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Digital port integration and terminal efficiency: Evidence from vessel, truck, and container turnaround times in Japanese container terminals

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DIGITAL PORT INTEGRATION AND TERMINAL EFFICIENCY

EVIDENCE FROM VESSEL, TRUCK,
AND CONTAINER TURNAROUND TIMES
IN JAPANESE CONTAINER TERMINALS

Daigo Shiraishi, Ryuichi Shibasaki, Wenru Zhang, and Yesim Elhan-Kayalar

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ABSTRACT

This study examines port terminal efficiency through an empirical analysis of the turnaround times of vessels, trucks, and containers entering and leaving selected Japanese container terminals. Using a comprehensive dataset combining terminal operator records, vessel movement data, and liner service data, we analyze patterns in vessel berthing, truck arrival, truck turnaround, container round trip, and container dwell times across multiple ports. Our findings reveal distinct temporal patterns in terminal operations—with significant variations between import and export containers—and demonstrate that vessel calls, container types, and time of day significantly influence operational efficiency. Regression analyses indicate that turnaround times are primarily affected by terminal controlled factors. Based on these findings, we propose policy recommendations for dynamic scheduling systems, operational standardization, and infrastructure optimization. Our results contribute to the growing literature on port digitalization and provide evidence-based guidance for terminal operators and policymakers seeking to enhance port efficiency through digital integration.

Keywords: port efficiency, digital integration, container terminals, turnaround time, truck appointment systems, terminal operations

JEL codes: R41, R49

1. INTRODUCTION

Efficient ports play a pivotal role in facilitating the smooth functioning of global supply chains, with container terminals acting as essential hubs within international trade networks. These terminals serve as the key interfaces where goods are transferred between different modes of transport, enabling the movement of goods across the globe and linking producers and consumers worldwide. Given their centrality to trade operations, the efficiency of container terminals directly influences the speed, cost, and reliability of global trade flows. As international trade continues to grow, optimizing port operations and infrastructure has become increasingly vital for maintaining the competitiveness and resilience of national, regional, and global supply chains.

In recent years, the digitalization of port operations has emerged as a key strategy to enhance operational efficiency and reduce congestion. Japan, as one of the world's leading maritime nations, has been at the forefront of implementing innovative solutions to improve port productivity. Introducing the Container Fast Pass (CONPAS) system—an online truck booking system initially implemented at the Port of Yokohama in 2021 and subsequently expanded to other major Japanese ports—represents a significant step toward modernizing port operations in Japanese container terminals. Port congestion and inefficient truck queuing systems have long been recognized as major bottlenecks in container terminal operations (Li et al. 2022; Bai, Jia, and Xu 2024; Peng et al. 2023), leading to increased waiting times, higher operational costs, and environmental concerns due to idle vehicles. Traditional first-come, first-served systems have proven inadequate in managing the growing complexity of modern port operations, particularly in high volume terminals like Yokohama, which handles over 2.9 million twenty-foot equivalent units (TEUs) annually. Implementing the CONPAS aims to address these challenges by optimizing truck arrivals and reducing congestion through a structured appointment system that includes features such as real-time gate monitoring, dynamic time slot allocation, and integration with terminal operating systems. Against such a background, this study provides a comprehensive analysis to clarify the port terminal efficiency and characteristics of international maritime container transport in Japan by focusing on vessel, truck, and container turnaround times in and outside the terminal using data acquired from the terminal operating system (TOS) and other sources.

This paper is organized as follows. Section 2 presents a comprehensive review of the literature on port appointment systems and their impact on operational efficiency, including comparative analyses of similar systems implemented in other Asian ports. Section 3 describes our diverse data sources, including TOS data, automatic identification system (AIS) satellite data for vessel movement analysis, and MDS Transmodal Containership Databank (MDS) data, which collectively provide a multifaceted view of port operations. Section 4 presents our analytical results, examining vessel, truck, and container turnaround times entering and leaving Japanese container terminals, complemented by regression analyses to identify key determinants of operational efficiency. Finally, Section 5 concludes with policy implications and recommendations for the future implementation of digital booking systems in port operations, including specific guidelines for system optimization and potential applications in other Japanese ports.

2. LITERATURE REVIEW

Haralambides (2017) and Neise (2018) highlighted the crucial role of container terminals in global supply chains, emphasizing their contribution to facilitating trade and driving economic growth. With the increasing volume of container shipping due to deeper global economic integration, the efficiency and operational capabilities of ports have become essential. Kizilay and Eliiyi (2021) and Song (2021) emphasized that analyzing terminal operations can optimize processes, accelerate cargo handling, reduce vessel and cargo detention times, and lower transportation costs. For port authorities, shipping companies, and logistics providers, these analyses not only revealed potential value but also provided a competitive advantage. As cargo flows and market demands become more complex, a deeper understanding of terminal dynamics is necessary. Therefore, terminal analysis can improve both economic benefits and service quality, while enhancing adaptability to changing market conditions.

To enhance container terminal efficiency, researchers have approached terminal analysis from various angles. Yoon et al. (2023) used machine learning techniques to predict vessel dwell time at Busan New Port, leveraging a comprehensive dataset of 41 months of terminal berth schedules and vessel details. Their results, showing that all machine learning models outperformed the terminal's existing reference model, implied that machine learning could significantly enhance the accuracy of vessel dwell time estimates, thereby benefiting shipping terminal operations. Huynh (2008) examined how container dwell time affects terminal throughput and rehandling productivity under non-mixed and mixed storage strategies. The findings showed that longer dwell times improved productivity in non-mixed storage but reduced it in mixed storage. Using TOS data, terminals can refine storage strategies, reduce rehandling, and enhance overall throughput efficiency. Abdelmagid, Gheith, and Eltawil (2022) developed a binary programming model to improve truck appointment scheduling, minimizing waiting time, demurrage, and delivery costs. This approach also optimized workload distribution and significantly reduced truck turnaround times. Bolin-Lucero and Hammond (2023) explored how roll on, roll off terminal operations influenced the estimated time of arrival for container cargo. Their findings showed that implementing a truck appointment system and using real-time data significantly improved estimated time of arrival prediction accuracy, thereby enhancing supply chain efficiency. Dwarakish (2019) focused on optimizing the vessel turnaround duration at New Mangalore Port Trust. Through his analysis, he pinpointed critical elements such as port congestion and loading and unloading rates as the main determinants influencing port performance. Riadi, Putra, and Budiyanto (2023) used discrete event simulation to examine the impact of truck terminal numbers on yard throughput, finding that yard throughput peaked at 809 containers if eight truck terminals were available for a 1,000 TEU shipload. Mathias et al. (2024) proposed a novel method for evaluating container terminal operations using operational data from rubber-tired gantry equipment and simulation modeling to optimize container handling efficiency. Despite these advances, one significant limitation of existing studies is the lack of integration with real-time, multidimensional data. This constrains the ability to address the complexities and dynamic nature of modern container terminal operations. Park, Kim, and Bae (2024) proposed a predictive discrete event simulation approach to predict operation times in container terminals. They used data collected from the TOS of Busan New Port Terminal to enhance the predictive performance of operation times. They demonstrated that the proposed predictive discrete event simulation approach outperforms alternative approaches in predicting the operation times of container terminals.

With the advent of the big data era, the analysis and optimization of container terminals have transitioned from traditional methods to data-driven approaches (Inutsuka et al., 2024; Mathias et al., 2024). By collecting and processing multidimensional data from sources such as the vessel's AIS, TOS data, sensors, and other related systems, researchers can gain deeper insights into terminal operations. This shift enables the identification of hidden patterns and optimization opportunities, allowing port authorities and logistics providers to make more informed and effective decisions. For example, K. Yasuda et al. (2024) proposed a method for terminal congestion analysis at container ports using satellite images and AIS data. They developed a convolutional neural network model and an annotation tool to classify congestion levels in container yards, focusing on container shadows to estimate stack counts and assess reliability. While such studies demonstrated the potential of integrating diverse data sources, research that combines TOS data with AIS data for a comprehensive analysis of container terminal operations remains limited, presenting an opportunity for further exploration.

Therefore, this study aims to fill this research gap by integrating TOS data with AIS data to analyze container terminal operations from multiple perspectives. Specifically, the study focuses on estimating the following key metrics across five terminals: (i) vessel berthing time (vessel turnaround time); (ii) time distribution of truck arrivals; (iii) turnaround time between truck arrivals and departures (truck turnaround time); (iv) round trip time of containers outside the terminal (container turnaround time outside the terminal); and (v) dwell time of containers in the terminal, measured between truck gate-in or gate-out and vessel loading and discharging (container turnaround time in the terminal). By combining these data sources, this research seeks to comprehensively analyze terminal dynamics, identify inefficiencies, and support the development of data-driven strategies to improve operational performance.

3. DATA

3.1 Terminal Operation Data

We obtained the TOS data from five terminals (A1, A2, B1, B2, and C1) of three international strategic container ports in Japan for analysis, as summarized in **Table 1**. The time period for all data is 2 months. We could obtain information from all terminals on whether each container is full or empty and whether it is gating in or gating out with time information. Only full import containers entering into the B1 terminal were forced to use CONPAS in the investigation period, while neither other types of containers nor containers in other terminals could use it at that time. The data obtained from A2 (for full containers only), B1, and C1 terminals contain information on the vessel where each container is loaded so that it can be linked to vessel information data obtained from an AIS, as explained in Section 4.5. Notably, we also tried to link the TOS and AIS data in the A1 terminal where only foreign loading or unloading ports are available; however, it is difficult to obtain the data with an acceptable accuracy level, and thus, we excluded it from the combined analysis in Section 4.5.

Table 1: Summary of Data Received at Port and Terminal Levels

Port		Port A		Port B		Port C
Terminal		A1	A2	B1	B2	C1
Period		July 2021 and July 2022	May and June 2024	July 2021 and July 2022	July 2021 and July 2022	July 2021 and July 2022
Cargo status	Full or empty	x	x	x	x	x
	Gate-in or gate-out	x	x	x	x	x
Truck	Gate-in time	x	x	x ^{a, b}	x	x ^a
	Loading and unloading time	x	x	x ^{a, b}	x	
	Gate-out time	x		x ^{a, c}	x ^c	
Vessel	Shipping company		x			x
	Ship name		x ^d	x		x
	Call sign		x ^d	x		
	Voyage no.		x ^d			x
	Loading and unloading port	x				
Container	Container no.		x		x	X ^e
	Container size	x			x	x
	Container height				x	x
	Container type	x			x	

^a no information on seconds.

^b only available for gate-in containers

^c only available for gate-out containers.

^d only available for full containers.

^e only available for empty containers.

Source: Authors' compilation.

3.2 Automatic Identification System Data

We also use satellite and terrestrial AIS data from Lloyd's List Intelligence, which includes vessel information on its name, flag, type, and size, as well as the arrival and departure dates of each port. **Table 2** shows the number of vessels calling at each terminal by size during the survey period. The table reveals that container ships that called at terminals in port B were much smaller (e.g., all vessels were less than 2,000 TEU in the B2 terminal) compared to ports A and C.

Table 2: Size Distribution of Container Ships Calling at Each Terminal (per 2 months)

	A1 Terminal	A2 Terminal	B1 Terminal	B2 Terminal	C1 Terminal
Up to 1,000 TEU	29	0	72	16	197
1,001–2,000 TEU	83	40	127	8	79
2,001–3,000 TEU	0	16	38	0	13
3,001–5,000 TEU	7	8	24	0	21
5,001–8,000 TEU	3	1	5	0	2
8,001–12,000 TEU	15	12	4	0	12

TEU = twenty-foot equivalent unit.

Source: Authors' calculations.

3.3 MDS Transmodal Containership Databank Data

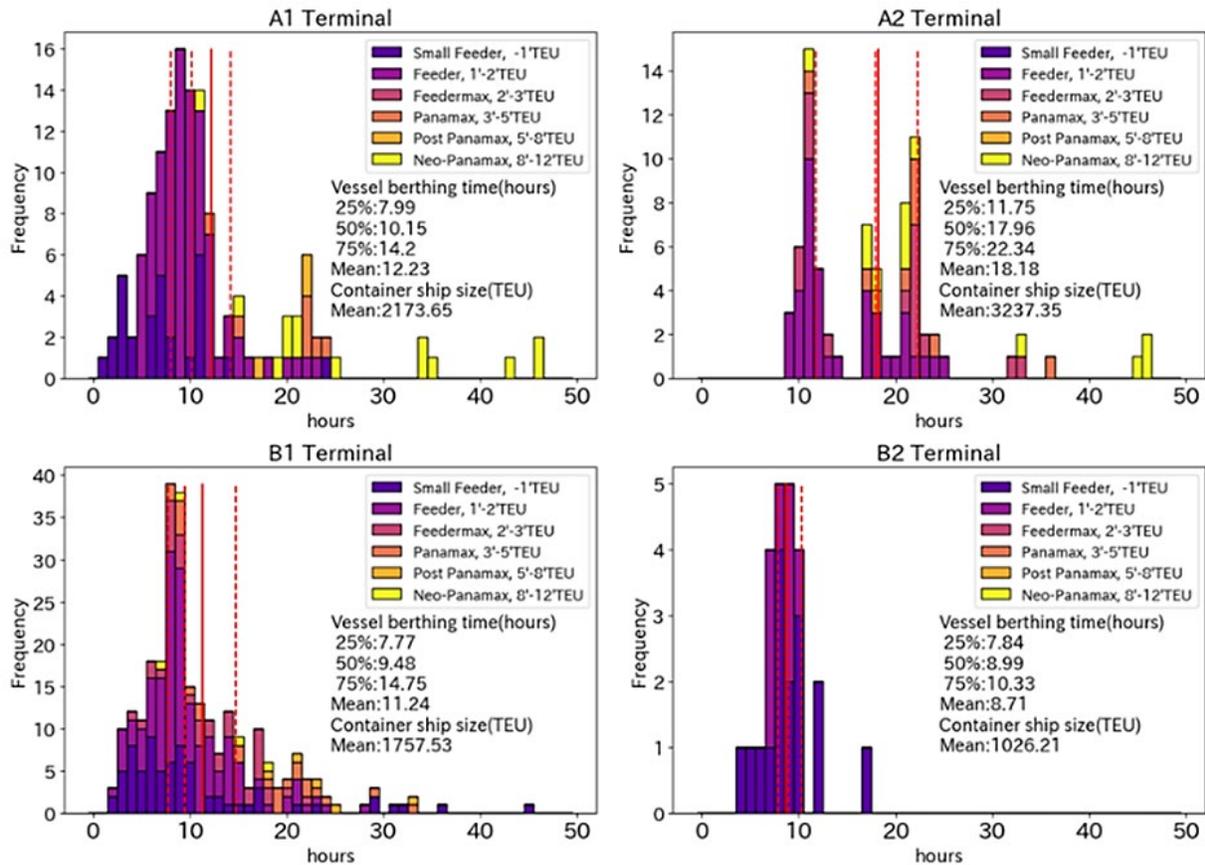
The MDS data are a comprehensive database on the global container shipping fleet with over 15,000 vessels, including key metrics such as ship specifications, ownership, capacity, speed, frequency of operational routes, and ports of call. We created a composite database that matches data from AIS and MDS using the International Maritime Organization's numbers of vessels engaging in each service, as listed in both databases, to help address the above missing data issue. Using data from three sources that were matched through the International Maritime Organization's numbers and vessel names, we generated a novel, composite database that addresses certain limitations we faced early in our analyses.

4. ANALYSIS RESULTS

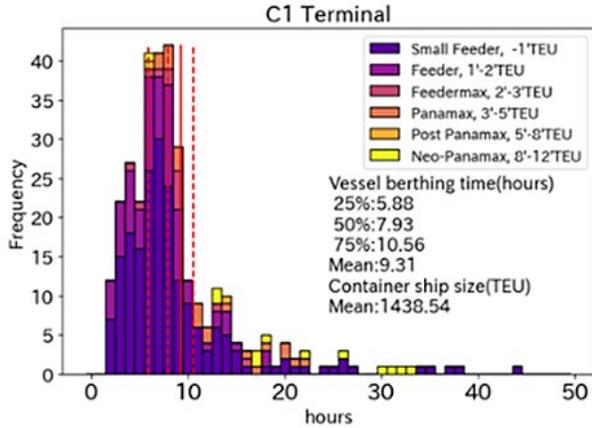
4.1 Vessel Berthing Time (Vessel Turnaround Time)

First, we tabulate the vessel berthing time for each terminal by extracting the time from vessel arrival to departure from AIS data, as shown in **Figure 1**. The figure reveals that around 95% of container ships departed within 24 hours from their arrival, while there is a general correlation between vessel size and berthing time.

Figure 1: Distribution of Vessel Berthing Time for Each Terminal



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TEU = twenty-foot equivalent unit.

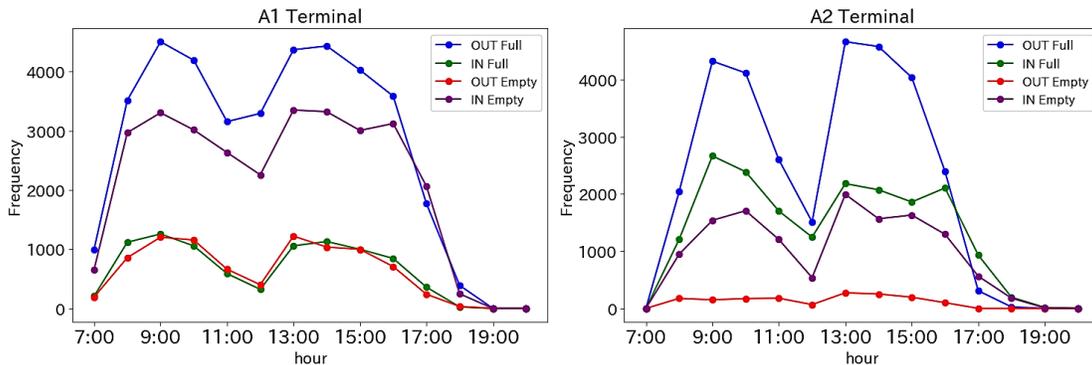
Source: Authors' calculations based on automatic identification system data.

4.2 Time Distribution of Truck Arrival

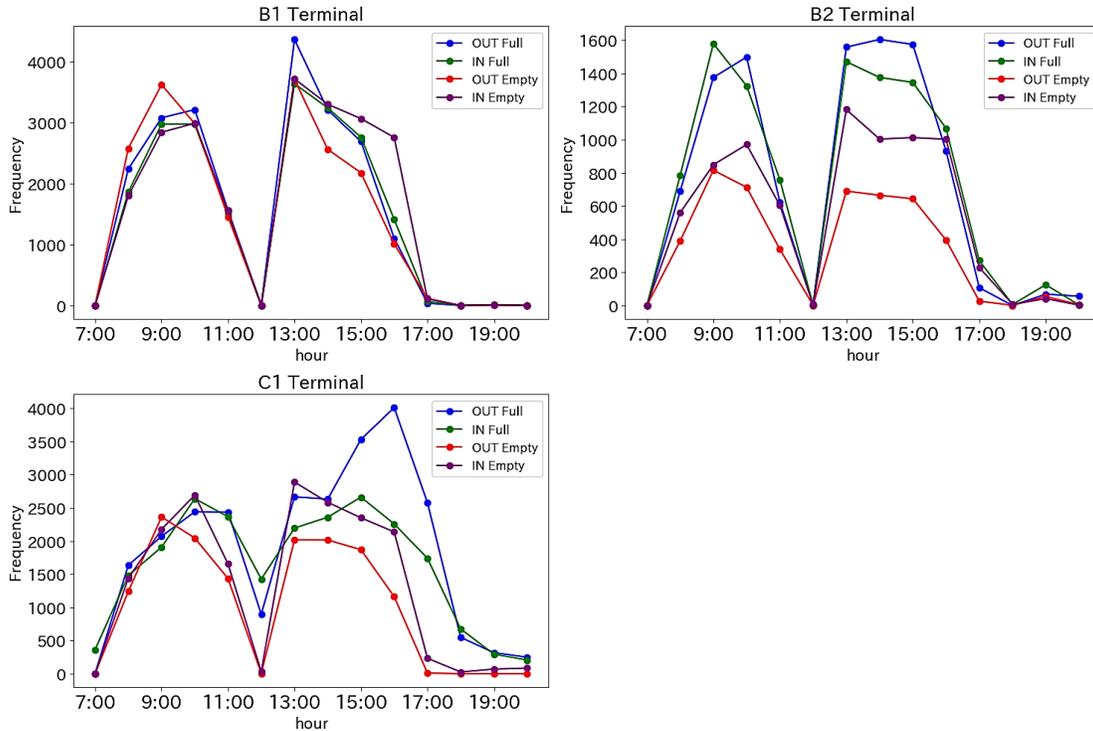
Next, we analyze truck arrival times from the obtained TOS data for each terminal. **Figure 2** shows the time distribution of trucks arriving at each terminal by container type (full or empty, and gate-in or gate-out). The time distribution is generally consistent among terminals in the daytime, with a break at noon and two peaks in the morning and afternoon.

In port A, both terminals imported many full containers (gate-out and full) compared to full export containers (gate-in and full). In the A1 terminal, the number of empty gate-in containers was almost the same as full gate-out containers, and that of empty gate-out containers was almost the same as full gate-in containers, reflecting that almost all export- and import-full containers were transported empty on their reverse trips, while there were significant differences between them in the A2 terminal. In addition, the noon break is characterized by a small valley in the A1 terminal compared to other terminals.

Figure 2: Time Distribution of Truck Arrival at Each Terminal by Container Type



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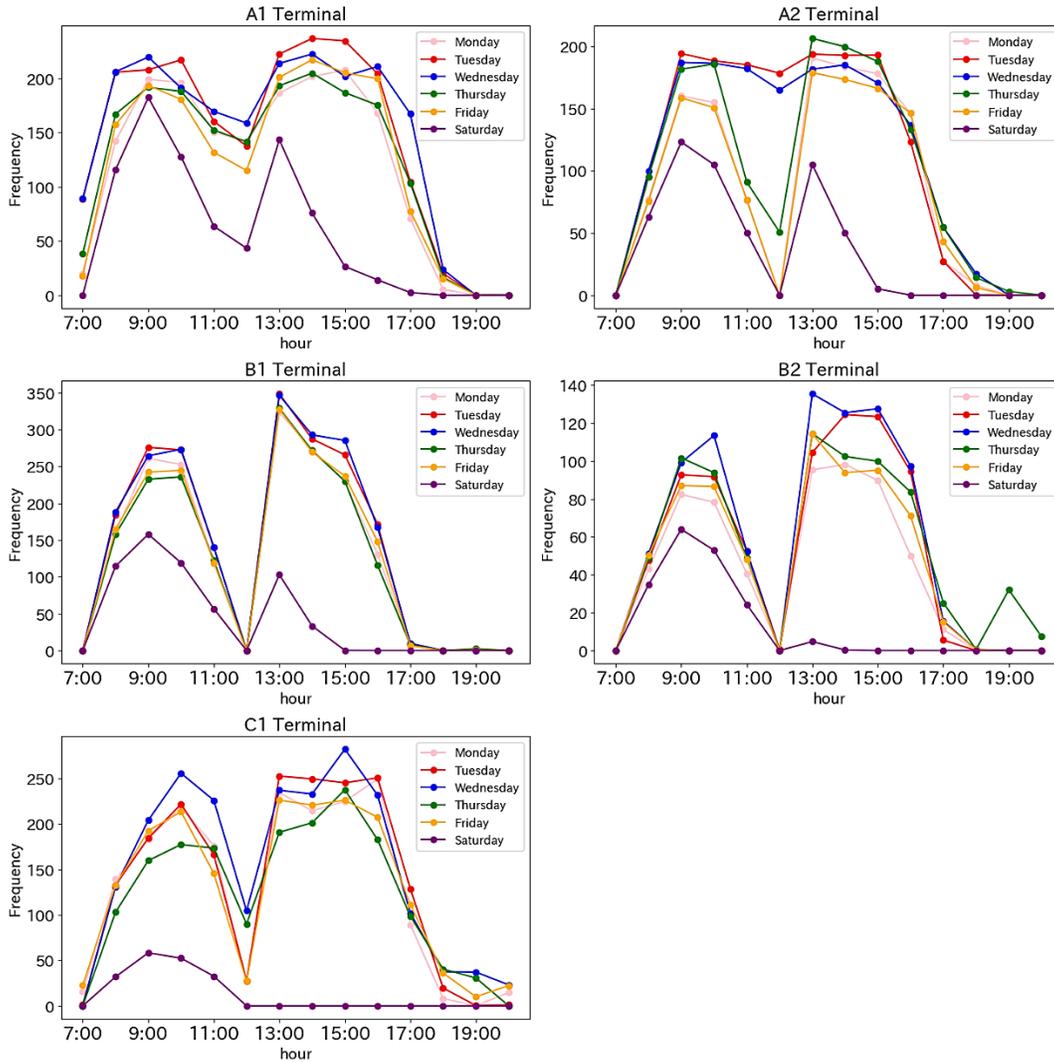
Source: Authors' calculations from terminal operating system data.

In each terminal in ports B and C, the number of export- and import-full containers was almost the same, while the balance between full and empty containers differed among terminals—they were almost the same in the B1 and C1 terminals, but there were more full containers than empty ones in the B2 terminal.

Overall, full import containers tended to arrive in the morning, while full export containers tended to arrive in the afternoon in all terminals. Similarly, gate-out empty containers (i.e., reverse trips of export containers) tended to arrive in the morning, while gate-in empty containers (i.e., reverse trips of import containers) tended to arrive in the afternoon in most terminals. Chi-squared tests examined the relationship between container type (import or export) and arrival time (morning or afternoon). The results showed a significant association. Specifically, full containers: $\chi^2(1) = 22.16$, $p = 6.76 \times 10^{-51}$; empty containers: $\chi^2(1) = 665.56$, $p = 9.21 \times 10^{-147}$. Based on these findings, it was concluded that there is a statistically significant relationship between container type and time of delivery.

Figure 3 shows the distribution of truck arrival time by day of the week for each container terminal. All terminals accept trucks from Monday through Saturday, with Saturday being characterized by a low number of trucks arriving. There were no significant differences for weekdays in most terminals, except for the A2 terminal, which had no lunch break on Tuesdays and Wednesdays.

Figure 3: Time Distribution of Truck Arrival at Each Terminal by Day of the Week



Source: Authors' calculations based on terminal operating system data.

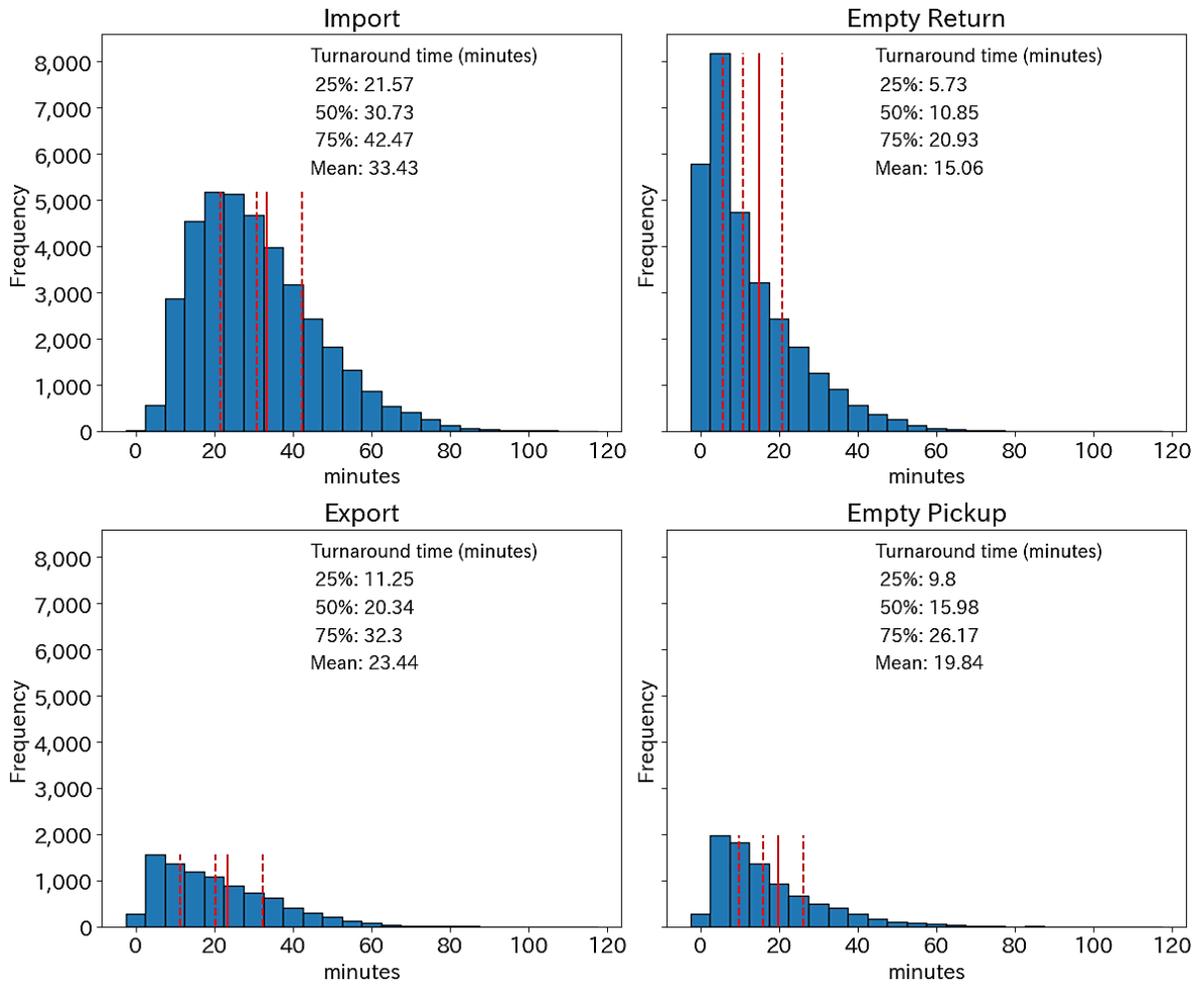
4.3 Turnaround Time Between Truck Arrival and Departure (Truck Turnaround Time)

Subsequently, we analyze the turnaround time for inbound and outbound trucks from gating in to gating out, which can be estimated in the A1, B1, and B2 terminals. We can estimate it for all container types in the A1 terminal, while it can be estimated only for outbound trucks (i.e., full import and empty gate-out containers) in the B1 and B2 terminal because of data availability. Notably, all outbound containers at the B2 terminal used the reservation system.

Figures 4–6 show the turnaround times by container type at each terminal. The results indicate that the truck turnaround time was generally shorter for empty returns (gating in), empty pickups (gating out), exports, and imports in that order. Only for full import containers, the peak of distribution was 16–20 minutes, while the distribution peaks were 4–8 minutes for other container types, suggesting that trucks often waited to be loaded in the terminal if they carried import containers. The turnaround times in the B1 and B2 terminals were shorter than those in

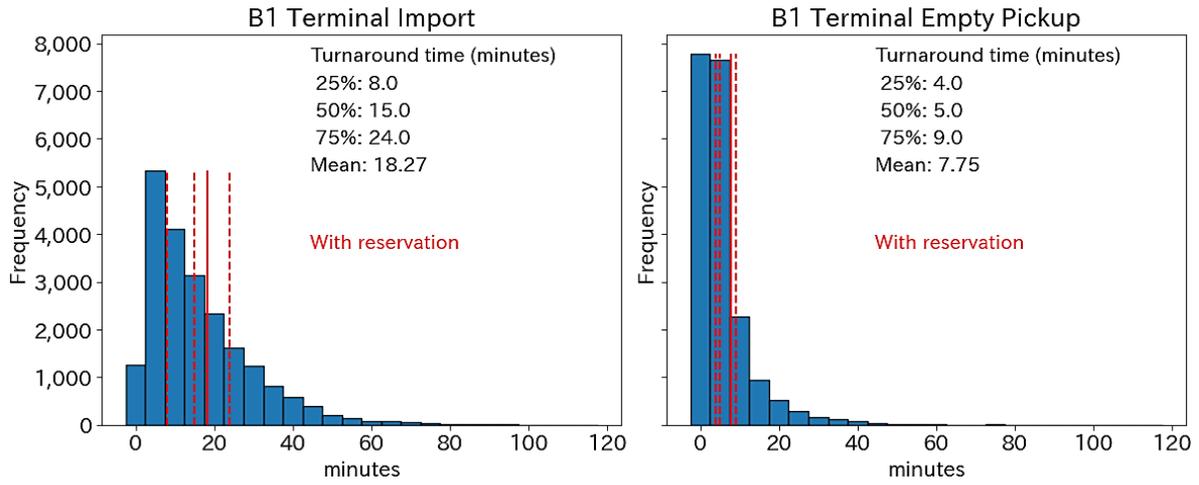
the A1 terminal for the same type of containers. Despite the difference in terminal size, it suggests that the reservation system was functioning.

Figure 4: Truck Turnaround Time Distribution by Container Type—A1 Terminal



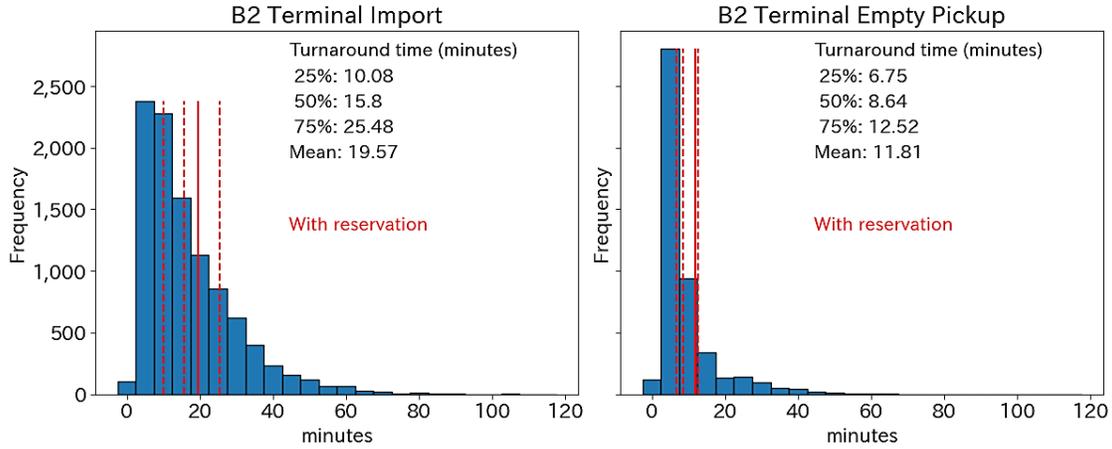
Source: Authors' calculations from terminal operating system data.

Figure 5: Truck Turnaround Time Distribution by Container Type—B1 Terminal



Source: Authors' calculations from terminal operating system data.

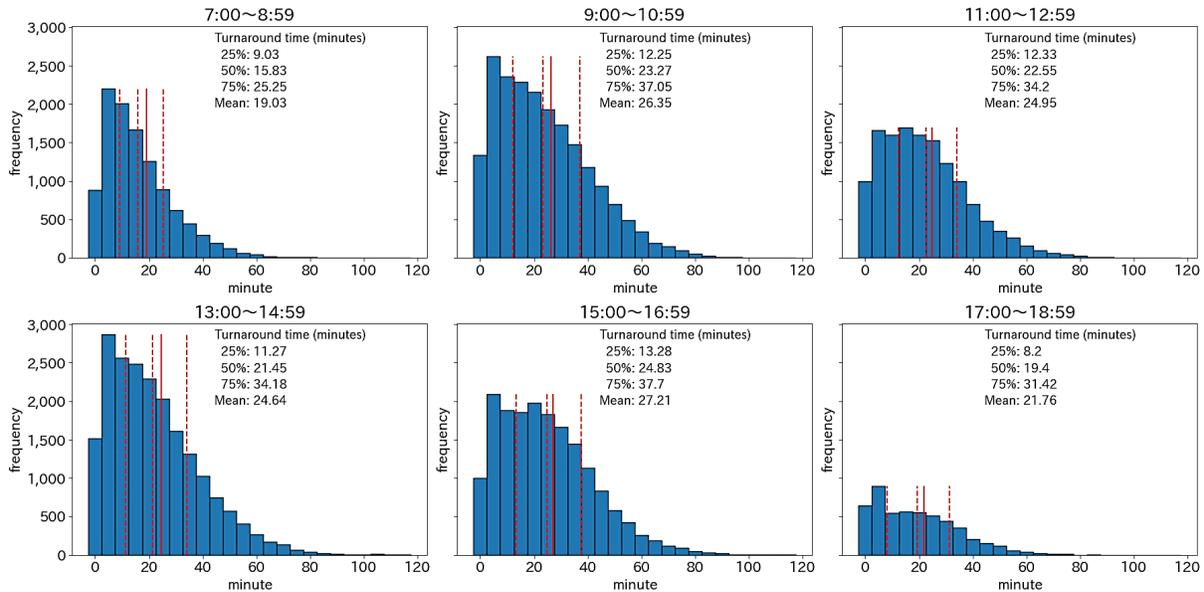
Figure 6: Truck Turnaround Time Distribution by Container Type—B2 Terminal



Source: Authors' calculations from terminal operating system data.

Figure 7 shows the distribution of truck turnaround times in the A1 terminal by time zone. Their average from 7 a.m. to 9 a.m. was 19 minutes, more than 5 minutes shorter than the other time zones. We also confirm there was no significant difference in the distribution, even at lunchtime.

Figure 7: Truck Turnaround Time Distribution for Each Time Zone—A1 Terminal

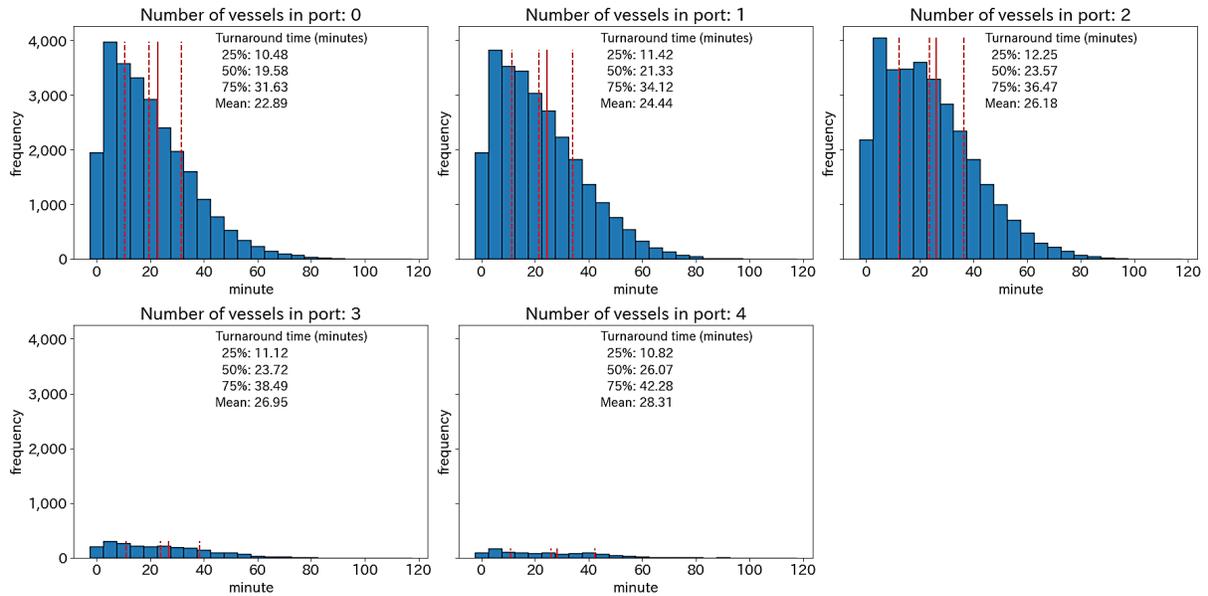


Source: Authors' calculations from terminal operating system data.

Next, **Figure 8** shows the distribution of truck turnaround times in the A1 terminal by the number of vessels calling, indicating that the average turnaround time was slightly longer if the number of vessels calling at the terminal increased. The same trend can be observed in terminals B1 and B2. This may be because the confusion in yard operations could increase if the number of vessels calling increases.

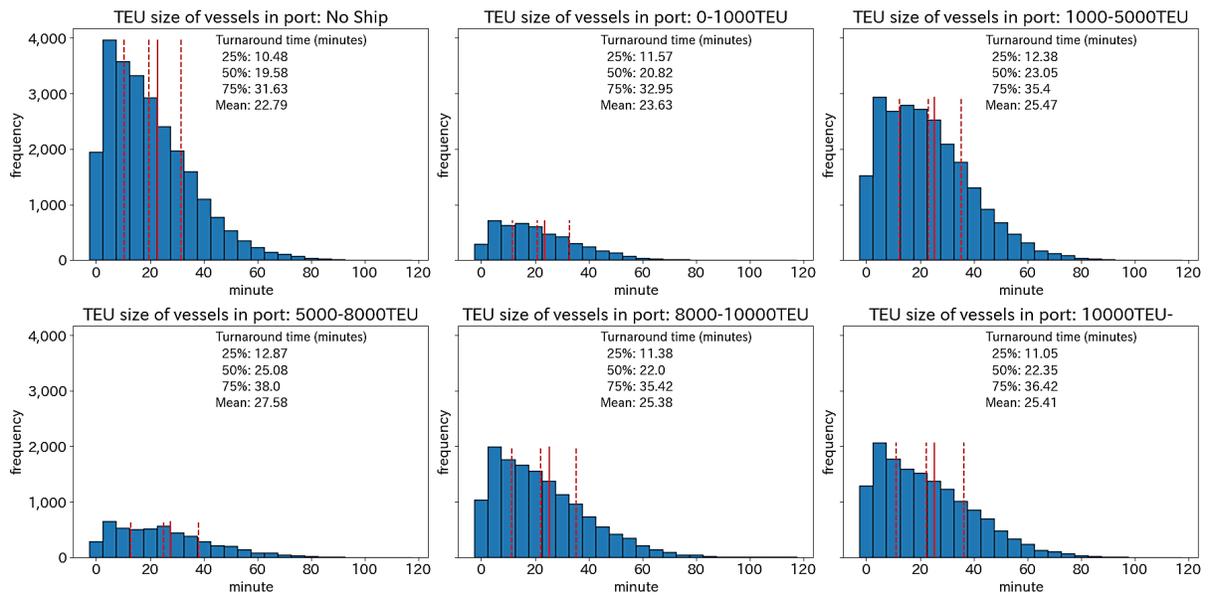
Figure 9 shows the distribution of truck turnaround times in the A1 terminal by average vessel size. Unlike the number of berthing vessels shown in Figure 8, there was no tendency for the average truck turnaround time, as the average vessel size increased if the vessel size was larger than 1,000 TEU.

Figure 8: Truck Turnaround Time Distribution by Number of Berthing Vessels—A1 Terminal



Source: Authors' calculations from terminal operating system and automatic identification system data.

Figure 9: Truck Turnaround Time Distribution by Average Vessel Size—A1 Terminal



TEU = twenty-foot equivalent unit.

Source: Authors' calculations from terminal operating system and automatic identification system data.

To identify the factors influencing truck turnaround times, we conducted a multiple regression analysis. The dependent variable is truck turnaround time (log transformed), and the independent variables include container types (empty or full, export or import, and dry or reefer); day of the week (weekday or Saturday); time (early morning: 7 a.m. to 8:59 a.m.; morning: 9 a.m. to 11:59 a.m.; midday: noon to 12:59 p.m.; afternoon: from 1 p.m. onward); and the number of ships berthed during the operation. We set empty gating-in containers to arrive early in the morning on weekdays as the reference.

Table 3 shows the estimation results of the regression models, which are developed for each terminal, and the combined data of both terminals. Overall, the multiple correlation coefficients are around 0.3–0.4. The coefficients of full and gating-out containers are positive in each model, as observed in Figures 4–6 for both terminals. Regarding the gate-in time, the coefficient in each time zone is positive in each model, reflecting that truck turnaround time is fastest in the early morning, as shown in Figure 7 for the A1 terminal. Lunchtime is the second fastest. The number of vessels calling at port also positively affects each model, as observed in Figure 8 for the A1 terminal. However, the signs of coefficients for Saturday operation and reefer containers differ by model: Saturday operations would be faster than weekdays because of less congestion in some terminals but slower because of a lack of available workers in others. The degree of congestion for reefer containers compared to dry containers also depends on their stocking capacity.

Table 3: Regression Analysis Results for Truck Turnaround Times

Explained Variable	Dependent Variable: Truck Turnaround Time (Coefficient and T-value)			
	A1 Terminal	B1 Terminal	B2 Terminal	Total
Constant	6.1628*** (807.80)	5.7183*** (452.72)	6.2711*** (359.20)	6.2130*** (980.32)
Full containers	0.5891*** (102.81)	0.8677*** (126.86)	0.4970*** (48.12)	0.6786*** (167.17)
Gate-out containers	0.4327*** (75.85)	–	–	0.3718*** (71.57)
Date_Saturday	0.0780*** (9.69)	–0.3691*** (–25.45)	–0.0776*** (–3.43)	–0.0364*** (–5.39)
Gatein_hour_morning	0.2690*** (34.88)	0.0861*** (7.63)	0.0121 (0.70)	0.1953*** (32.35)
Gatein_hour_noon	0.2364*** (22.11)	–	–	0.1715*** (17.04)
Gatein_hour_afternoon	0.2619*** (35.66)	0.0178 (1.62)	0.1533*** (9.04)	0.1927*** (33.32)
Reefer containers	–0.0358*** (–4.31)	–	0.1602*** (9.89)	–
Number ships	0.0570*** (22.82)	0.0505*** (19.17)	0.0526*** (4.24)	0.0593*** (33.46)
Dummy for B1 terminal	–	–	–	–0.9417*** (–169.59)
Dummy for B2 terminal	–	–	–	–0.5126*** (–77.26)
Adj. R-squared	0.323	0.299	0.155	0.384
No. of observations	85,850	41,404	14,841	142,095

*** p<0.01, ** p<0.05, and * p<0.1.

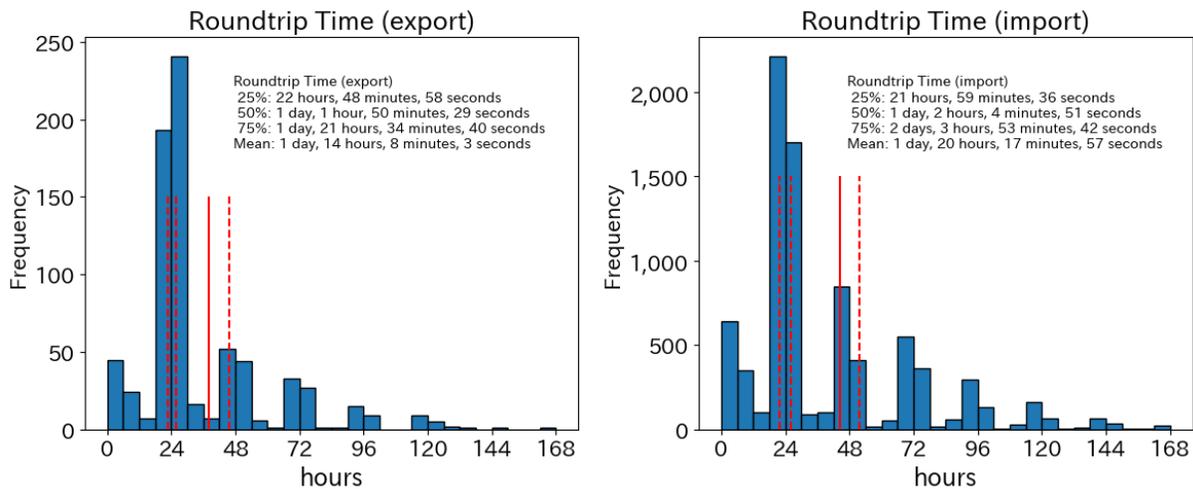
Source: Authors' calculations.

4.4 Round Trip Time of Containers Outside the Terminal (Container Turnaround Time Outside the Terminal)

This subsection focuses on the round trip time of containers outside the terminal, which is defined as the time from when the container left the terminal as an empty container to when it was delivered to the terminal as a full export container after vanning, or the time from when the container left the terminal as a full import container to when it was returned to the terminal as an empty container after devanning. We analyze terminals A2 and B2 in this subsection because of data availability.

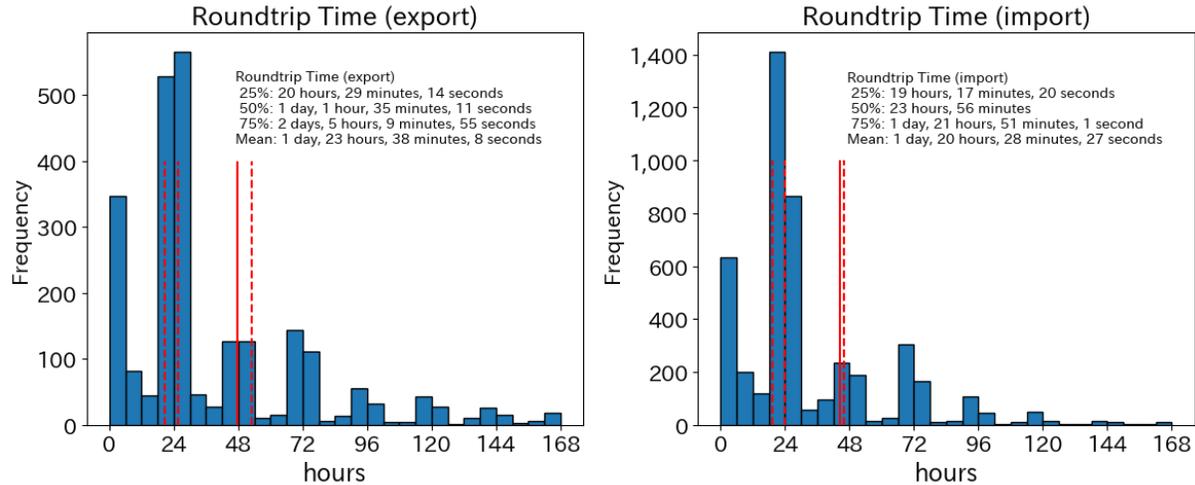
Figures 10 and 11 show histograms of the round trip time for A2 and B2 terminals, respectively. Although in the B2 terminal more containers returned in less than 6 hours than in the A2 terminal, there are some common observations. First, the round trip time for export containers peaked at between 24 and 30 hours, while that for import containers peaked at between 16 and 24 hours. Peaks occur every 24 hours because the terminal gates open during the daytime. In addition, no containers returned beyond more than 1 week (168 hours).

Figure 10: Round Trip Time of Containers Outside the Terminal—A2 Terminal



Source: Authors' calculations based on terminal operating system data.

Figure 11: Round Trip Time of Containers Outside the Terminal—B2 Terminal



Source: Authors' calculations based on terminal operating system data.

4.5 Dwell Time of Full Containers in the Terminal between Truck Gate-in or Gate-out and Vessel Departing or Arriving (Container Turnaround Time in the Terminal)

This subsection analyzes the terminal dwell time of full containers. Since this requires that each container be linked to the vessel from which it is loaded or unloaded, the analysis targets the A2, B1, and C1 terminals. The vessel information is combined with AIS data based on the vessel name and call sign included in the TOS data of each terminal. Notably, empty containers are considered in the subsequent subsection because the definition of the vessel information for empty containers is different.

We consider two options for combining TOS and AIS data. The first option aims to increase the matching rates of containers and vessels as much as possible, while the second option aims to focus on matching accuracy. The details of the combining method are described below by export and import.

Export (gate-in) full containers:

- Option 1: Identify the first vessel leaving 48 hours (i.e., container yard cut time) after a truck arrived at the terminal with the vessel name or call sign.
- Option 2: Identify the vessel leaving after a truck arrived if the vessel called at the terminal once during a month after the truck's arrival.

Import (gate-out) full containers:

- Option 1: Identify the last vessel arriving 24 hours before a truck arrived at the terminal.
- Option 2: Identify the vessel arriving before a truck arrived if the vessel called at the terminal once during a month before the truck's arrival.

Table 4 summarizes the estimated matching rates of both options applying to each terminal. The matching rates of Option 1 are more than 80%, while those of Option 2 are around 50%–70%. In the following analysis, we use the matching results by Option 2 for the sake of accuracy, although the matching rates are smaller.

Table 4: Rates of Matched Full Containers with Vessels

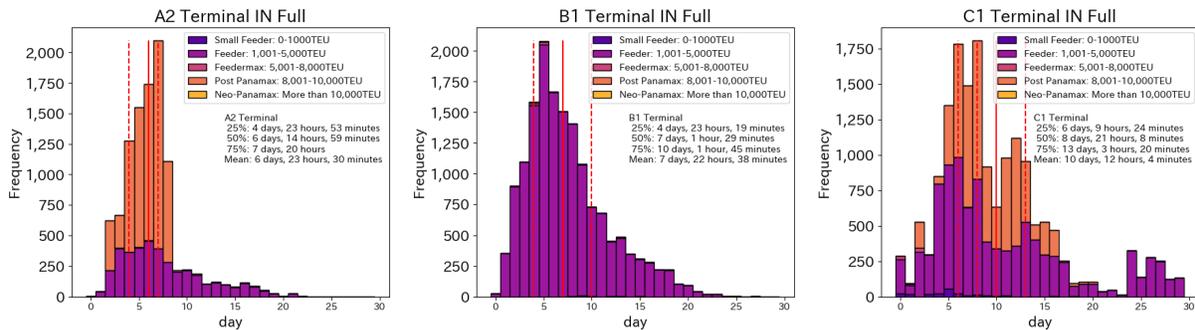
		A2 Terminal		B1 Terminal		C1 Terminal	
		Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Number of vessels		55		296		483	
Export	number	18,579		20,436		26,584	
	rate	99.3%	56.3%	94.4%	77.0%	88.9%	62.0%
Import	number	30,600		21,486		28,210	
	rate	99.4%	49.7%	94.1%	57.6%	85.8%	56.2%

Source: Authors' calculations.

Figure 12 shows the distribution of dwell times (colored by vessel size) for full export containers from the gating-in of a truck to the departure time of the vessel at each terminal. At all terminals, the dwell time was less than 48 hours (2 days) for only a few containers, which is consistent with the general container yard cut time, ensuring the accuracy of data combining. The dwell time in the A2 terminal was the shortest, with very few containers staying more than 1 week, especially for the largest container ships.

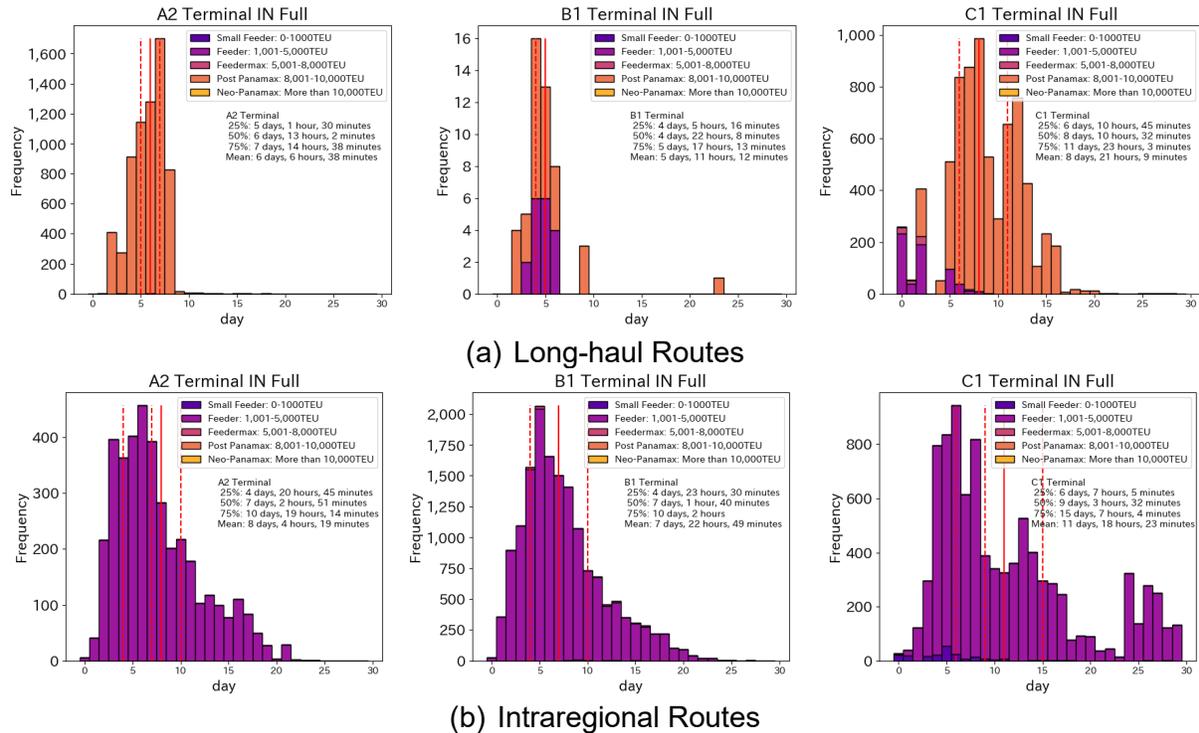
Figure 13 represents the dwell time distribution of export-full containers for long-haul (including Europe; North, Central, and South America; and Africa) and intraregional routes. Notably, the information on shipping routes is provided by the MDS container ship database, and very few containers were transported on long-haul routes in the B1 terminal. Comparing these figures indicates that the dwell times of export-full containers were distributed with longer tails for intraregional routes in all terminals compared to long-haul routes.

Figure 12: Dwell Time Distribution of All Export-full Containers Leaving Each Terminal



Source: Authors' calculations from terminal operating system and automatic identification system data.

Figure 13: Dwell Time Distribution of Export-full Containers Leaving Each Terminal by Route

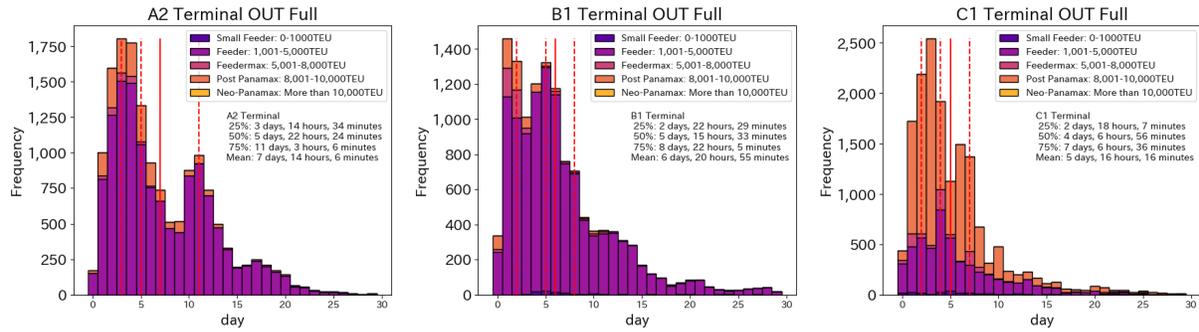


Source: Authors' calculations from terminal operating system, automatic identification system, and MDS data.

Figure 14 shows the distributions of dwell times for import-full containers (colored by vessel size) from the vessel arrival to the gating-out by a truck at each container terminal. Similar to full export containers, we find that a dwell time was less than 24 hours (1 day) for very few containers, reflecting the necessary hours for import procedures. The average dwell time was the smallest in the C1 terminal for import containers, while it was the longest for export containers. The figure also indicates that containers imported with larger vessels tended to stay for a shorter time in each terminal. Although a truck reservation system for import containers was implemented at the B1 terminal, the figure does not clearly show the effect of this system.

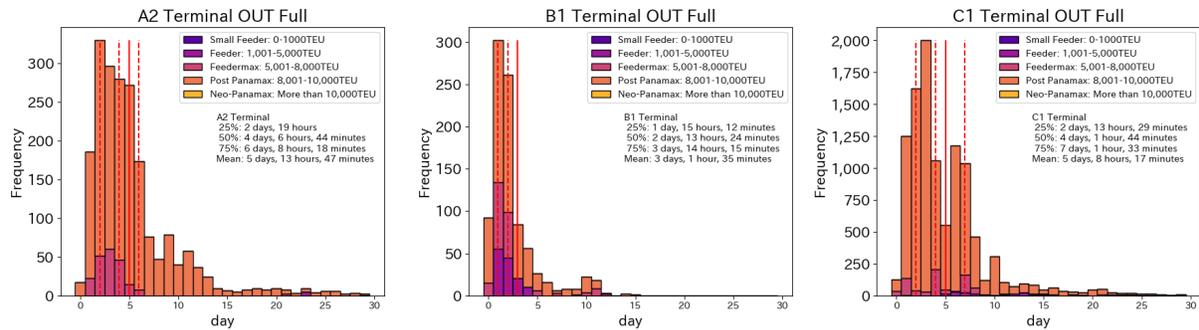
Figure 15 represents the dwell time distribution of full import containers for long-haul and intraregional routes, respectively. The general trends on the results that container dwell times were longer for intraregional routes in all terminals compared to long-haul routes were similar to those of export containers, although a few import containers were transported on long-haul routes in the A2 terminal, differing from the case of exports. Containers at the A2 terminal on intraregional routes peaked twice, once on the fourth day and once on the 11th day.

Figure 14: Dwell Time Distribution of All Import-full Containers Arriving at Each Terminal

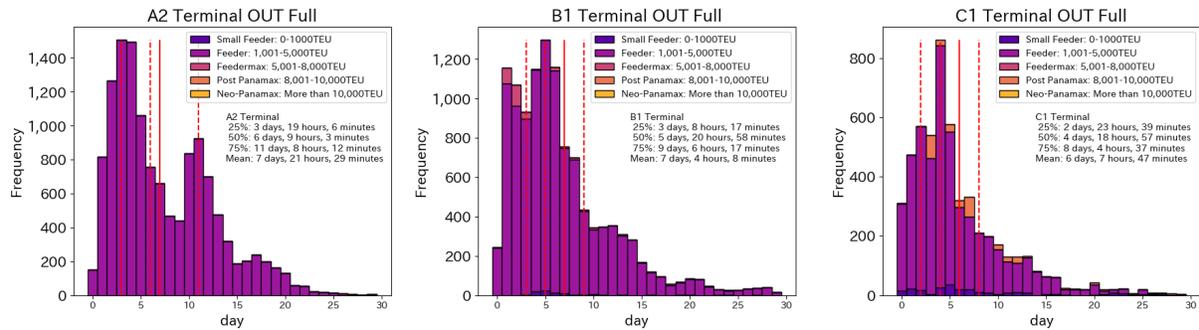


Source: Authors' calculations from terminal operating system and automatic identification system data.

Figure 15: Dwell Time Distribution of Import-full Containers Leaving Each Terminal by Route



(a) Long-haul Routes



(b) Intraregional Routes

Source: Authors' calculations from terminal operating system, automatic identification system, and MDS data.

We also develop multiple regression models to describe the dwell time of full containers in the terminal (log-transformed) with container types (export or import), the day of the week (weekday or Saturday) of truck arrival, size of vessels that carry containers, and annual frequency of the liner service. We exclude the type of routes (long-haul or intraregional) because it

significantly correlates with vessel size. We set export containers on board the vessel with a capacity of less than 2,000 TEU, arriving on weekdays as the reference.

Table 5 shows the model estimation results developed for each terminal and the combined data of all terminals. Overall, the multiple correlation coefficients (around or less than 0.2) are much smaller than the models developed in Section 4.3; thus, the analysis is just for reference. While the coefficients of import containers and the capacity of onboard vessels with more than 8,000 TEU are negative in each model, signs of other coefficients are different among the models.

Table 5: Regression Analysis Results for Full Container Dwell Time

Explanatory Variable	Dependent Variable: Full Container Dwell Time (Coefficient and T-value)			
	A2 Terminal	B1 Terminal	C1 Terminal	Total
Constant	1.9074*** (127.88)	2.1734*** (98.61)	2.0823*** (78.91)	2.1320*** (201.32)
Import containers	-0.2366*** (-25.67)	-0.2924*** (-34.78)	-0.7139*** (-85.42)	-0.4018*** (-83.55)
Date_Saturday	0.1829*** (10.23)	0.2501*** (15.08)	-0.0880** (-2.22)	0.1760*** (14.21)
2,000–4,000 TEU	0.1861*** (14.50)	0.1343*** (14.45)	-0.3453*** (-19.03)	0.0366*** (5.09)
4,001–8,000 TEU	-0.4178*** (-34.91)	-0.1201*** (-10.83)	0.0596*** (3.86)	-0.1472*** (-19.96)
8,001–10,000 TEU	-0.4483*** (-33.89)	-0.6495*** (-23.26)	-0.0716*** (-4.91)	-0.2775*** (-35.44)
Annual_service_frequency	0.0061*** (24.32)	-0.0056*** (-13.12)	0.0029*** (6.66)	0.0007*** (3.72)
B1_flag	–	–	–	-0.1838*** (-27.05)
C1_flag	–	–	–	0.0253*** (4.19)
Adj. R-squared	0.102	0.095	0.208	0.091
No. Observations	25665	28102	32346	86113

TEU = twenty-foot equivalent unit.

*** p<0.01, ** p<0.05, and * p<0.1

Source: Authors' calculations.

5. CONCLUSION AND POLICY RECOMMENDATIONS

This study provides comprehensive empirical evidence on the operational patterns and efficiency determinants in container terminal operations, focusing on truck movements, container handling, and temporal distributions. Our analysis reveals several key insights with important implications for terminal operations management and policy development.

The analysis demonstrates clear temporal patterns in terminal operations, with distinct morning and afternoon peaks in truck arrivals and systematic variations across different container types. Our chi-squared tests confirm a significant relationship between container type and arrival time, with full import containers predominantly arriving in the morning and full export containers arriving in the afternoon at these terminals. This temporal segregation, while organizationally convenient, creates operational pressures during peak periods. The observed patterns suggest

that current terminal operations are characterized by predictable but suboptimal distribution of truck traffic, leading to potential congestion during peak hours.

Our regression analyses reveal that operational efficiency, measured through truck and container turnaround times in the terminal, is significantly influenced by multiple factors. Notably, truck turnaround times increase with the number of vessel calls at a terminal, suggesting capacity constraints during high activity periods by sharing some facilities such as yard cranes. The analysis of container dwell times shows that full export containers generally maintain dwell times of under 7 days, with the A2 terminal demonstrating the smallest dwell times because it mainly serves long-haul shipping with larger container ships. Meanwhile, some containers for intraregional shipping with smaller container ships stay longer in the terminals, which are used as storage places.

The distinct operational characteristics observed across different terminals provide valuable insights. The A2 terminal's elimination of lunch breaks on Tuesdays and Wednesdays represents an adaptive response to peak demand, while the C1 terminal's nighttime operations demonstrate the potential for extended operating hours. The balanced distribution of export- and import-full containers in ports B and C, contrasting with port A's import-heavy operations, suggests different optimal strategies may be needed for different port profiles.

Based on these findings, we propose several detailed policy recommendations. First, terminals can consider implementing dynamic scheduling systems that include smart truck appointment systems, specifically targeting the observed morning peak for import containers and afternoon peak for export containers. These systems would incorporate time-based incentive mechanisms offering 15%–20% reduced handling fees for off-peak hour deliveries, along with surge pricing during peak hours for exports and imports. Dedicated time windows can also be created for empty container returns based on vessel schedules.

Infrastructure and resource optimization requires installing automated gate systems capable of handling 120% of peak hour volumes and implementing dedicated lanes for empty container returns during off-peak hours. Yard space allocation may be optimized with dynamic zoning based on container dwell time patterns, and specialized handling areas may be developed for terminals with significant empty container volumes. Information systems can also be enhanced to deploy real-time tracking systems for both full and empty containers, while implementing predictive analytics using historical data to forecast peak periods. Integrated systems connecting vessel arrival data with truck appointment scheduling should be developed alongside mobile applications for real-time updates on terminal conditions and waiting times.

Operational standardization and best practices should be prioritized. Flexible break schedules similar to terminal A2's Tuesday–Wednesday model should be implemented during high volume periods. Terminal-specific performance metrics should be developed to account for different import–export balances. Regulatory frameworks requiring terminals to maintain minimum handling speeds during vessel calls can also be considered, along with systematic reporting of key performance indicators for all terminals.

While they are outside the scope of this paper, the authors also note that there is scope to explore the following key areas in future research. A quantitative assessment of the impact of dynamic pricing on truck arrival patterns would provide valuable insights for policy refinement. Analysis of the relationship between vessel size and terminal efficiency across different ports could inform infrastructure development decisions. Investigation of empty container logistic optimization strategies would address a significant operational challenge. Evaluation of nighttime

operations expansion potential across all terminals could reveal opportunities for capacity enhancement. Combining this dataset with the detailed movement data of container semitrailers—extracted from the ETC 2.0 (R. Yasuda et al., 2024; Zheng et al., 2024)—could further expand the analysis with information on customer locations and type (e.g., factory, warehouse, and depot). Finally, studying the environmental impact of current truck arrival patterns could identify potential improvements in sustainability.

The findings of this study not only contribute to the growing body of knowledge on terminal operations but also provide practical, evidence-based support for policymakers and terminal operators in their efforts to enhance operational efficiency. The significant variations in operational patterns and efficiency metrics across terminals suggest that while standardized approaches are valuable, terminal-specific adaptations will be crucial for successfully implementing these recommendations.

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Digital Port Integration and Terminal Efficiency

Evidence from Vessel, Truck, and Container Turnaround Times in Japanese Container Terminals

This paper examines port terminal efficiency through an empirical analysis of turnaround (arrival, waiting, and departure) times for vessels, trucks, and containers at selected Japanese container terminals. Using a novel dataset that combines terminal operator records, vessel movement data, and liner service data, the analysis reveals that vessel calls, container types, and time of day significantly influence operational efficiency, and that turnaround times are primarily affected by terminal-controlled factors. The study proposes policy recommendations for dynamic scheduling systems, operational standardization, and infrastructure optimization. The results contribute to the growing literature on port digitalization and provide evidence-based guidance for terminal operators and policymakers seeking to enhance port efficiency through digital integration.

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