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Modelling container dwell time, throughput, and rehandle productivity at Lekki Freeport Terminal

Modelowanie czasu zatrzymania kontenerów, przepustowości i wydajności ponownego obsłużenia w Lekki Freeport Terminal

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Abstract:
Research objectives and hypothesis/research questions
It aims at identifying the influence of container dwell time to define the yard operational performance based on the comparison of throughput and rehandling performance operating with various storage strategies.
Research methods
Since the global trade has become sensitive, terminal operations in the effective movement of the containers have become a critical aspect in reducing congestion. To facilitate the analysis, this paper introduces simple methods to evaluate the effect of container dwell time and storage policies on import throughput, storage density, and rehandling productivity. To estimate the expected number of rehandles when delivering an import container to a road truck, a Monte Carlo Simulation (MCS) method is utilized. The MCS method is an approach for iteratively evaluating a deterministic model using sets of random numbers as inputs. There are three important reasons for employing the MCS method. First, it allows us to make conclusions about the variance of the expected rehandles as a function of stack height and storage strategies. Second, it allows us to conveniently solve for ad hoc rehandling strategies – unique rehandling strategies employed

by Lekki Freeport Terminal(LFT), when the bay is full. Third, it circumvents the need to make restrictive assumptions regarding the probability of containers of being delivered to external trucks. In essence, MCS provides a robust way of estimating the number of rehandles.
Main results
The results demonstrate that extended dwell times lead to operational bottlenecks, resulting in reduced yard efficiency and increased rehandling requirements. This is particularly evident when analyzing rehandling under equal and non-equal probability models, where higher dwell variability amplifies inefficiencies. By improving dwell time management, terminals can achieve better throughput performance and streamline rehandling processes. Furthermore, the study demonstrates that probabilistic modeling provides valuable insights into rehandling outcomes, enabling terminals to predict and mitigate potential productivity losses. Addressing dwell time challenges is critical for enhancing container yard operations and accommodating increasing trade volumes efficiently.
Implications for theory and practice
The findings provide a quantitative model of improving the performance at LFT and at other similar terminals.

Keywords:
throughput, Monte Carlo simulation, Lekki Freeport Terminal, dwell time, rehandling productivity

Abstrakt:
Cel badań i hipotezy/pytania badawcze
Przedmiotem badań jest identyfikacja wpływu czasu zatrzymania kontenerów w celu określenia wydajności operacyjnej placu na podstawie porównania przepustowości i wydajności ponownego przeładunku z różnymi strategiami magazynowania.
Metody badawcze
Ponieważ globalny handel stał się wrażliwy, operacje terminalowe w zakresie efektywnego przewozu kontenerów stały się kluczowym elementem w ograniczaniu korków. Aby ułatwić analizę, artykuł wprowadza proste metody oceny wpływu czasu pozostawania kontenerów i polityk magazynowania na przepustowość importu, gęstość magazynowania oraz wydajność ponownego przetwarzania. Żeby oszacować przewidywaną liczbę przesunięć podczas dostarczania kontenera importowego do ciężarówki drogowej, stosuje się metodę symulacji Monte Carlo (MCS). Metoda MCS to podejście do iteracyjnej oceny modelu deterministycznego z wykorzystaniem zbiorów liczb losowych jako danych wejściowych. Istnieją trzy ważne powody stosowania metody MCS. Po pierwsze, pozwala wyciągać wnioski na temat zmienności oczekiwanych ponownych obsług w zależności od wysokości stosu i strategii przechowywania. Po drugie, umożliwia wygodnie rozwiązywać strategie ad hoc ponownej obsługi – unikalne strategie przeładunku stosowane przez Lekki Freeport Terminal (LFT), gdy zatoka jest pełna. Po trzecie, omija konieczność przyjmowania ograniczeń dotyczących prawdopodobieństwa dostarczania kontenerów do zewnętrznych ciężarówek. W istocie MCS zapewnia solidny sposób szacowania liczby ponownych obsług.
Główne wyniki
Wyniki pokazują, że wydłużone czasy zatrzymania prowadzą do wąskich gardeł operacyjnych, co skutkuje spadkiem efektywności placu i zwiększeniem wymagań dotyczących ponownego przeładunku. Jest to szczególnie widoczne w sytuacji analizy ponownego przetwarzania w modelach równego i nierównego prawdopodobieństwa, w przypadku których wyższa zmienność czasu zatrzymania wzmacnia nieefektywności. W wyniku poprawy zarządzania czasem zatrzymania terminale mogą osiągnąć lepszą wydajność przepustowości i usprawnić procesy ponownego przetwarzania. Ponadto badanie pokazuje, że modelowanie probabilistyczne dostarcza cennych informacji na temat wyników ponownego przetwarzania, umożliwiając terminalom przewidywanie i ograniczanie potencjalnych strat produktywności. Rozwiązanie problemów z czasem zatrzymania jest kluczowe dla usprawnienia działalności placu kontenerowego i efektywnego radzenia sobie ze wzrostem wolumenów handlu.
Implikacje dla teorii i praktyki
Wyniki stanowią model ilościowy poprawiający wydajność w LFT i innych podobnych terminalach.

Słowa kluczowe:
przepustowość, symulacja Monte Carlo, Lekki Freeport Terminal, czas zatrzymania, ponowne zarządzanie produktywnością

Introduction

Containerization has greatly influenced world trade since it has changed the manner in which the goods are shipped in the world. Trade liberalization and more trade integration have majorly facilitated the use of containerization due to the significant increase in the trade of commodities and the demand of both capital and consumer goods associated with these developments (Watada, Roy, Kadikar et al., 2019). This shift has helped countries located far apart in the map conduct business, thus fostering economic prosperity and global collaboration (Coşar, Demir, 2018). Data shows that the overall increase in containerized trade internationally was at a compound rate of 12% between 2001 and 2005, with a projected growth rate of 6.5% up to 2011 (Huynh, 2008). The contribution of containerization toward the emergence of international trade is tangible; container shipping proved to be a cornerstone of international trade facilitating a seamless movement of goods across continents and fostering the growth of international trading coalitions (Ding, Wang, 2022). Studies have emphasized the close correlation that exists between world trade growth and port containerization, where effective container handling at the ports is vital in supporting flows of international trade and economic growth (Notteboom, Yang, Xu, 2020). The evolution of containerization has led to the massification of ports, turning them into crucial nodes in the global trade system (Hlali, Hammami, 2019).

This evolution of containerization has had a profound impact on port development and trade dynamics globally (Hlali, Hammami, 2019). In response to this growing trade demands, container ports have turned towards smart port concepts in order to increase the level of productivity, efficiency, and competitiveness. The birth of inland ports such as the dry ports has made container traffic in the supply chain easy and this has increased the competitiveness of seaports (Jeevan, Othman, Saharuddin et al., 2018). However, the continuous growth of global containerized trade presents both opportunities and challenges for port terminals worldwide. Translating global growth estimates to specific port terminals can be challenging due to various factors such as lack of data on vessel capacity, terminal efficiencies, and vessel speeds (Eskafi, Kowsari, Dastgheib et al., 2021a). Despite these challenges, the maritime industry acknowledges the continuous growth in container volumes along global trade routes, leading to occasional shocks that strain port container terminals (Eskafi, Kowsari, Dastgheib et al., 2021b). For example, while container volumes surged by more than 12% in the Asia-North America trade lane in 2004, they increased by 17% in the Asia-Europe trade lane, surpassing predictions and creating higher demand for ports in the latter lane (Eskafi, Ulfarsson, 2022). As a result, port authorities have recently invested considerable effort in improving their marine container terminal operations. Many terminals face challenges in adding more berths and container terminals due to limited space for expansion. Constructing new "greenfield" terminals has become increasingly difficult due to rising construction costs, stricter

environmental permitting requirements, and the need to address environmental justice concerns. Consequently, terminal operators prioritize enhancing throughput and productivity (Smith, 2021). Among the strategies to accomplish this are new technology implementation, existing technology upgrades, and implementing/using chassis pooling, reducing container dwell time, increasing storage density, blocking containers, and making extended gate hours (Chen, Wang, 2021).

The introduction of new and improved technologies to streamline processes and increase operational efficiency is one effective strategy (Eskafi, Kowsari, Dastgheib et al., 2021a). By leveraging technological advancements such as automation, data analytics, and digitalization, terminals can enhance their operational capabilities, reduce turnaround times, and improve overall productivity. These technologies enable terminals to handle larger volumes of containers more effectively, thereby increasing throughput without the need for physical expansion. Another strategy commonly adopted by terminal operators is the implementation of chassis pooling, which involves sharing chassis among multiple shipping lines and trucking companies to optimize equipment utilization and reduce turnaround times (Eskafi, Kowsari, Dastgheib et al., 2021b). The potential solution to the problem lies in the fact that pooling resources can become an effective way of decreasing the idle time of the equipment, enhancing the efficiency, and ultimately boosting the productivity of the entire terminal.

Reducing container dwell time is another critical strategy employed by terminal operators to enhance throughput and operational efficiency (Eskafi, Kowsari, Dastgheib et al., 2021a). By streamlining processes, optimizing container handling procedures, and minimizing delays, terminals can expedite the movement of containers through the terminal, ultimately increasing throughput and reducing congestion. Blocking containers, a strategy that involves grouping containers destined for the same location together to streamline handling and transportation processes, is another effective way to improve operational efficiency and increase throughput (Eskafi, Kowsari, Dastgheib et al., 2021b). By consolidating containers based on their final destination, terminals can reduce handling times, minimize repositioning efforts, and enhance overall operational efficiency. Extending gate hours is a strategy that many terminals adopt to increase operational flexibility, accommodate fluctuating demand, and optimize resource utilization (Eskafi, Ulfarsson, 2022). By extending operating hours, terminals can spread out peak traffic periods, reduce congestion, and improve overall efficiency, ultimately leading to increased throughput and enhanced terminal performance.

Increasing storage density within terminals is also a key strategy to maximize space utilization and enhance operational efficiency (Eskafi, Kowsari, Dastgheib et al., 2021a). For imports, the storage density (i.e., yard storage productivity) can be increased by stacking containers higher and/or stacking recently unloaded (termed new) imports on top of those that are already in the yard (termed old).

However, higher stacks, especially mixed ones, require additional rehandling (shuffling) of containers in retrieving the target container. The higher the number of rehandling moves associated with an import delivery to a road truck, the lower the rehandling productivity as defined below (equation 1). Rehandling productivity significantly affects truck turn time (the total time it takes a truck to complete its import or export transaction).

Hence, terminal operators must balance storage density with rehandling productivity: the ratio of number of import deliveries to total number of import moves. With truck turn time being a prominent issue because of environmental concerns, keeping truck turn time low is a high priority item for most terminals.

$$\text{Rehandle Productivity} = \frac{\text{Throughput}}{\text{Total Moves}}. \tag{1}$$

Where throughput is the number of import deliveries and total moves is the total number of the import moves. In practice, when port authorities or terminal operators set the free time or increase storage density, the decision is often made without a clear understanding of their effects on throughput and rehandling productivity. This is partly because practical methods that deal specifically with the effect of dwell time on throughput and productivity are limited in the literature and detailed analysis via simulation is too costly and time-consuming. This paper seeks to shed light on this subject and deals specifically with yard throughput and rehandling productivity of imports.

In this work, the impact of container dwell time on yard import throughput and rehandling productivity are examined for two import storage strategies: 1) non-mixed – no stacking of new import containers on top of old ones, and 2) mixed – stacking of new imports on top of old ones. With the non-mixed strategy, throughput and storage density are lower; however, rehandling productivity is higher. Some terminals employ the non-mixed storage policy in an effort to minimize rehandling. With the mixed strategy, throughput and productivity are higher although rehandling productivity is lower. Terminals that are space constrained typically employ the mixed storage strategy.

To facilitate the analysis, this paper introduces simple methods to evaluate the effect of container dwell time and storage policies on import throughput, storage density, and rehandling productivity. To estimate the expected number of rehandles when delivering an import container to a road truck, a Monte Carlo Simulation (MCS) method is utilized. The MCS method is an approach for iteratively evaluating a deterministic model using sets of random numbers as inputs. There are three important reasons for employing the MCS method. First, it allows us to make conclusions about the variance of the expected rehandles as a function of stack height and storage strategies. Second, it allows us to conveniently solve for ad hoc

rehandling strategies (unique rehandling strategies employed by Lekki Freeport Terminal when the bay is full). Third, it circumvents the need to make restrictive assumptions regarding the probability of containers of being delivered to external trucks. In essence, MCS provides a robust way of estimating the number of rehandles.

Section 2 describes the container yard layout and type of handling equipment considered in this work. Section 3 introduces the mathematical models for the analysis. Section 4 discusses the various experiments and their results. Lastly, Section 5 summarizes the work performed and provides concluding remarks.

1. Overview of Lekki Freeport Terminal (LFT)

The establishment of free trade zones, such as the Hainan Free Trade Port, demonstrates a commitment to expanding economic opportunities and fostering international trade (Chen, Wang, 2021). These zones serve as centres for shipping, logistics, and emerging industries, driving economic growth and regional development (Eskafi, Kowsari, Dastgheib et al., 2021a). A comparative analysis of free trade zone policies in various regions highlights the impact of such zones on economic development and trade dynamics (Coşar, Demir, 2018).

In Nigeria, the creation of zones like the Lekki Free Trade Zone and the Ogun Zone underscores the importance of these areas as focal points for economic engagement (Adunbi, Stein, 2019; Ding, Wang, 2022). Through strategic alliances, infrastructure investments, and policy evaluations, Lekki Free Trade Zone serves as a catalyst for economic growth, job creation, and enhanced regional cooperation.

Lekki Freeport Terminal within the Lekki Free Trade Zone reflects broader trends in urbanization, economic development, and international trade initiatives. The Lekki Freeport Terminal, an extension of CMA CGM in Nigeria, represents a strategic collaboration aimed at enhancing port operations, investments, and contributing to the growth and modernization of port facilities in the region. It aligns with global trends in port development and strategic alliances within the shipping or maritime industry.

The Lekki Freeport Terminal is recognized as the first automated terminal in Nigeria, showcasing advancements in port operations within the country. This terminal utilizes automation technologies and sophisticated container handling equipment (CHEs), such as Ship-To-Shore cranes (STSs), Rubber Tyre Gantry cranes (RTGs), Empty Container Handler (ECHs), Reach Stacker (RS), and Terminal Tractors (TTs), to optimize container handling processes, improve operational efficiency, and raise the standards of port management in Nigeria. The integration of automation at the Lekki Freeport Terminal represents a significant shift towards modernizing port infrastructure, enhancing container handling, and the minimization of human interaction in the physical operations. This strategic move not only boosts

the terminal's operational capabilities but also positions it as a prominent player in the global maritime industry (Gerrits, Mes, Schuur, 2020). Moreover, the adoption of automation technologies at the Lekki Freeport Terminal aligns with global trends in port development, highlighting the significance of efficiency, reliability, and technological innovation in port operations. By leading the automation efforts in Nigeria, the terminal establishes a model for future advancements in the country's maritime sector.

The container yard and the berthing of vessels at the Lekki Freeport Terminal are integral components of the terminal's operations, playing crucial roles in facilitating the efficient handling and transfer of containers between water and land transportation modes. Berth allocation is a critical process in the transfer of containers between vessels and the terminal. It involves assigning berthing positions and determining the number of cranes required to service each vessel within a given planning horizon (Eskafi, Kowsari, Dastgheib et al., 2021b). Efficient berth allocation is essential for ensuring timely vessel turnaround, minimizing delays, and optimizing operational costs at the terminal (Eskafi, Ulfarsson, 2022).

The layout and operation of the container yard are essential considerations in terminal planning and management. Studies have highlighted the importance of yard layout optimization, including the logical modeling of yard operations with equipment such as rubber-tired gantry cranes and trucks (Speer, Fischer, 2017). Effective yard planning not only enhances the efficiency of container handling within the yard but also improves the overall performance of the terminal handling system (Speer, Fischer, 2017). The container yard serves as a temporary storage area where containers are held before being further transported by trucks, barges, trains, or vessels (Hlali, Hammami, 2020). It is a dynamic space where containers are organized, stacked, and managed to optimize operational efficiency and facilitate the smooth flow of cargo within the terminal.

In the context of the Lekki Freeport Terminal, the simultaneous allocation of berths and quay cranes is crucial for accommodating multiple vessels and ensuring fast turnaround times for mega-containerships (Eskafi, Kowsari, Dastgheib et al., 2021a). The efficient movement of containers within the yard, from gate-in to gate-out, and between storage locations, is essential for maintaining operational efficiency and minimizing dwell times (Kerem Coşar, Demir, 2018).

The Lekki Freeport Terminal has an initial draft of 16.5 metres, with the potential for further dredging. The terminal is able to handle 2.5 million twenty-foot standard containers per year. It is strategically divided into three distinct areas: Area 1, Area 2, and Area 3, each comprising blocks labeled from A to K (letter I excluded). These areas and blocks serve specific functions momentous to the efficient handling and management of containers within the terminal.

In Area 1, Area 2, and Area 3, Blocks A and B are designated for the storage of export containers awaiting loading onto vessels, whereas Blocks C, D, and E are utilized for storing import containers received from vessels. Notably, Block F in

both Area 1 and Area 2 is reserved for reefer containers, ensuring the appropriate storage conditions for temperature-sensitive cargo.

Additionally, Blocks 1G, 2G, 3G, and 1H are dedicated to import delivery, where containers must have undergone examination by government officials and payment processing by agents before release to external trucks. Block 2H is currently used for maintenance activities, including both preventive and corrective servicing of Rubber-Tyre-Gantry (RTG) cranes. Block 3E serves a specialized role by accommodating out-of-gauge (OOG) cargo, which is prepared for delivery to external trucks or export via vessel loading. Block 3H is currently used for the seal cutting of import containers prior to inspection by relevant port authorities.

Furthermore, Areas 1J, 2J, 3J, 1K, 2K, and 3K are specifically designated for empty containers arriving from various sources such as barges, vessels, and external trucks. These areas act as temporary holding spaces for empty containers before they are processed and dispatched to external trucks or vessels for further transportation. The operational layout and allocation of these areas and blocks within Lekki Freeport Terminal align with industry best practices in container terminal management and optimization. By strategically designating spaces for different container types and cargo, the terminal can streamline operations, enhance efficiency, and ensure a seamless flow of goods.

2. Mathematical model

2.1. Background

Most contemporary container terminals stack their containers rather than storing them on chassis (Eskafi, Kowsari, Dastgheib et al., 2021b). A typical block, as shown in Figure 1, is divided into bays. In most operations, 20-foot and 40-foot containers are not mixed within the same bay: 20-foot containers occupy one bay, while 40-foot containers occupy two bays. Each slot in a bay is identified by a row letter and tier number. For example, A1 denotes the position in row A and tier 1. Row A is the row adjacent to the truck lane.

Stacking containers saves space but necessitates rehandling, which requires additional time and effort. To retrieve a container positioned at the bottom of a stack, containers above it must first be rehandled. The handling equipment discussed in this study is the Rubber-Tired Gantry (RTG) crane. The RTG cranes at Lekki Freeport Terminal (LFT) span seven rows and enable a 1-over-6 stacking operation, meaning the crane can lift one container over a stack six containers high. Figures 1 and 2 illustrate the operational process of an RTG crane within a bay. Each bay must provide adequate space for rehandling operations, adhering to the 1-over-7 stacking limit. This constraint exists because the RTG crane cannot efficiently move

containers between adjacent bays. A bay consisting of six rows and four tiers typically holds fewer than 24 containers. However, at LFT, the maximum capacity of a bay measuring seven rows by seven tiers is limited to 49 containers.

Fig. 1. Section view of the bay with RTG
Source: LFT

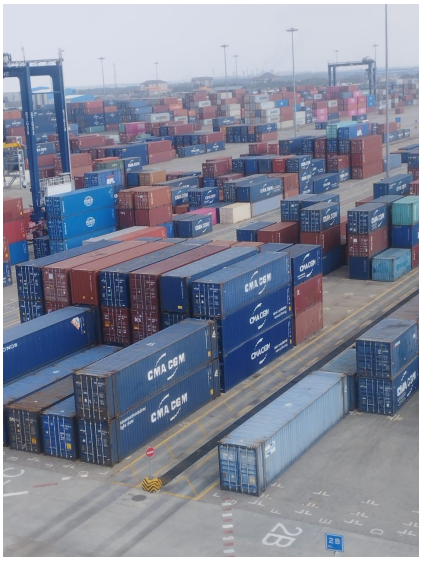

Fig. 2. Configuration of block container
Source: LFT

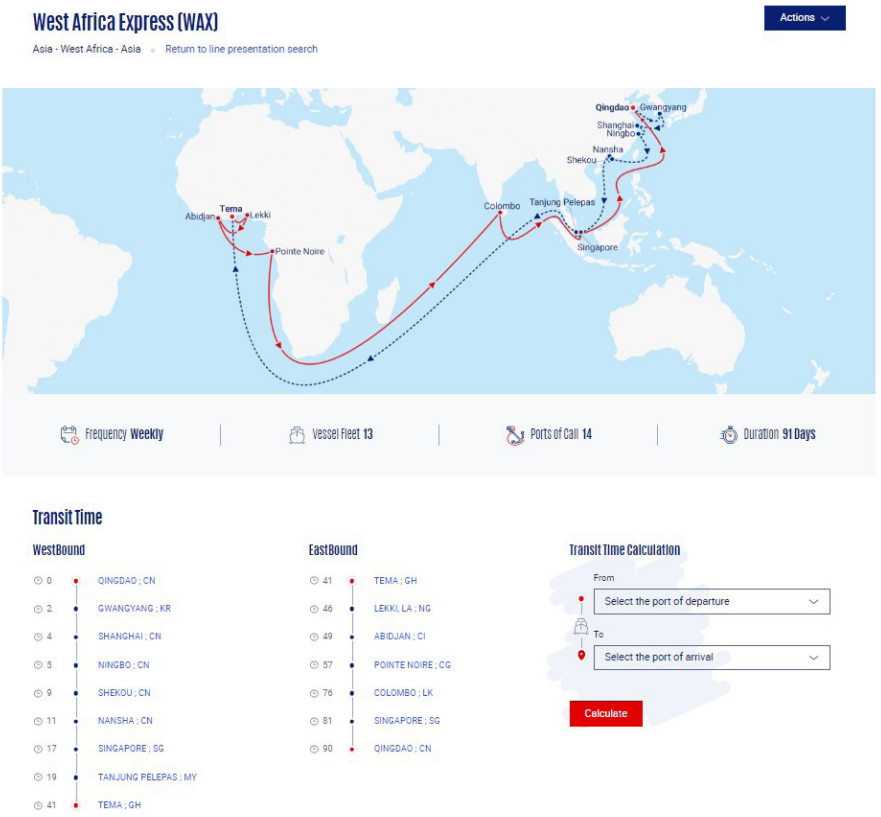

Fig. 3. CMA-CGM services
Source: https://www.cma-cgm.com/ebusiness/schedules/line-services/flyer/WAX (accessed: 10.08.2025)

2.2. Model

We introduce the model formulation and notations used to compute import throughput and describes how the MCS method is applied to estimate the number of container rehandles.

We assume that maritime carriers employ diverse liner services, S, to convey products along designated trade routes and ports. A service is required to visit a designated set of ports according to a preset pro forma, P_s, utilizing N vessels. As Figure 3 shown, the steamship company operates in the North Europe, West Africa, and Asia commerce route, scheduled to visit fourteen ports with a pro forma duration of seven days. Thirteen vessels are employed to adhere to this schedule.

It is common practice for operators to preconfigure services, vessels, and ports of call in their terminal operating systems (TOS). Assigning a voyage *i* to a vessel from service *S* is thus a vital requirement of the terminal operator in day-to-day operations. Service *S* is represented by the i_s notation for the *i*th inbound/outbound voyage. Once a voyage is assigned, the next step for the terminal operator is to specify the vessel's schedule. Information required at this stage are:

- Vessel berthing position; berth 1 or berth 2;
- Vessel estimated time of arrival (ETA);
- Vessel's estimated time of departure (ETD);
- The beginning date for receiving export containers;
- The cutoff date for receiving export containers.

Since D_s represents the time of service *S*'s initial voyage, then the departure time of the th voyage of that service can be expressed mathematically as:

$$D_i = D_s + (i_s - 1)\rho_s. \tag{2}$$

For example, if D_s for a service is *t* on day 0 and $\rho_s = 7$ days (i.e., weekly service), then the departure time of the first voyage is *t* on day 0 [$t + (1 - 1)7 = t + 0$]. Likewise, the second voyage's departure time is *t* on day 7 [$t + (2 - 1)7 = t + 7$] as well $t + 14$ and $t + 21$ for the third is *t* on day 14 and fourth is *t* on day 21 voyage's departure time respectively, and so on. Note that the notations make no distinction between vessels within a service. It is irrelevant to the terminal and customers which vessel is being used. All that matters is that service meet its pro forma. A service is designed to unload a relatively constant number of TEUs at each terminal. The volume to be unloaded is denoted as C_s^{imp}. The proportion of import containers that are delivered with dwell days after the vessel's departure is represented as $I_s^{imp}(x)$.

The cumulative number of import containers unloaded to the container yard at time *t* for all service *S* can be calculated using the following mathematical expression below. Also, the annual yard throughput for imports is $\sigma(365)$. Technically, the definition of yard throughput is TEUs per year/gross acre (National Research Council, 1986). However, in this paper, we will use the term *throughput* simply to indicate the TEUs handled per year. This is done to avoid misrepresenting a container's productivity because throughput is often reported differently and gross acre is counted differently by different terminals.

$$\sigma(t) = \sum_{s=1}^{S}\sum_{i=1}^{i_s} C_s^{imp} H(t - D_i), \tag{3}$$

where: *S* – total number of services (shipping lines) calling at the LFT,
i_s – maximum th voyage of service *S* up to time *t* (i.e., $i_s \rho_s$),
D_s – time of the very first voyage for service *S*,
ρ_s – frequency (in days) of service *S*'s voyages,

C_s^{imp} – volume of import containers unloaded during the ith voyage for service s,

H – heaviside step function, which ensures that the cumulative count only begins once the voyage occurs (i.e., it activates only when $t \geq D_i$), defined piece-wisely as:

$$H(x) = \begin{cases} 1, & x \geq 1 \\ 0, & x < 0 \end{cases}. \tag{4}$$

The equation (3) sums up all the import containers unloaded from multiple shipping services, accounting for the vessels' scheduled arrival times and their dwell time in LFT terminal. The term $H(t - (D_s + (i - 1)\rho_s))$ is a step function that essentially tracks whether the vessel has already arrived at time t. The cumulative number of unloaded containers grows as more voyages arrive at LFT terminal over time. It is essential to compute the cumulative number of delivered imports at time t for all services (S), given as:

$$\Phi(t) = \sum_{s=1}^{S} \sum_{i=1}^{i_s} C_s^{imp} I_s^{imp}\left(t - D_i\right). \tag{5}$$

Where $I_s^{imp}\left(t - D_i\right)$ is the cumulative proportion of import containers from service , delivered by time after the vessel has arrived. Equation (5) sums up the number of containers that have been delivered by truck based on their dwell time. It accounts for the time after the containers are unloaded and the process of external trucks picking up the containers from the LFT terminal.

The number of import containers in the yard at the start of day t is:

$$Y(t) = \sigma(t) - \phi(t - 1). \tag{6}$$

Assuming import containers are unloaded first before being delivered to external trucks or road trucks. Hence, the daily average stack height is:

$$\text{Stack Height}(t) = \frac{Y(t)}{I(20)}. \tag{7}$$

Where $I(20)$ is the s.

It has been stated that the container yard import throughput and storage density can be increased by stacking containers higher and/or by employing mixed storage policy. The rehandling productivity will be diminished. The expected number of rehandles (R) is:

$$\mathbb{E}[R] = \sum_{i=1}^{a} \sum_{j=1}^{h_a} P_{i,j} \cdot r_{i,j}. \tag{8}$$

Where h_a denotes the height of the stack a, P_{a,h_a} denotes the probability that a container in position (a, h_a) is selected and r_{a,h_a} is the number of rehandles required to retrieve the target container in slot (a, h_a). The above equation (8) calculates the expected number of rehandles by considering all possible locations of the target container and any interfering containers. It accounts for scenarios where no rehandling is needed (when $h_a = a$) and where multiple rehandles are required (when $a < h_a$). This allows terminal operators to understand the impact of different stacking configurations and storage policies on rehandling productivity.

Equation (8) is solved with the MSC Method. MCS is a probabilistic model that can include an element of uncertainty or randomness in its prediction: it predicts possible outcomes of an uncertain event producing different results each time. This method is used to analyse past data and predict a range of future outcomes based on a choice of action. The MCS method is used for three important reasons. First, it allows conclusions about the variance of the expected rehandles as a function of stack height and storage strategies to be made. Second, it conveniently solves ad hoc rehandling strategies. Third, it circumvents the need to assume all containers in a bay have equal probability of being selected.

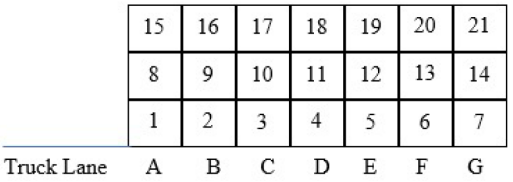

Fig. 4. Configuration of a full bay
Source: own elaboration

Table 1. Number of rehandles associated with each slot when bay is full

Tier	Stack A	Stack B	Stack C	Stack D	Stack E	Stack F	Stack G
3	0	0	0	0	0	0	0
2	2	2	2	2	2	2	2
1	4	4	4	4	4	4	4

Source: own elaboration

The above diagram depicts the current configuration of a full bay at Lekki Freeport Terminal (LFT) import delivery blocks. As a current practice, LFT leave the fourth tier upward for rehandles. This is a standing order by the present Chief Operational Officer (COO), which implies that with 1-over-6 RTG operations, spaces must be kept open from the fourth tier upward to allow the RTG to shuffle containers to access the bottom container of each stack. Also, one could consider

this as a safety rule because RTGs are not permitted to gantry with container from one bay to another. However, with time and when business picks up, there will be full utilization of each bay in the block. As a result of such instruction, whenever a bay is full and a bottom container needs to be retrieved, as shown in the above diagram, the actual number of rehandles will be determined. With Monte Carlo Simulation (MCS), this can easily be addressed by defining the associated number of rehandles for every container in the bay.

Table 1 shows how this can be accomplished. Let's assume there is full bay as shown in Figure 4 above for now and all containers are equally likely to be picked for delivery. The true expected value $E[R]$, using Equation 5, is 2.00, the expected number of rehandles per container in one row is $\frac{2}{7}$, and 0.67 as the expected number of rehandles for a pick-up of a next target container from the bay. The number of rehandles that occur on a given day can be estimated using Monte Carlo Simulation (MCS) by randomly selecting one of the 21 containers in the bay utilizing a uniform distribution. Depending on which container is selected, the associated number of rehandles is derived as illustrated in Figure 4. If, for example, the selected container is container 1 (refer to Figure 4), then the number of rehandles is 4 – before delivering 1 to the external truck: move container 15 to C4 and container 8 to B4; after delivering 2, move container 8 to A1 and container 15 to A2.

A sample size of 500 is assumed as an example. The number of rehandles for each of the 500 containers is first derived and then an average is calculated. This average would be the estimated number of rehandles for one repetition. To obtain the sample average and variance, the experiment would be repeated over many repetitions. Trial experiments show that it would take about 10,000 repetitions to provide a good estimate. Figure 5 show the MCS outcome for the expected number of rehandles when a bay is full of ad hoc rehandling strategies and equal probability of selecting a container in the bay.

Table 3 and Figure 6 demonstrate that the MCS method is a consistent estimator of the expected number of rehandles in the full bay example. A consistent estimator of a parameter is one whose sampling distribution becomes ever more tightly concentrated around the true parameter value as the sample size increases. As shown, the standard deviation decreases as the sample size increases. That is, the sample distribution becomes more tightly concentrated around the true parameter value as the sample size increases. The MCS runs were generated using Python programming language. In subsequent experiments, a sample size of 1,000 and repetition of 10,000 were used as these values were found to yield good estimates without requiring much additional computation time.

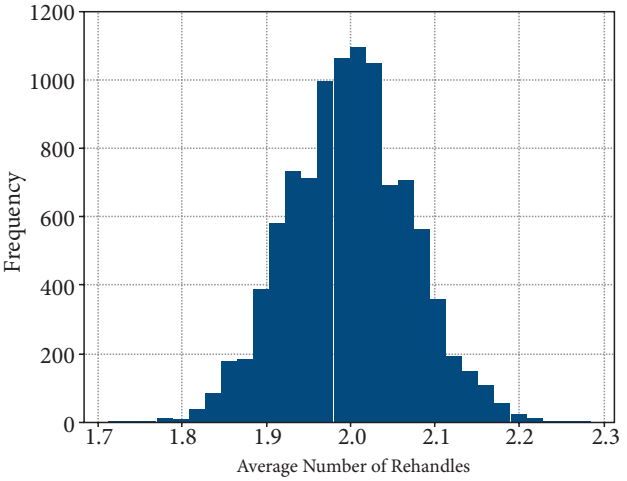

Fig. 5. Histogram of expected rehandles
Source: own elaboration

Table 2. Summary of estimated number of rehandles for a full bay

Statistical Description	Value
Average rehandles	2.0002
Standard Deviation	0.0729
Maximum	2.3000
Minimum	1.7040

Source: own elaboration

Table 3. MCS consistency results

Repetition	Sample Size	Mean Rehandles	Standard Deviation
10,000	100	2.0004	0.1648
10,000	200	1.9998	0.1165
10,000	300	1.9999	0.0941
10,000	400	1.9998	0.0814
10,000	500	2.0002	0.0723
10,000	600	1.9998	0.0668
10,000	700	2.0003	0.0622
10,000	800	1.9999	0.0573
10,000	900	2.0003	0.0539
10,000	1000	2.0001	0.0517

Source: own elaboration

3. Analysis and discussion

The analysis is carried out using the model formulated in Section 3, applied to several experiments to gain insight into the effects of container dwell time on rehandle productivity and import delivery throughput in LFT. The experiments consider one container block with 40 bays, 7 rows, and 3 tiers for a total capacity of 840 TEUs (equivalent to 420 FEUs, maximum of 21 TEUs per bay or 21 FEUs per bay). This is a typical block size at LFT. The experiments assume import containers are delivered in equal proportions. Furthermore, during delivery, the ad hoc rehandling strategy is used, where the RTG operator must make additional rehandling moves to clear slots C4 and B4 like in the above example or maintain only three tiers.

3.1. Non-mixed storage policy

This is the current policy at Lekki Freeport Terminal (LFT) for the storage of containers at the yard or the delivery blocks. The non-mixed storage policy examines the effect of dwell time on throughput and rehandle productivity. With this storage policy, once a designated area of the yard is allocated to a service for imports, that space can only be used to store one vessel's imports from that service. The next vessel's import containers cannot be stored in the designated space until all the previous vessel's containers have been delivered to external trucks. Therefore, the service call frequency (P1) is dictated by the container dwell time. The following parameters are used from the model equations above:

- 1 service: $D_1 = 0$, $C_1^{imp} = 840$ TEUs, and $I_1^{imp}(x) = \dfrac{840}{\rho_1}$,
- Dwell time dictates ρ_1. Thus, ρ_1 = dwell time,
- Vary ρ_1 (7, 14, 21, 28, 35).

Figure 7 shows the relationship between annual effective import throughput and various import dwell periods under the non-mixed storage policy. The effective throughput values were obtained using both Equation 3 and 4, which can be conveniently solved for in Python. It can be seen that the shorter the dwell time, the higher the throughput. Hence, dwell time can be considered "unproductive" since the container is not making progress toward its destination when it is waiting. Additional throughput can be achieved by simply reducing the container dwell time. In practice, dwell time cannot be completely eliminated because some amount of dwell time is expected whenever there is a change in transportation mode. For example, with imports, paperwork needs to be processed for the release of a container or if a container needs to be inspected by the National Agency for Food and Drugs Administration and Control (NAFDAC), Nigeria Customs Service, or National Drug Law Enforcement Agency (NDLEA), it cannot leave the terminal until the inspection is completed.

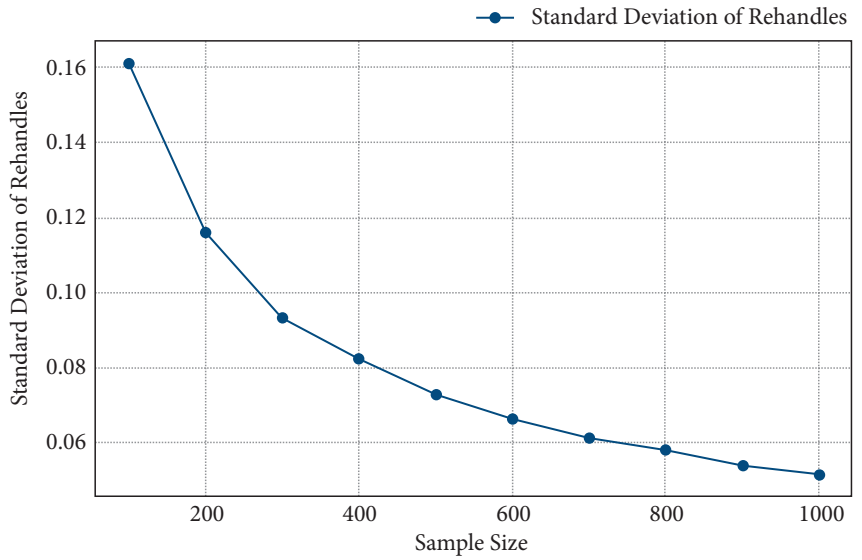

Fig. 6. Consistency of MCS Estimate
Source: own elaboration

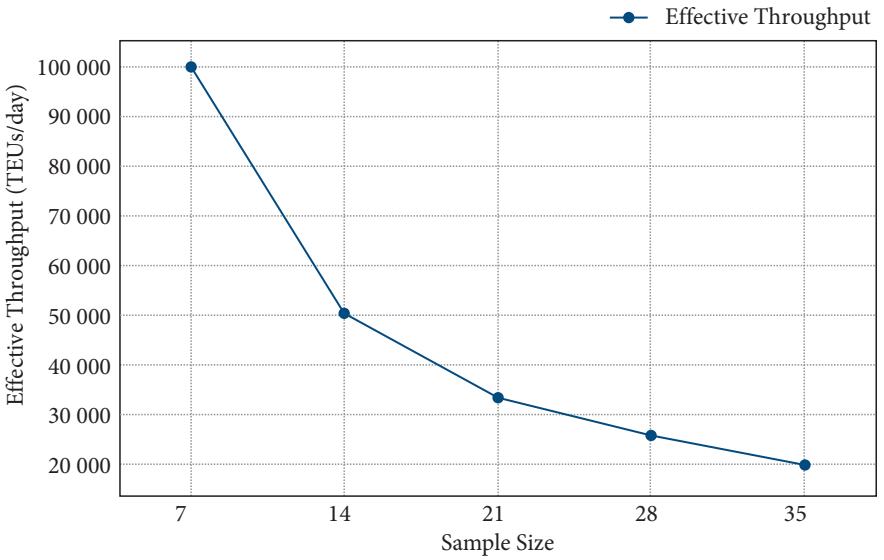

Fig. 7. Effect of dwell time on annual import throughput under non-mixed storage policy
Source: own elaboration

The motivation for employing the non-mixed storage policy is to minimize rehandling, and the following experiment examines the gain in rehandling productivity. To apply the proposed MCS method for a given stack height, a specific bay configuration must be assumed. Table 4 shows the assumed bay configurations for average stack heights ranging from 1.0 to 3.1. This work considers 3.1 to be the maximum average stack height due to the need to reserve from tier 4 upward in a bay.

Table 4. #Rehandles associated with each slot when bay is full (Varied Average Stack Heights)

Bay Configuration	Stack A	Stack B	Stack C	Stack D	Stack E	Stack F	Stack G	Avg. Stack Height
1	1	1	1	1	1	1	1	1.00
2	2	1	1	1	1	1	1	1.14
3	2	2	1	1	1	1	1	1.29
4	2	2	2	1	1	1	1	1.43
5	2	2	2	2	1	1	1	1.57
6	2	2	2	2	2	1	1	1.71
7	2	2	2	2	2	2	1	1.86
8	2	2	2	2	2	2	2	2.00
9	3	2	2	2	2	2	2	2.14
10	3	3	2	2	2	2	2	2.29
11	3	3	3	2	2	2	2	2.43
12	3	3	3	3	2	2	2	2.57
13	3	3	3	3	3	2	2	2.71
14	3	3	3	3	3	3	2	2.86
15	3	3	3	3	3	3	3	3.00

Source: own elaboration

Table 5 shows the expected number of rehandles for various average stack heights. As expected, the number of handles increases as the stack height increases. The 95% confidence interval highlights the tightness of the sample distribution. Figure 8 Illustrates the relationship between expected rehandles and average stack height under non-mixed storage policy. it shows that the rehandle increases with stack height due to the increased difficulty of accessing containers at the bottom. Beyond an average stack height of 2.5, the increase slows and rehandles slightly decrease near 3.0, suggesting possible efficiency improvements or optimal handling at higher stacks. This highlights the impact of stacking height on rehandling and the importance of optimising storage strategies to improve operational efficiency.

Table 5. Expected rehandles for various average stack heights

Bay Configuration	Avg. Stack Height	Expected Rehandle	Standard Deviation	95% Confidence Interval (Lower, Upper)
1	1.00	0	0	(0, 0)
2	1.14	0.1423	0.3494	(0.1355, 0.1491)
3	1.29	0.2829	0.4504	(0.2741, 0.2917)
4	1.43	0.4557	0.5084	(0.4453, 0.4661)
5	1.57	0.5631	0.5036	(0.5522, 0.5740)
6	1.71	0.7128	0.5231	(0.7014, 0.7242)
7	1.86	0.8321	0.5453	(0.8203, 0.8439)
8	2.00	0.9658	0.5517	(0.9535, 0.9781)
9	2.14	1.1194	0.5370	(1.1065, 1.1323)
10	2.29	1.2173	0.5505	(1.2038, 1.2308)
11	2.43	1.3162	0.5653	(1.3019, 1.3305)
12	2.57	1.3991	0.5637	(1.3843, 1.4139)
13	2.71	1.4672	0.5704	(1.4520, 1.4824)
14	2.86	1.4907	0.5704	(1.4754, 1.5059)
15	3.00	1.5045	0.5000	(1.4947, 1.5143)

Source: own elaboration

From equation 1, we can determine the re-handling productivity given as the ratio of the throughput to the total moves. It is a measure used in container terminal operations to evaluate the efficiency of container retrieval and stacking processes. Rehandling productivity also describes the ratio of useful move (i.e. container deliveries) to the total moves performed in the yard. First, it is essential to show the corresponding average stack height for the throughput shown in Figure 9 for the different dwell times. The trend in which the height of the stack decreases with increasing dwell time is identical to how the throughput decreases in Figure 7.

$$H_{\text{avg}} = \frac{T}{T_{\text{max}}} \times H_{\text{max}}. \tag{9}$$

Where H_{avg} is average stack height. It indicates how densely containers are stored, affecting rehandle requirements. T is the throughput (TEU/time unit) that measures terminal activity and drives yard occupancy and operational efficiency. T_{max} is the maximum throughput that serves as a baseline to compare and normalize other throughput values. H_{max} represents the maximum stack height useful for scaling average stack height values and the upper limit for stacking density. Figure 8 and Figure 9 are produced using Equation 1, Equation 8 and setting $H_{\text{max}} = 2.00$ may not represent a literal limit but is used as a benchmark for comparison.

In addition, the choice $H_{max} = 2.00$ is arbitrary in the sense that it simplifies scaling, providing a consistent range to compare the height of the stack in different dwell times.

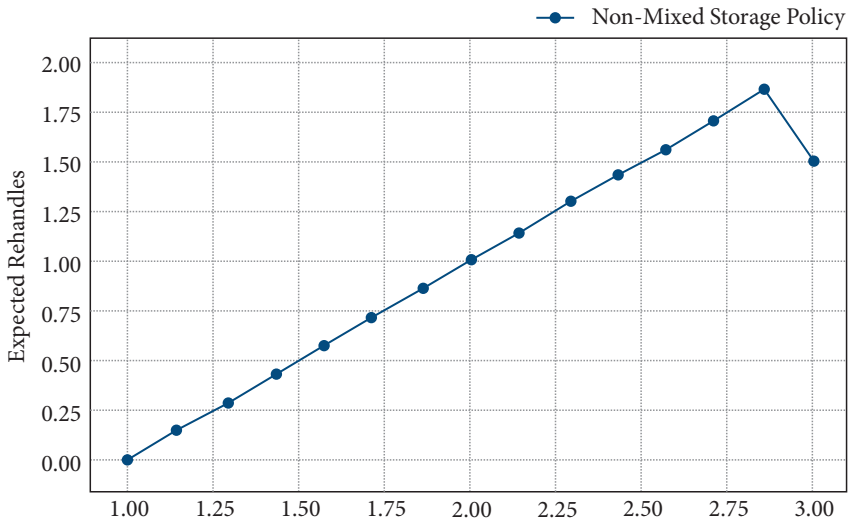

Fig. 8. Relationship between expected number of rehandles and stack height
Source: own elaboration

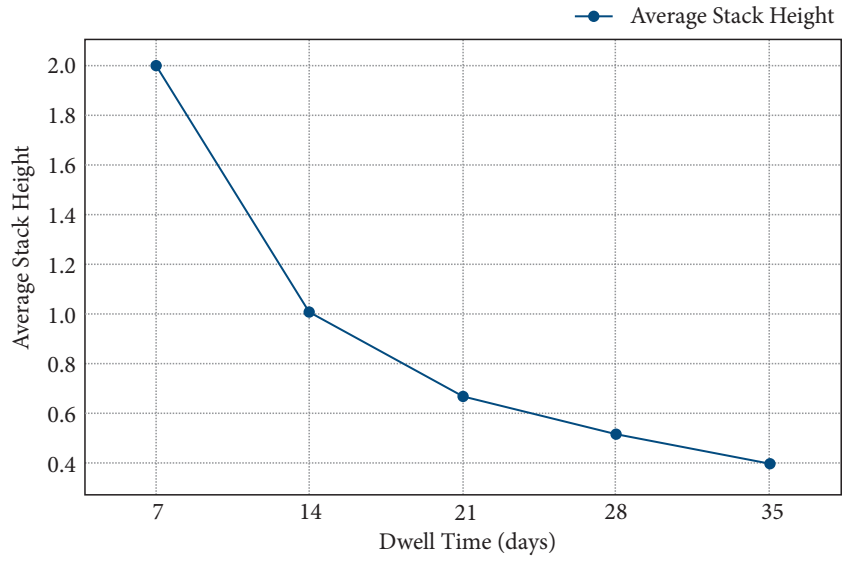

Fig. 9. Effect of dwell time on average stack height under non-mixed storage policy
Source: own elaboration

As illustrated in Figure 7, throughput declines as dwell time increases. A lower throughput results in fewer containers within the block, leading to a reduced average stack height. Figure 9 presents the average stack height corresponding to the throughput depicted in Figure 7 across various dwell times. The trend indicates that as dwell time rises, stack height similarly decreases, mirroring the reduction in throughput. For Figure 10, rehandling productivity increases linearly as dwell time increases. This indicates that longer dwell times result in more efficient rehandling processes.

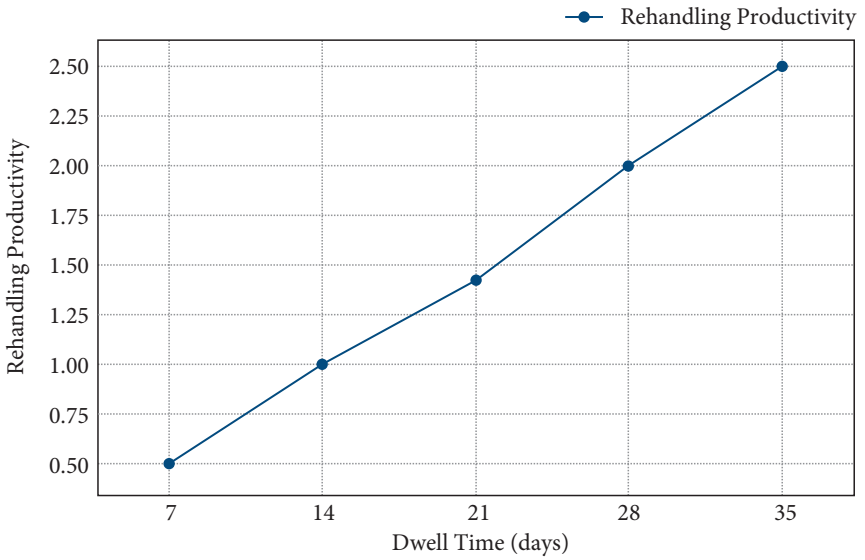

Fig. 10. Effect of dwell time on rehandling productivity under non-mixed storage policy
Source: own elaboration

3.2. Mixed storage policy

As mentioned, an alternative to increase throughput is to employ the mixed storage policy. Given the experiment parameters shown below, the second set of experiments examines the gain in throughput and loss of rehandling productivity when new imports are stacked on top of old ones:

- 2 services: $D_1 = 0$, $D_2 = 2$, and $\rho_1 = \rho_2 = 7$;
- 3 services: $D_1 = 0$, $D_2 = 2$, $D_3 = 4$, and $\rho_1 = \rho_2 = \rho_3 = 7$;
- 4 services: $D_1 = 0$, $D_2 = 2$, $D_3 = 4$, $D_4 = 6$, and $\rho_1 = \rho_2 = \rho_3 = \rho_4 = 7$;
- Varying $\rho_1 = (7, 14, 21, 28, 35)$.
- $I_s^{\text{imp}}(x) = \dfrac{C_s^{\text{imp}}}{\text{dwell time}}$, where C_s^{imp} is to be determined.

To determine how much throughput can be gained through the use of the mixed storage policy, the optimal values of C_1^{imp} (number of import containers to be unloaded off of a vessel) can be obtained by solving the following optimization problem defined as an objective function below for the decision variable C_s^{imp}, set to zero before each optimization run:

$$\max Z = \sum_s C_i^{\text{imp}} \tag{10}$$

Subject to:

- $\sigma(t) - \Phi(t) \leq 840$ TEUs, $\forall t = 1,2,...,365$;
- $C_i^{\text{imp}} \geq 0, \forall i = 1,2,...,s$.

This defined objective function aims to maximize annual terminal throughput by optimizing yard space usage, balancing multiple services, and minimizing the impact of container dwell time. It incorporates operational constraints, ensuring practical and efficient resource allocation to enhance terminal productivity. Equations 3, 5, and 10 are implemented in Python programming language, computing the solution by using the same starting point for each run/search, which is straightforward and produces the plot of the effective dwell time for the maximum annual import throughput.

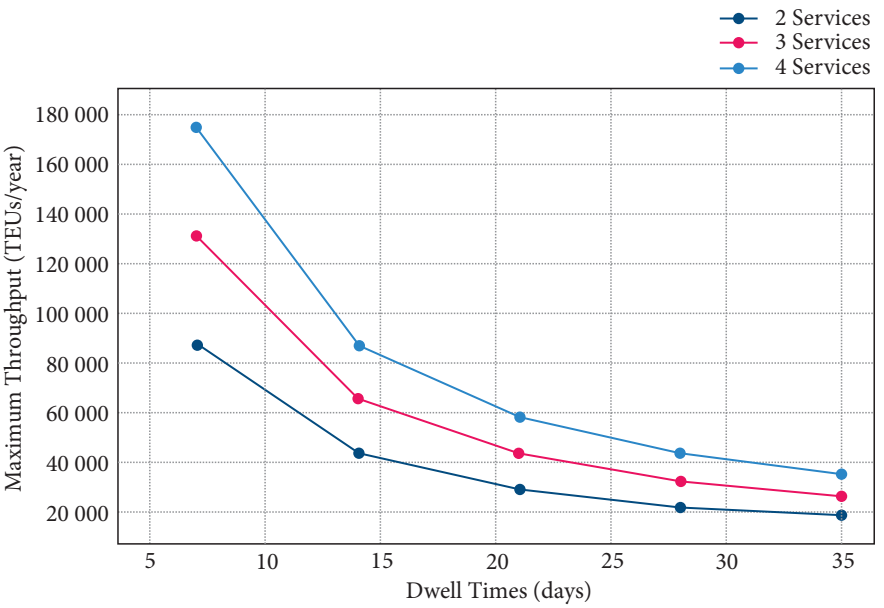

Fig. 11. Effect of dwell time on maximum annual import throughput under mixed storage policy
Source: own elaboration

Figure 11 demonstrates the interplay between container dwell time and maximum annual import throughput under mixed storage policy for different numbers of shipping services (2, 3, and 4). Across all services, increased container dwell time leads to a significant reduction in annual throughput. This decline is attributed to the accumulation of containers in the terminal, which limits space for new arrivals and hinders operational efficiency. Four services consistently achieve the highest throughput, starting around 180,000 TEUs/year at 7 days of dwell time and dropping to approximately 60,000 TEUs/year at 35 days. For two services, maximum throughput is notably lower, starting at around 50,000 TEUs/year and declining to approximately 20,000 TEUs/year. This pattern reflects the terminal's ability to handle larger volumes efficiently when servicing more shipping lines. The steepest throughput drop occurs between 7 and 21 days, where significant reductions – up to 70,000 TEUs for four services – emphasize the need to optimize dwell times during this sensitive window. Shortening dwell times, particularly for the configurations with more services, maximizes throughput and prevents yard congestion. For a terminal like Lekki Freeport Terminal, focusing on minimizing dwell times within the first 21 days offers the greatest impact on maintaining high productivity and throughput.

It is momentous to mention here that under the mixed storage policy, new import containers are stacked on top of older arrivals. Therefore, containers located at the bottom of a stack are more likely to be chosen for delivery. Let's assume that containers in tier second have twice the likelihood of being delivered compared to those in tier third. Similarly, containers in tier first are twice as likely to be delivered as those in tier second. Based on this assumption, we assign the following weights: a weight of 1 to containers in tier third ($\xi_3 = 1$), 2 to containers in tier second ($\xi_2 = 2$), and 4 to containers in tier first ($\xi_1 = 4$). It is important to note that this assumption is merely a subjective estimate of what might be typical, and there is no data to validate it. Additionally, the way terminal operating data is stored does not allow for the calculation of the number of rehandles for a container upon delivery, according to the author's understanding of the Navis system used by LFT. Alternative values could certainly be employed for analysis.

Let $P(X_{a,c})$ be the event that a container in row and tier is selected for delivery, then the probability for each tier $P(X_{a,c})$ is uniform:

$$P\left(X_{a,c}\right) = \frac{1}{H_{\text{avg}}}.$$

Where H_{avg} is the overall average stack height, and the expected rehandle (ER) is given as:

$$E_{\text{Requal}} = \sum_{c=1}^{H} P\left(X_{a,c}\right) \cdot \left(H_{\text{avg}} - c\right), \tag{11}$$

which can also be rewritten as:

$$E_{\text{Requal}} = \frac{1}{H_{\text{avg}}} \sum_{c=1}^{H} (H_{\text{avg}} - c). \tag{12}$$

However, considering the reality that some containers are more likely to be picked than others, it implies that the probability depends on the weight and will not be equal. So we have:

$$P\left(X_{a,c}\right) = \frac{\xi_c}{\sum_{i=1}^{H} \omega_i \xi_i}. \tag{13}$$

Where ω_i is the proportion of containers in tier c. The non-equal expected number of rehandles ($ER_{\text{non-equal}}$) is defined as:

$$ER_{\text{non-equal}} = \sum_{c=1}^{H} P\left(X_{a,c}\right) \cdot (H - c). \tag{14}$$

Implementing equations (10), (11), (12), and (13) in Python, the table and plot below are generated.

Table 6. Number of rehandles associated with each slot when bay is full

Bay Configuration	Average Stack Height	for Equal Probability	for Non-Equal Probability	Standard Deviation (Equal, Non-Equal)
1	1.00	0	0	(0, 0)
2	1.14	0.1228	1.9346	(0.0061, 0.0967)
3	1.29	0.2248	1.8734	(0.0112, 0.0937)
4	1.43	0.3007	1.8250	(0.0150, 0.0912)
5	1.57	0.3631	1.7782	(0.0182, 0.0889)
6	1.71	0.4152	1.7380	(0.0208, 0.0869)
7	1.86	0.4624	1.6993	(0.0231, 0.0850)
8	2.00	0.5000	1.6667	(0.0250, 0.0833)
9	2.14	0.5981	1.6287	(0.0299, 0.0814)
10	2.29	0.6900	1.5898	(0.0345, 0.0795)
11	2.43	0.7654	1.5552	(0.0383, 0.0778)
12	2.57	0.8327	1.5221	(0.0416, 0.0761)
13	2.71	0.8930	1.4905	(0.0447, 0.0745)
14	2.86	0.9510	1.4527	(0.0476, 0.0729)
15	3.00	1.000	1.4286	(0.0500, 0.0714)

Source: own elaboration

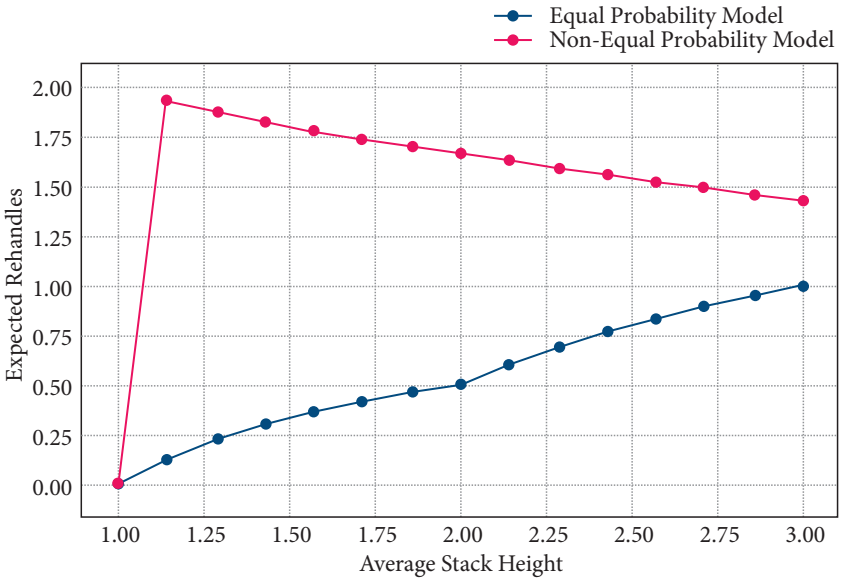

Fig. 12. Comparison of $E[R]$ with equal probability *versus* $E[R]$ with non-equal probability
Source: own elaboration

The graph in Figure 12 illustrates the relationship between expected rehandles and average stack height for the two models: Equal Probability and Non-Equal Probability. For the equal probability, rehandles increase steadily with stack height, indicating uniform container retrieval probabilities. For the non-equal probability, rehandles are highest at lower stack heights and decrease as stack height increases, reflecting prioritized retrieval of certain containers. The non-equal probability model better mirrors real-world operations, where retrieval prioritization reduces rehandling at higher stack height. Figure 13 illustrates the relationship between container dwell time (in days) and average stack height (in tiers) for a mixed storage policy across three service scenarios (2, 3, and 4 services). For all service scenarios, the average stack height increases as the container dwell time increases. This trend reflects the accumulation of containers in the storage yard over time.

For the 4 services, the stack height begins at a higher level (e.g., 2.5 tiers at 7 days) and increases more gradually compared to other scenarios. This suggests higher initial container handling intensity, reducing the impact of extended dwell times. Similarly, the 3-services stack height grows more steadily, indicating a balanced workload between container arrival and retrieval, and for the two services, stack height starts lower and increases more sharply compared to four services, showing that fewer services result in higher sensitivity to increasing dwell times. There is a minimal increase beyond 21 days for all scenarios, as the growth rate in stack height

slows down significantly after 21 days. This plateau effect implies that operational saturation is reached, or container turnover stabilizes over longer dwell periods.

Also, considering the operational implications, facilities with more services (e.g., four services) maintain better control over stack height due to frequent container retrieval. Ports with fewer services need to account for rapid stack height growth, which may lead to space constraints and reduced yard efficiency. This pattern emphasizes the importance of optimizing service frequency to manage yard congestion effectively.

Figure 14 demonstrates the relationship between container dwell time (in days) and rehandling productivity for a mixed storage policy under three service scenarios (two, third, and four services). Rehandling productivity decreases with increasing container dwell time, and the trend varies across service levels. Specifically, rehandling productivity decreases consistently as dwell time increases, reflecting the operational challenge of retrieving containers stored deeper in the stack, which requires more rehandling operations.

The impact of service count is evident: the four services scenario shows the lowest rehandling productivity throughout all dwell times, starting at 0.25 at 7 days and declining to 0.20 at 35 days. The reduced productivity is due to higher initial stack heights, which increase the likelihood of rehandling for each retrieval. Rehandling productivity for the 3 services begins at a higher value (0.40 at 7 days) compared to the 4-services scenario, but declines steadily to 0.25 at 35 days, reflecting a moderate impact of dwell time.

It is observed that 2 Services has the highest initial rehandling productivity (0.55 at 7 days), and although it also declines, it remains higher than the other scenarios across all dwell times. This reflects better operational efficiency with fewer services due to lower initial stack heights. The rate of decline in rehandling productivity slows beyond 21 days for all scenarios, suggesting that after a certain point, operational conditions stabilize, and the impact of increased dwell times diminishes.

The operational implications are clear: facilities with four services experience lower rehandling productivity due to higher initial stack congestion. This highlights the need for operational strategies, such as effective stacking policies, to mitigate the impact of frequent container arrivals and retrievals. While facilities with fewer services exhibit better productivity initially, they still need to manage the gradual decline in efficiency as dwell time increases.

This plot emphasizes the importance of balancing service frequency and yard management practices to optimize rehandling productivity.

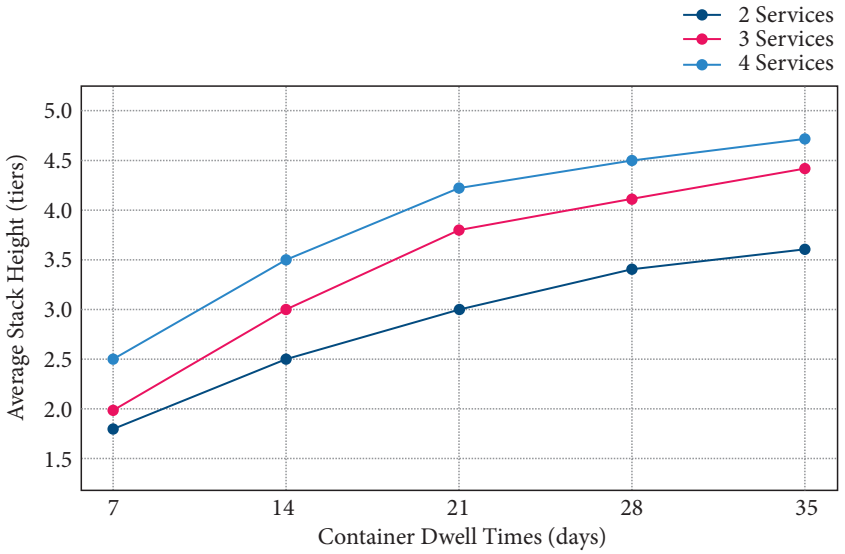

Fig. 13. Relationship between Average Stack Height and Container Dwell Time
Source: own elaboration

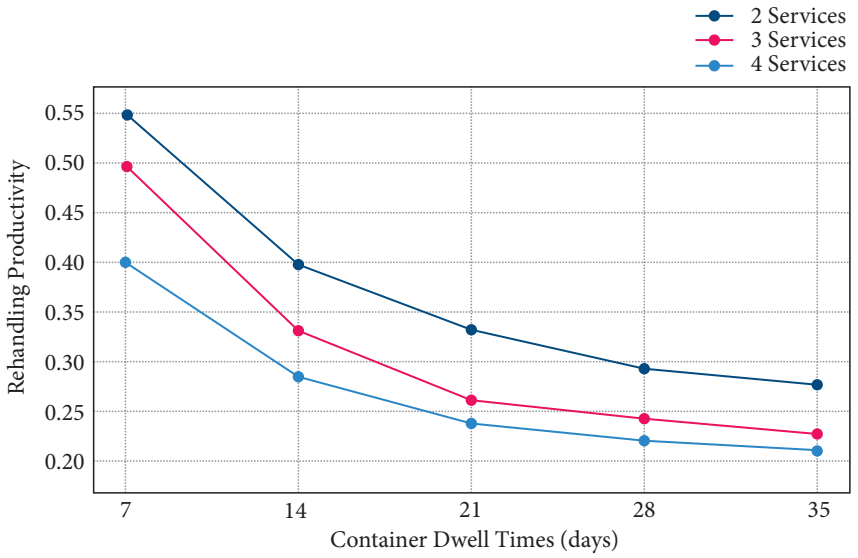

Fig. 14. Effect of dwell time on rehandling productivity
Source: own elaboration

Conclusions

This work set out to investigate how container dwell time impacts terminal throughput and rehandling productivity under different storage strategies, using mathematical modeling and Monte Carlo Simulation. The findings confirm that the objective was met: the analysis provides quantifiable insights into how dwell time reduction can improve yard operations and rehandling performance, particularly in automated terminals like Lekki Freeport Terminal.

The results demonstrate that extended dwell times lead to operational bottlenecks, resulting in reduced yard efficiency and increased rehandling requirements. This is particularly evident when analyzing rehandling under equal and non-equal probability models, where higher dwell variability amplifies inefficiencies. By improving dwell time management, terminals can achieve better throughput performance and streamline rehandling processes. Furthermore, the study demonstrates that probabilistic modeling provides valuable insights into rehandling outcomes, enabling terminals to predict and mitigate potential productivity losses. Addressing dwell time challenges is critical for enhancing container yard operations and accommodating increasing trade volumes efficiently.

Based on these findings, the following recommendations are proposed. If adopted, maritime terminals can significantly improve operational efficiency, reduce costs, and meet the demands of increasing global trade:

- **Implement Dwell Time Policies:** Terminals should adopt strict policies to incentivize timely removal of containers, such as tiered storage fees or penalties for prolonged dwell times;
- **Enhance Yard Management Systems:** Use advanced yard management technologies to monitor and predict dwell time patterns, allowing proactive resource allocation and reducing unnecessary rehandling;
- **Adopt Data-Driven Approaches:** Leverage predictive analytics and probabilistic models to anticipate rehandling requirements, optimize container placement, and minimize unnecessary moves;
- **Collaborate with Stakeholders:** Encourage collaboration with shipping lines, freight forwarders, and customs/port authorities to streamline documentation and clearance processes, reducing delays and overall dwell times;
- **Continuous Monitoring:** Establish performance metrics and continuous monitoring systems to measure the effectiveness of dwell time reduction strategies and their impact on throughput and productivity.

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