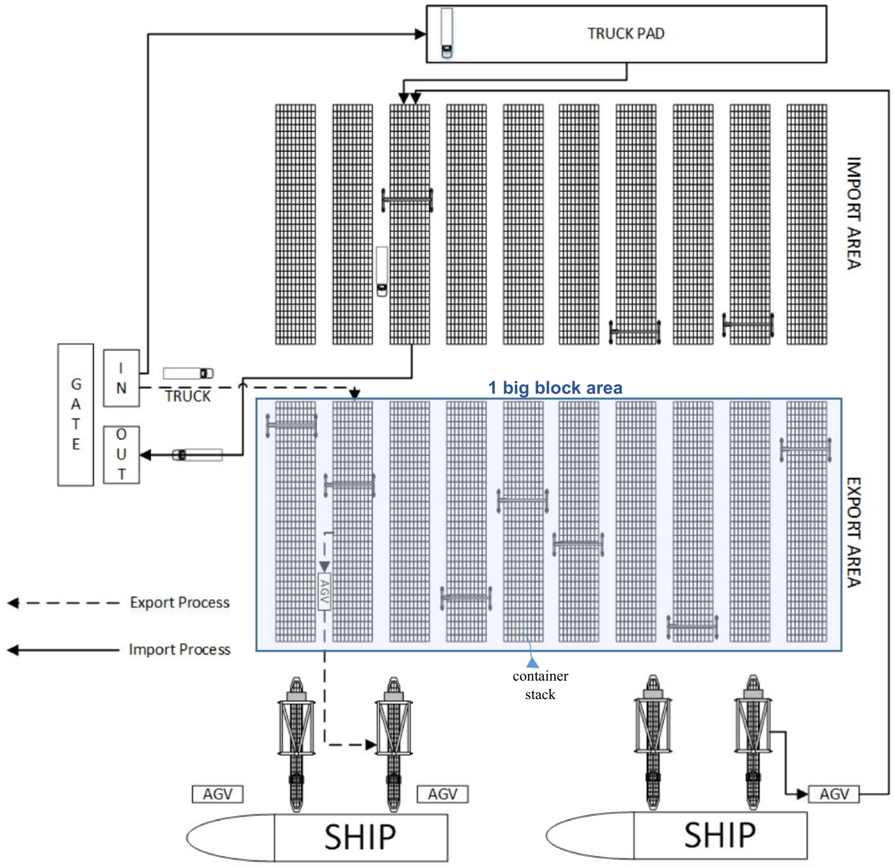


Fig. 5 Proposed terminal layout

equidistant shortest paths in a rectangular environment for solving VRP in a PI environment.

3 Container handling strategy in PI terminals

3.1 Problem definition

The main function of a container terminal is to facilitate the transfer of containers and cargo from and to ships and other inland modes of transport, such as trucks and trains. Therefore, the container handling process is crucial in ensuring effective and efficient transportation and controls the arrangement as well as the transportation of containers within the terminal. Poor container handling causes more traveling distances, time, and resources and generates more carbon emissions to the environment. This paper proposes two strategies for handling containers in PI standard. Moreover, the carbon emissions produced by each strategy are evaluated, through simulation, to figure out the best environmentally friendly strategy for handling modular containers.

The three physical innovations for supporting the successful implementation of the PI scenario in this paper are the use of modular containers, keeping in mind the efficiency and effectiveness of a logistics transportation network, PI yard layout, and PI handling vehicles (AGV). One of the pioneering examples of a port that has begun implementing those three innovations of PI is the Port of Rotterdam in the Netherlands. The port has been actively working to integrate PI principles to enhance logistics efficiency and sustainability. A modular container refers to a single load of demand received by the terminal, requiring storage and subsequent delivery. In the PI, the container has modular dimensions to simplify handling, storing, interlocking, snapping to a structure, and transporting.

In this paper, Fig. 4 illustrates the height and width dimensions of modular containers as determined by various combinations of the following dimensions: 1.2 m, 2.4 m, 3.6 m, 4.8 m, 6 m, and 12 m (Montreuil et al. 2014).

The PI yard layout in this research is assumed to use automated yard containers which have recently been implemented in many sizes (medium and large) in modern automated terminals, including Rotterdam, Singapore, Shanghai and Hamburg, potentially used to support PI standards.

Zhang et al. (2023) concluded that manual container terminals typically utilize a horizontal yard layout, while automated terminals often adopt a vertical yard layout. These differing yard designs result in variations in vehicle travel routes, the interaction points between vehicles and yard cranes, and the travel paths of yard cranes. These distinctions ultimately impact terminal efficiency, such as yard utilization and throughput. To quantify these factors, Zhang et al. (2023) compared the operational efficiency of horizontal and vertical layouts, which resulted in vehicle travel distances being shorter in a vertical layout. Therefore, in this paper, the vertical yard layout is adopted in the simulation of the PI automated container terminal, as illustrated in Fig. 5. In a PI-automated container terminal, Here, the yard layout is transverse to the shore and the import and export blocks are horizontal. As a result, AGVs move between the front of the quayside and the yard blocks. The yard layout is assumed to have two areas; export and import, separated into one large part called blocks. There is only one large block per area, which is divided into 10 container stacks. The two transit roads are located horizontally close to the berth for AGVs and close to the truck pad for the trucks; all other roads are working roads. It is assumed that each stack is served by a stacker crane that loads and unloads the modular containers to and from the designated work lanes. Queue rules are critical in various operations, such as logistics, and customer service, where efficient processing of tasks, jobs, or requests is needed. The choice of queue discipline can significantly affect system performance, including wait times, throughput, and overall efficiency. In this paper, the modular containers are assumed to be served on a first-come, first-served (FCFS) basis, as this is simple and fair (Raicu et al. 2023), ensuring that no item waits disproportionately long. Several stacking methods prioritize stability, space optimization,

Table 2 Simulation parameters

Parameters	Value
Working days	30 days/ month
Terminal size	300 m × 1,500 m (medium size)
Terminal capacity	10,000 containers
Equipment	Stacker crane, AGVs, truck
Speed of the equipment	25 km/ h

and safety in stacking modular containers, depending on factors like container size, purpose, load-bearing capacity, and environmental conditions. In this paper, we considered applying block stacking methods (grid formation) which placed modular containers side by side to create a solid block, with multiple modular containers stacked vertically in each grid position. The block stacking method maximizes both vertical and horizontal space and allows efficient use of forklifts and cranes in container yard environments. For decarbonization comparisons, we measured the effectiveness of block stacking methods in two different sequencing strategies; scenario 0 (SC0) and scenario 1 (SC1) which are explained in more detail in the appendix.

Figure 5 also illustrates terminal operations for import and export (dashed line) containers, which is used to determine the origin and destination nodes of containers in the simulation. For exports, the truck enters the terminal from the gate to the export stacking area. The stacker crane will stack and move the containers. Finally, the AGVs come to transport the containers from the export stacking area to the ship. Conversely, the AGVs will move the import containers from the ship to the import stacking area. An empty truck will pick up the import container from the truck pad to the designated picking point in the import stacking area and transport it to the final destination inside the terminal. In this research, the total distance traveled by the truck and the AGVs for import and export containers is calculated using a VRP based on the Dijkstra algorithm, as explained in the appendix.

3.2 Modeling GHG (CO_2) emissions

We measure the level of carbon dioxide (CO_2) produced by container trucks and AGVs to evaluate the benefit of implementing the two container handling strategies proposed in this research. We utilize Eq. (1) for CO_2 emissions estimation, drawing upon the original formula developed by The National Institute for Land and Infrastructure Management (NILIM 2003) of Japan.

$$CO_2 = l_{ij}(278.448 + 0.048059v_{ij}^2 - 5.1227v_{ij} + \frac{2347.1}{v_{ij}} \tag{1}$$

where:

CO_2: total carbon oxide emissions (gr).

l_{ij}: length of road link between nodes i and j (km).

v_{ij}: speed of vehicle traveling on road link between nodes i and j (km/ h).

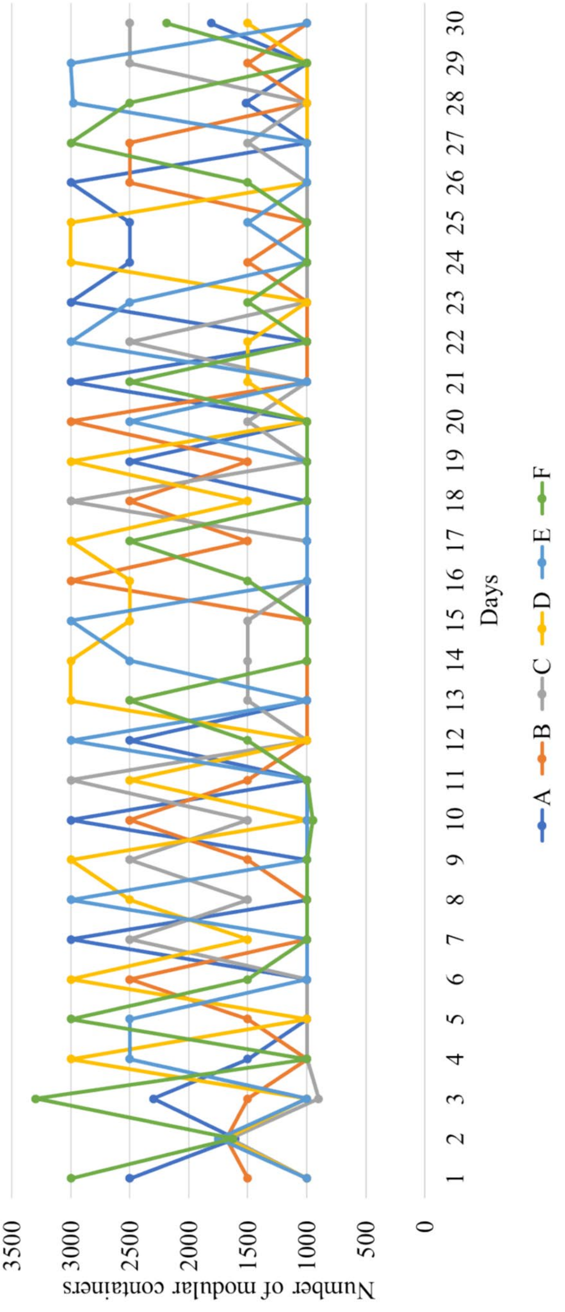


Fig. 6 Distribution of demand per container type

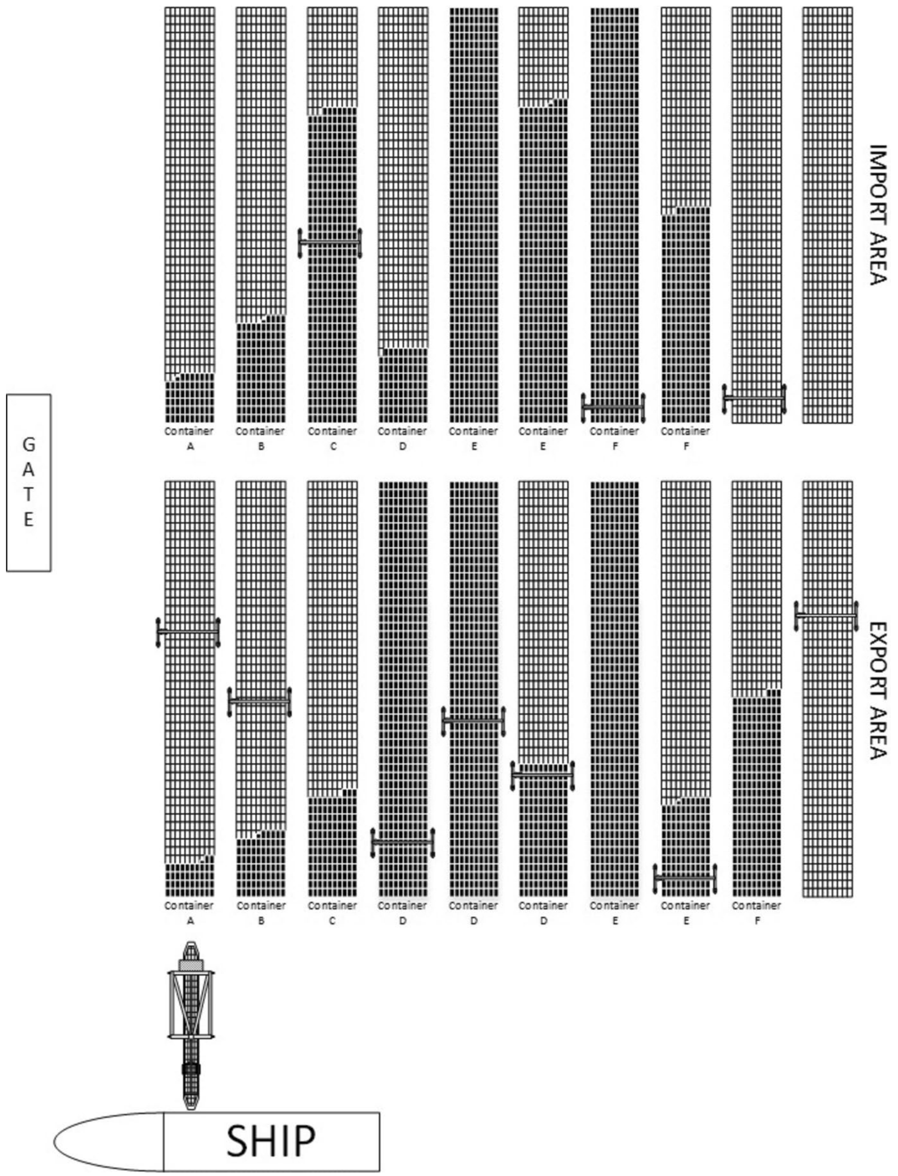


Fig. 7 Containers stacking result using SC0 strategy

4 Simulation of the proposed strategies

4.1 Simulation's environment

To assess the decarbonization effects of modular container handling in the physical internet paradigm, we simulated the use of block-stacking methods using two

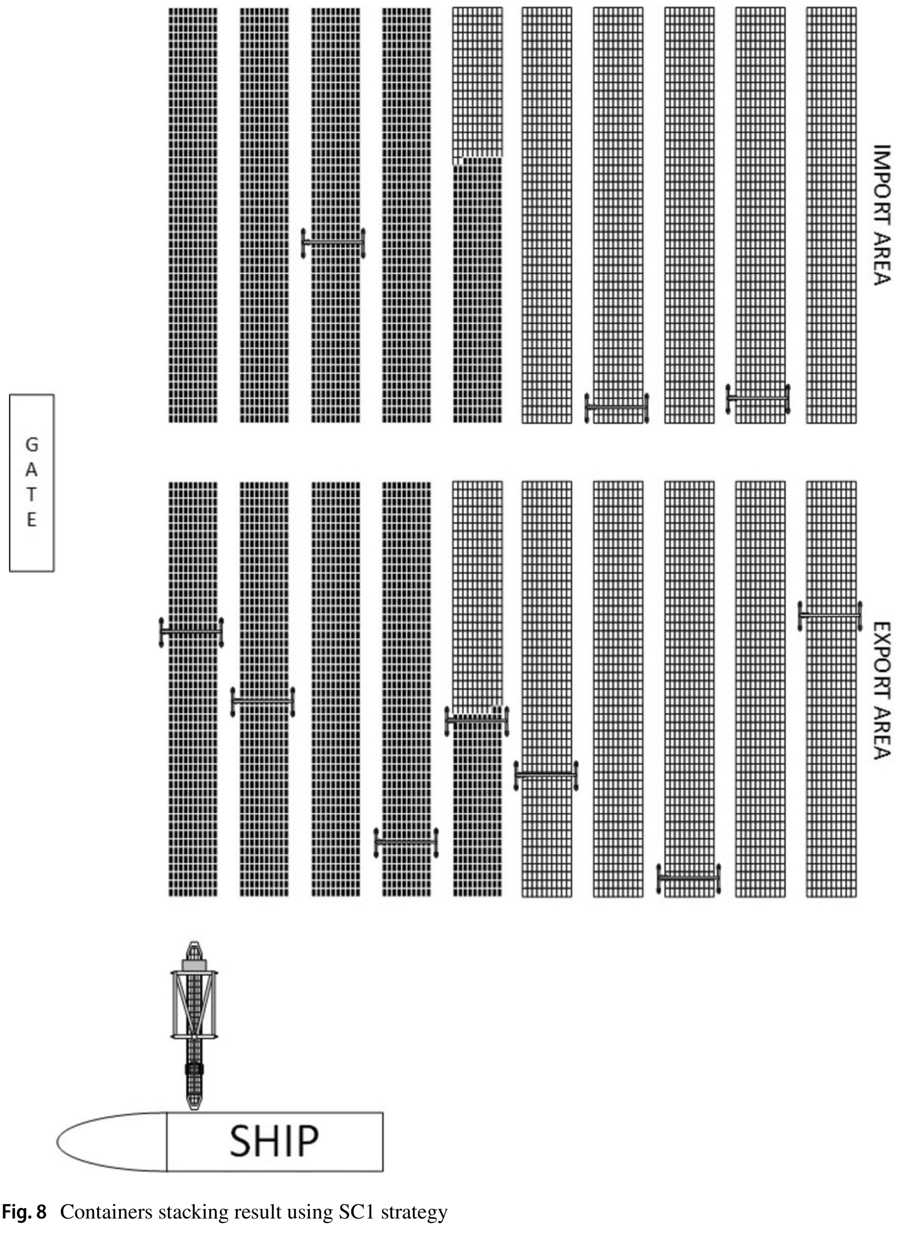


Fig. 8 Containers stacking result using SC1 strategy

different sequencing strategies; scenario 0 (SC0) and scenario 1 (SC1). We assume that the first scenario (SC0) is the initial handling strategy, whereby a modular container is arranged by type in the stacking area of import and export. The second scenario (SC1) assumes that the modular container can be stored in many possible combinations. All containers stored in the stacking area are delivered on the same day using FCFS sequencing rules. We conducted simulations including key variables with inherent fluctuations of the total number of modular containers received by the terminal. Notably, we assumed a 65% coefficient of variation (CV) for these variables, representing their relative variability. The specific parameters chosen for the simulations are listed in Table 2.

4.2 Simulation parameters

Simulations were iterated for 30 working days, representing one month of container handling. The terminal is assumed to be of medium size, with a handling capacity of 10,000 containers per day. As stated previously, the automated yard used in the simulation is equipped with stacker cranes, AGVs, and trucks which are assumed to have an average speed of 25 km per hour.

4.3 Simulation data

To simulate real-world fluctuations, we generated 30 days of demand data from a normal distribution. Figure 6 illustrates the resulting pattern. The demand data was used in the simulations of SC0 and SC1.

5 Performance of the proposed strategy

5.1 Shortening travel distances

Figures 7 and 8 present a simulation example of container stacking in our hypothetical terminal layout using SC0 and SC1. In Fig. 7, SC0 shows that when modular containers are stacked by type within each block, numerous empty spaces appear in the stacking yard, which impacts handling efficiency. In contrast, Fig. 8 illustrates SC1, where modular containers are stacked in combination, resulting in optimal space utilization near the designated pick-up point. Additionally, we assessed the advantages of the proposed strategy by calculating the total travel distance for stacking activities in both SC0 and SC1 using Eq. (2).

The distances traveled for handling modular containers in SC0 and SC1 are given in Fig. 9. In the SC0 simulation, where the modular containers are stacked by type, the total distance is on average 0.7% higher than in SC1, where the modular containers are stacked by combination in the yard. By stacking containers in combination (SC1 strategy), the terminal operator can effectively utilize the nearest space (grid), thus saving travel distance.

To get more insight, Fig. 10 provides the comparison of the demand data and the difference between SC0 and SC1 as percentage of distance traveled. It can be observed that the highest difference in total distance traveled in SC0 and SC1 is 1.2% using the demand data received by the terminal on day 8. The simulation on day 8 showed that SC1 is better than SC0 in minimizing the total distance traveled for handling modular containers. Total distance can be shortened by up to 1.2%, which is equivalent to 396.260 km.

The distribution of demand data on day 8 for modular container types is mostly around the standard TEU size (8 × 8×20 feet), such as type E. This result proves that the modular containers in a PI-enabled container terminal, which can be combined and stacked together in the yard, can effectively reduce the total distance traveled in the terminal using the SC1 sequencing strategy.

5.2 Reduction of carbon emissions

We measure the environmental benefit of the proposed strategy by calculating the total carbon dioxide (CO_2) emissions using Eq. (1) for the stacking activities of modular containers in SC0 and SC1, as shown in Fig. 11.

As SC1 can save up to 1.2% of the total distance compared to SC0, it also reduces carbon emissions by 1.2% more than SC0, which is equivalent to 108.7 tons of CO_2. Moreover, to investigate the importance of this reduction, we quantify the carbon reduction effects of SC1.

Our research results indicate that the reduction of 108 tons of CO_2 per day is equivalent to 0.01 GtC (gigatons of carbon) per year in a terminal handling 10,000 TEUs per day. Since the world's top 100 container ports handled approximately 658 million TEUs in 2022 (Lauriat 2023), implementing our proposed model in these terminals would result in a reduction of 1.95 GtC per year, a significant contribution to reducing atmospheric CO_2 levels. The Global Carbon Budget (Friedlingstein et al. 2023) reports that the global atmosphere contains approximately 392.55 GtC. Our proposed model contributes to a reduction of 1.93 GtC from the atmosphere, representing a 0.5% reduction in global CO_2 levels. This may seem small, but it is important to remember that even small reductions accumulate over time and have significant impacts. Friedlingstein et al. (2023) also used several climate models to assess the feasibility of different emission reduction scenarios, to keep global warming below 2 °C and 1.5 °C and found that scenarios with annual reductions of 0.5% or more are needed to achieve the 1.5 °C global goal with high probability. Therefore, the reduction of 1.95 GtC, or 0.5% of global emissions per year, by implementing the SC1 strategy proposed in this study, for stacking modular containers in a PI-enabled container terminal, is a concrete contribution to mitigating climate change.

6 Conclusions

This research proposed and simulated two sequencing strategies based on the Dijkstra algorithm, designed to optimize the routing of vehicles moving modular containers at terminals within the framework of the Physical Internet. The simulation results proved that the PI modular containers, which can be combined and stacked together in the yard, can be handled effectively using an SC1 strategy compared to SC0, where the modular containers are stacked by type in the stacking area of the

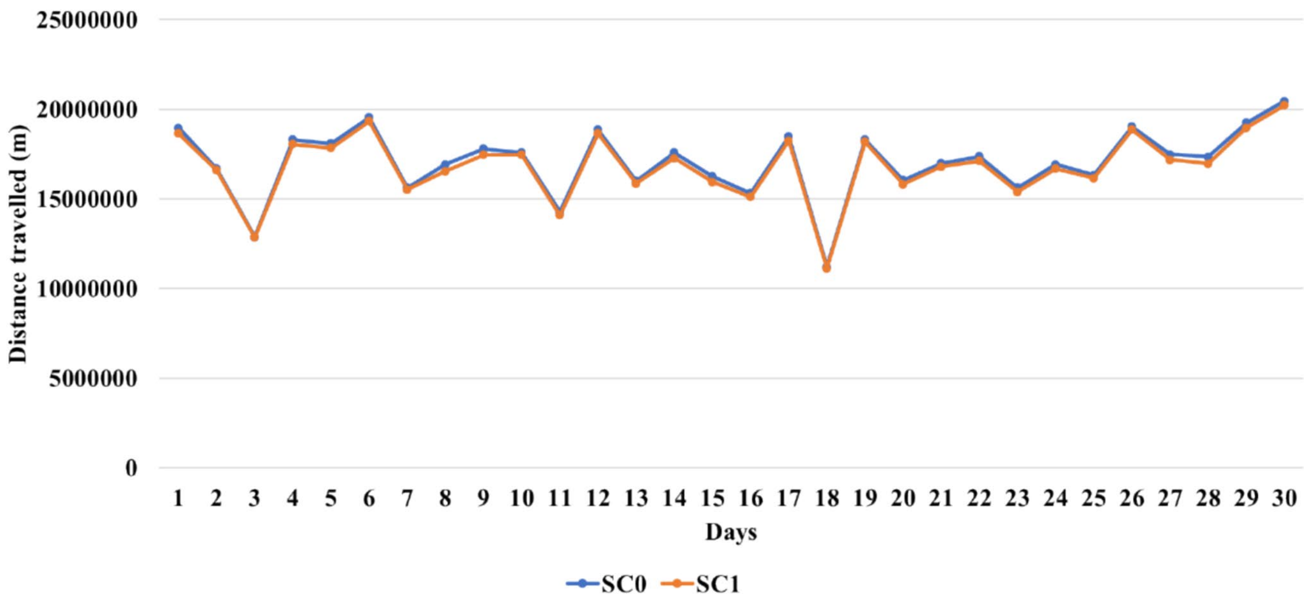


Fig. 9 Distance traveled for handling modular containers

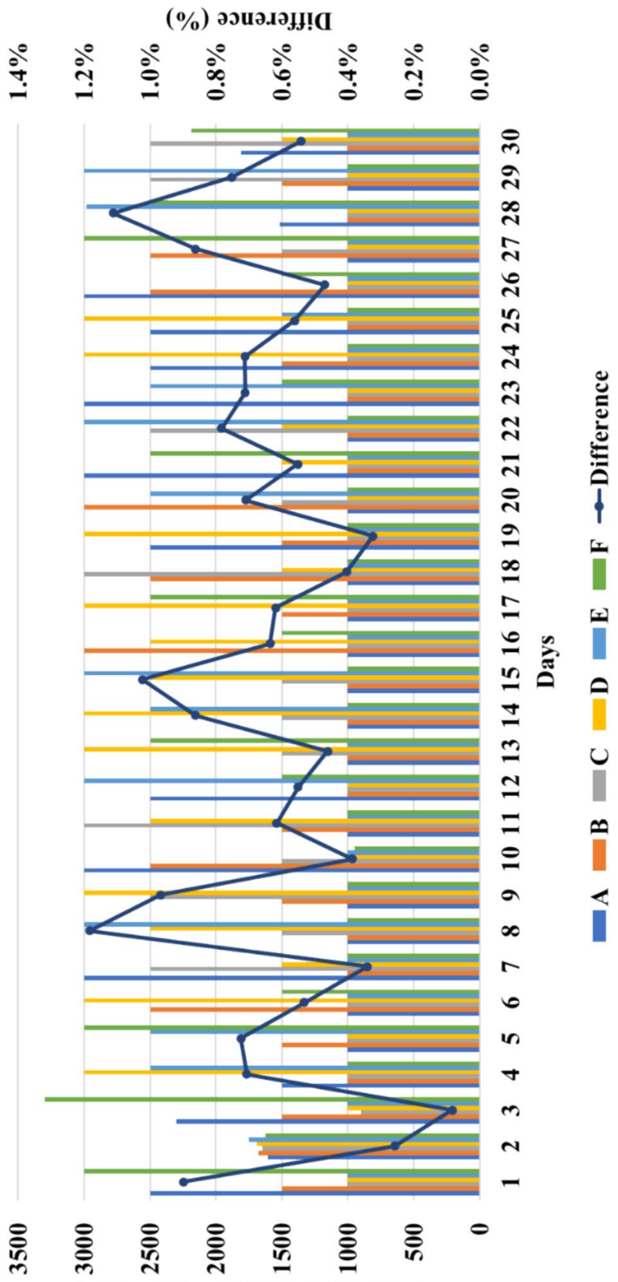


Fig. 10 Comparison of demand data and distance traveled

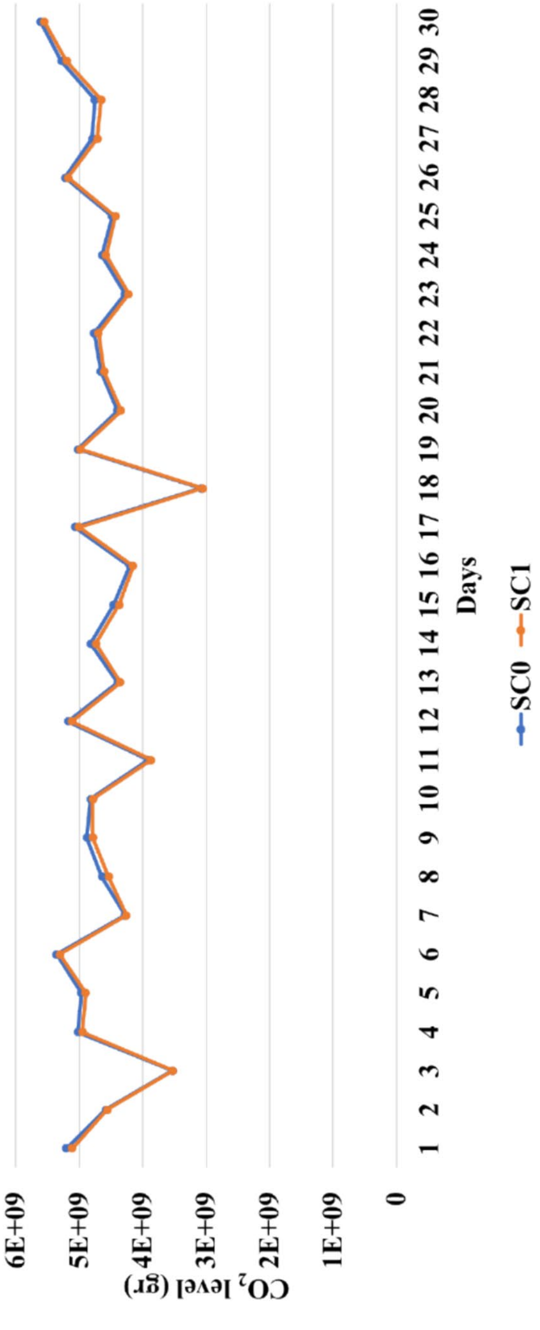


Fig. 11 CO_2 levels for SC0 and SC1

terminal. By strategically stacking modular containers using a combination of SC1 strategy, terminal operators can leverage the available grid space more effectively, thus saving total travel time up to 1.2%, leading to a 0.5% reduction in global CO_2 emissions. This research also demonstrated that the implementation of the SC1 strategy in PI-enabled terminals is a positive step towards mitigating climate change. We acknowledge a limitation of our study in that it only addresses 6 of the 18 container types proposed by Montreuil et al. (2014). Future research could aim to extend our model to include simulations that strategize the management of all 18 container types.

Appendix: Sequencing rules

In this research, the Dijkstra Algorithm is used to determine the shortest path for each import and export container handled in the terminal. The algorithm calculates the minimum sum of weights between two nodes in a graph. The stacking yard road network, which can be represented as a graph, generated from an underlying road network obtained from the terminal layout of Fig. 5.

The graph consists of nodes, which in this paper represent the location of the grid for modular container stacking. The size of each grid is determined as 1.2×2.4 m, equal to container type A, which is the smallest size of the modular containers assumed in this paper. A grid represents a junction connecting two or more paths; an edge represents a road connecting the grids. The block is organized as a matrix, made up of multiple grids (G^{th}), with G representing the total number of these grids in the block. The shortest path in the container handling process is achieved by implementing the following procedure.

Initialize origin node-I, and destination node-J, as a fixed location in the G^{th} grid, representing the location node of Gate-in and Berth depending on whether it is an import or export activity. Then, get a list of all nodes, G_k, where $k = \{1, 2, 3, ..\}$ indicating the location of nodes in the grid G, resulting in a list of possible nodes to be evaluated by Dijkstra.

The next step calculates the distance from the origin node to the nearby node. These are the intermediate points between the origin and the destination. Nearby nodes (N) are part of the grid, with each node represented as $\mathrm{N_j}$, where N_j belongs to the set of all possible nodes in the grid G_k $N_j \in G_k, j = \{1, 2, 3 \ldots ..\}$). Thus, we can calculate the distance to neighboring node $d(i, N_j)$ and $d(N_j, j)$ by applying Dijkstra's algorithm. Given the origin, destination, and all possible nodes, we calculate the total distance (D) for each node, using Eq. (2);

$$D = d(I, N_1) + d(N_1, N_2) + d(N_2, N_3) + \ldots + d(N_j, J) \tag{2}$$

This algorithm generates a sequence of nodes for the container's traversal and identifies an alternative location for placing the container in the yard. This study presents two scenarios, Scenario 0 (SC0) and Scenario 1 (SC1), distinguished by the container stacking regulations in the container yard. The sequencing rule varies across scenarios. In SC0, identical containers are arranged in stacks on the grids within the same block. In alternative grids generated by the sequencing algorithm, incoming modular containers are stacked on the nearest accessible grid to the destination node.

In the SC0, the container types are represented as $C = \{A, B, C, D, E, F\}$, with corresponding incoming quantities denoted by n, where $n = \{nA, nB, nC, nD, nE, nF\}$. $d(I, N_1), d(N_1, N_2), \ldots, (N_{j-1}, N_j), d(N_j, J)$ Previously, we obtained the sequence grid resulted from Dijkstra. Therefore, the nearest grids can be represented as $N = \{\ldots., N_{j-2}, N_{j-1}, N_j\}$. Afterwards, the algorithm identifies the nearest vacant grid and subsequently stacks the container. If the grid N_j is not empty, verify whether the container type on the grid matches the incoming container; if it does, proceed to stack the container. Continue to iterate the checking algorithm until an available grid is identified, at which point the incoming container can be stacked.

In SC1, different types of modular containers, C_l where $l = \{A, B, C, D, E, F\}$ is allowed to be stacked together considering available space on a grid $N = \{\ldots., N_{j-2}, N_{j-1}, N_j\}$ Each container is characterized by its specific width (wC_l) and length (lC_l), while each grid is defined by its width (wN_{jm}) and length (lN_{jm}). In this case, the algorithm focuses on prioritizing stacking the larger container first, which is common practice for fully or semi-automated container terminals, such as those at the Port of Rotterdam (Netherlands)[3] and Port of Qingdao (China).[4] The algorithm then arranges the set of containers in descending order by size, both length and width. The algorithm initially arranges containers in descending order of their area (aC_l), whereby containers with larger areas will be placed earlier in the list. If two or more containers have the same area (aC_l), the algorithm uses their width (wC_l) as a tiebreaker, which means that the container with a larger width will be placed before the one with a smaller width, even if their areas are identical. Then iterate through different types of containers by identifying the grid N with the largest area (FN_j) that can accommodate the current container. We check this using Eq. (3).

$$wC_l \leq wN_{jm} \text{ and } lC_l \leq lN_{jm} \tag{3}$$

If the aforementioned equations are satisfied, indicating that a grid N exists, the container is positioned in that grid. Consequently, the decision variable x_{CN} is set to 1 to indicate whether container type C is placed in grid N, and FN_j is updated accordingly. Otherwise, $x_{CN} = 0$, and identify the nearest grid N to the target node J that can hold the container, then position it there.

Acknowledgments The authors thank MEL's Editor-in-Chief for his support throughout the revision process.

Funding This work was supported by JSPS KAKENHI Grant Numbers JP 23K04076. The research reported in this publication was partially supported by the International Affairs Special Funding from the Graduate School of Maritime Sciences, Kobe University.

[3] https://www.apmterminals.com/en/maasvlakte/about/our-terminal#:~:text=Our%20terminal%2C%20located%20on%20the,ships%20way%20into%20the%20future.

[4] https://www.apmterminals.com/en/qingdao/about/qingdao-new-qianwan-container-terminal#:~:text=The%20Qingdao%20New%20Qianwan%20Container,capacity%20of%204.2%20million%20TEU.

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