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From Efficiency to Safety: A Simulation-Based Framework for Evaluating Empty-Container Terminal Layouts

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Abstract

Empty container depot (ECD) design significantly impacts maritime terminal efficiency, yet traditional evaluation approaches assess limited operational factors, constraining comprehensive performance optimization. This study develops an integrated discrete event simulation (DES) framework that simultaneously evaluates lifting equipment utilization, truck turnaround times, and potential collisions to support terminal decision-making. This study combines operational efficiency metrics with safety analytics for non-automated ECDs using Top Lifters and Reach Stackers. Additionally, a regression analysis examines efficiency metrics' effect on safety risk. A case study at a Chilean multipurpose terminal reveals performance trade-offs between indicators under different operational scenarios, identifying substantial efficiency disparities between dry and refrigerated container operations. An analysis of four distinct collision zones with varying historical risk profiles showed the gate area had the highest potential collisions and a strong regression correlation with efficiency metrics. Similar models showed a poor fit in other conflict zones, evidencing the necessity for dedicated safety indicators complementing traditional measures. This integrated approach quantifies interdependencies between safety and efficiency metrics, helping terminal managers optimize layouts, expose traditional metric limitations, and reduce safety risks in space-constrained maritime terminals.



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Keywords: container terminal; truck turnaround time; equipment productivity; congestion; yard layout; safety; vehicles collision; performance indicators; simulation

1. Introduction

Maritime terminals function as critical nodes in the global supply chain infrastructure, serving as essential interfaces between maritime and land-based transportation networks. Currently, maritime terminals need to optimize operational efficiency while maintaining service quality due to the expected increase in maritime traffic [1].

Container yards are a key component of mid-size and small maritime terminals, often divided into separate sections for full (FCDs) and empty container depots (ECDs). Optimizing operations in both sections is critical for terminal efficiency, yet ECDs pose unique challenges due to their specific workflows and high space demands [2]. These challenges are further exacerbated by the growing constraints and competition in port environments [3,4]. While the yard layout directly influences terminal performance [5], the design and evaluation of ECDs remain understudied in the literature [6].

Traditional container yard layout design and evaluation predominantly employ mathematical modeling, simulation, and analytical methods, with a strong focus on operational

metrics such as efficiency, throughput capacity, cost, equipment utilization, and energy consumption [5–9]. Although safety considerations are often acknowledged in broader terminal design principles, existing quantitative evaluation models systematically exclude safety as a measurable performance criterion. This omission is critical: while studies analyze many factors, they fail to account for the inherent trade-offs between efficiency and safety, particularly in high-risk areas such as congested intersections or overlapping equipment pathways, and in non-automated terminals where the use of equipment such as Top Lifters and Reach Stackers to accommodate containers is considered.

This systematic exclusion of safety metrics from quantitative evaluations represents a significant methodological limitation, as it precludes a comprehensive assessment of how layout configurations simultaneously affect both operational performance and workplace safety outcomes.

This study develops an integrated evaluation framework employing discrete event simulation (DES) to assess empty container yard layouts across three critical dimensions: truck service level, resource utilization, and safety parameters. Unlike conventional approaches that evaluate these dimensions separately, our framework combines them within a unified analytical structure, enabling explicit quantification of their interdependencies. The framework's novelty lies in the three metrics system shown in Figure 1:

- **Truck Turnaround Time (TTT):** Measures throughput efficiency via the average duration trucks spend in the depot.
- **Distance Covered by lifting equipment (DCLE):** Quantifies equipment utilization through total travel distance per lifting equipment.
- **Number of Potential Collisions (NPCs):** Introduces a novel safety metric by counting simultaneous vehicle presence at high-risk intersections.

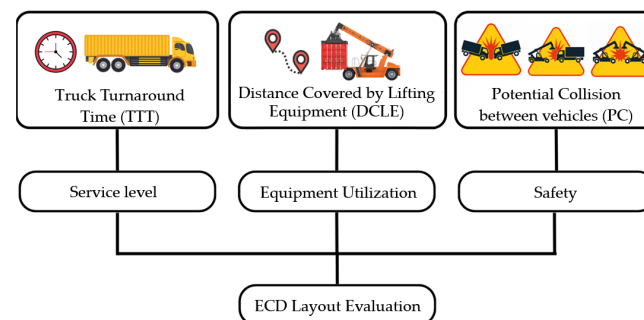


Figure 1. Key indicators—multidimensional framework for ECD evaluation.

To validate the proposed framework, we conducted a case study at a non-automated multipurpose terminal in Chile handling substantial empty container volumes. The terminal exemplifies real-world complexities: (1) specialized workflows, (2) bottlenecks in specific zones, (3) equipment coordination inefficiencies, and (4) high-risk intersections with documented incidents.

The case study goes beyond theoretical validation by demonstrating how the framework identifies and quantifies spatial-risk relationships. Specifically, it investigates whether truck arrival frequency significantly affects collision risks at dangerous intersections, examines how operational conditions influence potential collisions, determines whether extended truck turnaround times increase collision probability, and evaluates whether lifting equipment travel distances amplify collision risk through increased operational interference. Additionally, this study assesses whether traditional efficiency indicators (TTT and DCLE) can serve as safety predictors for potential collisions at critical intersections. Through scenario analysis, this research provides managerial insights to optimize

layout configurations that balance operational efficiency with safety performance in space-constrained maritime environments.

This paper is structured as follows: Section 2 presents the background in design and evaluation of yard layouts; Section 3 presents the methods; Section 4 details the case study; Section 5 explains the simulation model development; Section 6 shows the main results and some managerial insights, and Section 7 presents the main conclusions.

2. Literature Review

This literature review is specifically limited to articles that address layout design and evaluation in maritime terminals using simulation, analytical methods, and optimization approaches. Other articles associated with maritime terminals that do not address these specific issues are not considered in the review scope.

Researchers have conducted extensive research on container terminal layout optimization, focusing on yard configurations, equipment efficiency, and throughput maximization. The research mainly focuses on Automated Container Terminals (ACTs) [10,11]. Carlo et al. [12] differentiated between overall terminal layouts (which optimize the general arrangement of yards and gates) and block-level designs (which focus on stacking patterns and crane deployment within storage blocks). However, most studies concentrate on general yard management in maritime terminals [5], few have examined ECD-specific layouts [13], leaving a gap in research on ECDs. A general focus on truck services and equipment utilization is present in the literature; however, safety considerations are absent. This section summarizes key studies on container terminal layout design and evaluation, categorizing them by methodology, performance metrics, layout type (overall/block), terminal type, and equipment used.

As summarized in Table 1, most studies use a simulation-based approach to analyze container terminal performance, typically through operational indicators such as equipment utilization and truck turnaround times, which are closely linked to the overall container throughput [14–16]. In Carboni et al. [17], the environmental impact of operations is also considered through an emission-based indicator, while Sriphrabu & Chammanlor [18] include employee utilization as part of their performance metrics.

A smaller set of studies use optimization or analytical models [7,19–21] to deal with container storage allocation and resource planning problems. Despite the methodological diversity, most studies focus on full-container terminals and assume the use of gantry-based systems, including yard and quay cranes. While some papers consider a detailed modeling of vehicle movements and queueing [21], they often omit operational variability caused by traffic conflicts at intersections or interactions between vehicle flows and non-automated equipment. A notable exception is the hybrid traffic simulation framework proposed by Li et al. [22], which uses traffic-flow modeling and discrete event simulation to evaluate port planning and congestion at intersections. The model features dynamic layout configurations and a vertex coloring algorithm for handling intersection conflicts and offers a more realistic representation of traffic conditions within the port. However, this study is performed in the context of multipurpose terminals and does not address the specific characteristics of container handling systems (the reason why it is not considered in Table 1). Its relevance lies in demonstrating the feasibility and value of incorporating detailed traffic interactions, an aspect generally overlooked in the container terminal literature.

Another pattern observed in the reviewed studies is their emphasis on productivity-oriented performance indicators, mainly related to equipment and vehicle operations. Performance indicators such as crane utilization, container handling rate, and travel distances are the most common evaluation criteria (e.g., [13,16]). Although some studies include indicators related to vehicle flow efficiency (e.g., truck turnaround time), none of

them consider safety-related performance, despite the operational complexity and congestion risks in terminal yards. Moreover, only a few papers analyze layouts involving mobile lifting cranes or explore the specific operational constraints of empty container depots (ECDs), with the exception of Karakaya et al. [13], whose focus remains on aggregated yard performance.

Our work addresses these limitations by incorporating safety performance as a formal evaluation criterion alongside traditional productivity indicators. It also distinguishes from most studies by focusing on ECD operations, which involve different flow patterns and equipment behavior compared to full-container terminals. Unlike previous studies that rely exclusively on gantry-based systems, this study models operations involving mobile lifting cranes. This work addresses these limitations by incorporating safety performance as a formal evaluation criterion alongside traditional productivity metrics. It further distinguishes itself by focusing on ECD operations, which involve different flow patterns and equipment behavior compared to full-container terminals. Unlike previous studies that rely exclusively on gantry-based systems, this study models operations involving mobile lifting equipment (Top Lifters and Reach Stackers), a more typical ECD configuration in multipurpose settings. All these elements contribute to a more comprehensive assessment of terminal layout alternatives and their impact on both operational efficiency and safety outcomes.

Table 1. Summary of literature review on layout design and evaluation in maritime terminals.

Reference	Modeling Approach			Case Study	Container Type		Equipment		Indicators		
	Simulation	Analytical Methods	Optimization		Full	Empty	Gantry-Based Systems	Mobile Lifting	Vehicle	Equipment	Security
Abu Aisha et al. (2020) [23]			✓	✓	✓	✓	✓		✓	✓	
Carboni et al. (2024) [17]	✓			✓	✓		✓	✓	✓	✓	
Colak et al. (2018) [24]	✓			✓	✓		✓			✓	
Karakaya et al. (2022) [13]		✓		✓		✓		✓		✓	
Kemme (2012) [25]	✓				✓		✓			✓	
Kim et al. (2008) [26]		✓			✓		✓		✓	✓	
Kuznetsov et al. (2018) [14]	✓				✓	✓			✓	✓	
Lee et al. (2018) [6]		✓	✓		✓		✓		✓	✓	
Liu et al. (2004) [27]	✓			✓	✓		✓		✓	✓	
Lee & Kim (2010a) [28]	✓	✓			✓		✓			✓	
Lee & Kim (2010b) [29]		✓			✓		✓			✓	
Lee & Kim (2013) [30]		✓			✓				✓	✓	
Petering (2009) [31]	✓				✓		✓			✓	
Petering & Murty (2009) [32]	✓				✓		✓			✓	
Roy & Koster (2020) [33]	✓	✓			✓		✓		✓	✓	
Sriphrabu & Chammanlor (2020) [18]	✓			✓	✓	✓		✓	✓		
Srisurin et al. (2022) [15]	✓			✓	✓	✓	✓	✓	✓	✓	
Sun et al. (2012) [16]	✓			✓	✓	✓	✓		✓	✓	
Taner et al. (2014) [34]	✓				✓		✓			✓	
Wiese et al. (2010) [20]			✓		✓		✓		✓	✓	
Wiese et al. (2011) [19]		✓			✓	✓	✓		✓	✓	
Wiese et al. (2013) [7]		✓			✓			✓		✓	
Zhou et al. (2016) [21]	✓		✓	✓	✓		✓		✓	✓	
This work	✓			✓		✓		✓	✓	✓	✓

(✓) to indicate presence and blank spaces to indicate absence.

3. Methods

This project employs a comprehensive methodology to analyze and enhance ECD operations adapted from the framework proposed by Law & Kelton [35]. The approach centers on simulation-based analysis while integrating iterative feedback loops between phases. The main steps are process documentation; operational flows definition; data gathering and analysis; simulation model development; experimental design; and results analysis.

This section describes the steps of Law and Kelton's framework to analyze the interplay between truck arrival frequencies and operational conditions with truck turnaround times, distances covered by lifting equipment, and the number of potential collisions in ECD settings.

3.1. The Case Study: Process Documentation, Operational Flows Definition, and Data Gathering

Over two months, data was collected through regular terminal visits, including direct observation, interviews with depot supervisors and first-line operators, and systematic field notes on operational processes. Documentation and analysis covered all primary procedures associated with container services, lifting equipment utilization, and truck management. The thorough documentation allowed us to extract detailed process descriptions, capacity specifications, and operational decision logics.

Building upon this foundational data collection, detailed insights were captured into how trucks and containers moved through the depot, from entrance until departure, revealing variations in workflow logic. Iterative adjustments were made by revisiting the process documentation phase to clarify ambiguities and refine flow definitions. Finally, flowcharts were developed to improve visual comprehension of these complex processes.

Complementing the observational approach, additional data was gathered through field visits, internal datasets, and direct observation samples. The terminal provided access to the Terminal Operating System (TOS) and databases containing historical operational information, which facilitated timing process durations and measuring vehicle driving speeds.

Following data collection, we perform an exploratory data analysis (EDA) to uncover key operational patterns and establish baseline performance metrics that would inform subsequent analysis phases. Kolmogorov–Smirnov (KS) tests were employed to evaluate the appropriateness of the statistical distributions modeling inter-arrival and process times.

A case study description that contains the documentation process, operational flows definition, and data gathering is presented in Section 4.

3.2. Simulation Model Development and Experimental Design

The simulation model development involved creating a simulation model to replicate the depot's layout, workflows, and constraints using Simio version 15 [36]. The process began by analyzing the depot's physical structure, including storage blocks, processing areas, street networks, and collision-prone intersections. Work shift definitions were incorporated to account for varying operational schedules that influence lifting equipment availability and workflow efficiency.

Additionally, qualitative validation was conducted by yard operations and quality improvement teams through comparison of simulation outcomes with real-world performance trends. Identified discrepancies prompted iterative revisits to previous development phases, minimizing gaps between real and simulated systems while enhancing overall model robustness.

To evaluate depot operational performance, three key performance indicators were established based on critical operational challenges identified during field study. These

metrics enabled a comprehensive performance assessment and supported data-driven decision-making processes. The performance indicators are defined as follows:

- **Truck Turnaround Time (TTT):** Average time spent by trucks in the depot, categorized by type k . The truck types are defined in Section 4.2. Consider that n_k is the set of trucks of type k . Additionally, $T_{\text{entry},i}$ and $T_{\text{exit},i}$ are the arrival and departure time of truck $i \in n_k$. The TTT is as follows:

$$TTT_k = \frac{1}{|n_k|} \sum_{i \in n_k} (T_{\text{exit},i} - T_{\text{entry},i}) \quad (1)$$

- **Distance covered by lifting equipment (DCLE):** Total distance covered by each lifting equipment j during operations. Consider $m \in M_j$ is an equipment move, where M_j is the set of movements performed by equipment j . Also, d_m is the distance traveled in the move m . The DCLE is as follows:

$$DCLE_j = \sum_{m \in M_j} d_m \quad (2)$$

- **Number of potential collisions (PCs):** A counter of potential collisions in high-risk intersections S throughout the simulation period T . A potential collision event occurs when the number of vehicles or lifting equipment $N_{s,t}$ is greater or equal to two, and then simultaneously occupy the same intersection space $s \in S$ during time period $t \in T$, creating a safety hazard. This metric quantifies the frequency of such occurrences in a specific intersection s during the entire T operational periods using a binary indicator function I that captures when the collision condition is met. The PCs are defined as follows:

$$PC_s = \sum_{t \in T} I(N_{s,t} \geq 2) \quad (3)$$

Potential collisions (PCs) represent a metric not commonly addressed in the existing literature on layout evaluation for maritime terminals. While traditional studies focus primarily on metrics such as TTT and DCLE, the PC indicator introduces a safety-oriented perspective that has been largely overlooked in terminal operational assessments. The potential collision sites were determined based on historical conflictive points identified from the company's operational records and incident reports.

Six scenarios, based on the simulation model, were designed to evaluate this safety metric and traditional performance measures under different operational conditions at the depot. Specifically, these scenarios systematically combined different truck arrival frequencies with varying operational conditions (reefer-to-total container ratio). Through this systematic parameter alteration, this study aims to provide insights into the dynamics of key performance indicators and identify areas for potential improvement. Each simulation run spanned one day of operations, with 30 replications.

The parameterization of these scenarios relied on two complementary datasets documenting 2023 container operations: Dataset 1 provided monthly aggregate data on capacity utilization and damaged container proportions, offering reefer-specific insights (45% of containers were reefer units) but lacking operational detail. Dataset 2 captured detailed daily movements of dry and combined containers without storage location information. Together, they enabled comprehensive analysis across different temporal and operational scales.

Subsequently, drawing from this empirical foundation, truck arrivals were segmented into three categories (high-, regular, and low-frequency arrivals) based on terciles from daily movements, while reefer-to-total container ratios were defined at low and high levels corresponding to minimum and maximum monthly ratios from 2023 data.

Finally, a detailed overview of the simulation model development and experimental scenarios is presented in Section 5.

3.3. Analytical Framework for the Results Analysis

The results analysis employs a structured analytical framework to examine simulation outcomes and derive actionable insights for operational enhancement. The method integrates quantitative statistical evaluation with qualitative contextual interpretation. Numerical data analysis and visualization techniques identify trends and variations across experimental scenarios, while contextual evaluation provides a theoretical grounding for observed patterns and their operational implications.

Statistical significance testing is conducted using ANOVA to evaluate mean differences between scenario groups, enabling robust comparison of performance indicators across different operational conditions. This approach addresses whether truck arrival frequency significantly affects collision risks at dangerous intersections and examines how operational conditions, such as reefer-to-dry container proportions, influence potential collisions.

Poisson regression analysis is performed to investigate the effect of TTT and DCLE on the number of potential collisions. The analysis examines whether extended truck turnaround times and enlarged lifting equipment travel distances increase collision risks. Also, it explores if traditional efficiency indicators can serve as reliable safety predictors for collision estimation at critical intersections. The models are constructed based on a backward elimination as feature selection technique using p -values. Model fit is assessed using McFadden's pseudo R-squared [37] to evaluate the explanatory power of efficiency metrics in predicting collision occurrence patterns.

This comprehensive analytical approach enables the identification of operational bottlenecks and efficiency enhancement opportunities, transforming simulation data into practical insights for ECD evaluation.

4. A Case Study in a Multipurpose Maritime Terminal

This study examines a multipurpose maritime terminal in southern Chile that serves as a critical hub for regional industrial development, handling significant volumes of empty containers primarily for pulp wood consolidation and international trade.

The terminal's ECD faces three major operational challenges. First, structural limitations from separate processing zones create bottlenecks and container flow disruptions, causing queues that extend into access roads. Second, coordination difficulties arise as Reach Stackers and Top Lifters operate across multiple areas, resulting in increased idle time and excessive travel distances. Third, critical safety concerns stem from dangerous intersections with poor visibility that increase accident risks between trucks and lifting equipment problems underscored by previous collision incidents.

4.1. Documentation Process

The depot's operational framework encompasses three primary simulation elements that interact to drive facility activities: (1) Trucks: dynamic entities that flow through the system to deliver or collect containers, while also acting as spatial resources that occupy physical space and create movement constraints affecting efficiency and safety. (2) Containers: primary entities being processed, including 1 and 2 TEU dry containers and 2 TEU reefer containers, each with specific attributes determining processing requirements, storage locations, and handling procedures. (3) Lifting Equipment: mobile resources providing dual functionality—processing capacity for container operations and spatial occupation requiring coordinated movement. Reach Stackers and Top Lifters each have

specific operational capabilities and constraints that must be managed to prevent conflicts and ensure safe, efficient operations across the depot.

The container terminal features nine storage blocks with distinct capacities and purposes. Figure 2 shows the main storage and service yard sections. Five blocks handle operative dry containers: B1 with 702 TEU capacity, B2 with 605 TEU, B3 with 455 TEU, B4 with 480 TEU, and Block A1 with 820 TEU capacity. The remaining blocks serve specialized functions, including B5 for non-operative dry containers (320 TEU), B6 for both non-operative dry and reefer containers (460 TEU), B7 for mixed operative and non-operative reefer containers (550 TEU), and A2 exclusively for operative reefer containers (820 TEU). Additionally, the depot operates a workshop zone for damaged units, a washing zone for cleaning preparation, a pre-trip inspection (PTI) for reefer containers for potential repairs and malfunctioning refrigeration units, and the gate where drivers present withdrawal documentation and receive container location instructions. Also, collision risk areas were identified using historical conflict points from company operational records and incident reports (red points in Figure 2).

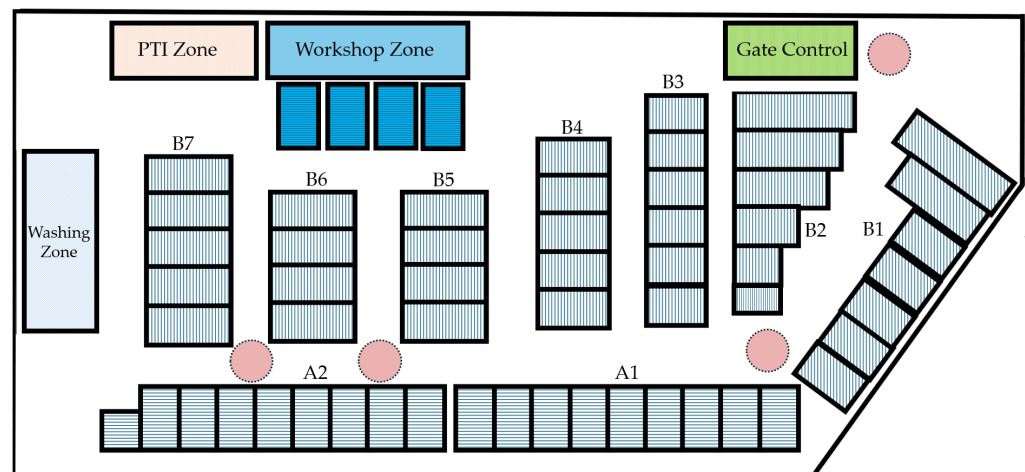


Figure 2. Empty container yard layout.

A brief description of each zone in an ECD is as follows:

- Gate Control zone: Manages truck flow and container verification. Documentation processing (Gate-in) handles the exchange between drivers and depot personnel where drivers present withdrawal documentation and receive location instructions, operating with single-truck capacity and variable processing times depending on truck origin. Container assessment (Inspection) conducts visual evaluations to identify structural damage while containers remain mounted on trucks, accommodating two trucks simultaneously with consistent processing durations regardless of origin. Administrative validation (Gate-Out) confirms loaded container accuracy and destination verification before departure, processing one truck at a time.
- Workshop and PTI zone: The depot operates two specialized processing zones for container maintenance and preparation. The Workshop zone handles structural damage repairs identified during inspection (Workshop Repair), accommodating 48 containers in four lines of 12 each, with maximum two lines processing concurrently following sequential inside-out arrangements for repairs ranging from minor replacements to extensive reconstructions. The Pre-Trip Inspection (PTI) zone exclusively manages reefer container refrigeration systems through multiple non-sequential processes: automated technical inspections (PTIs) of 44 containers in four lines of 11 each with simultaneous 4 h processing; flexible repair operations (PTI Repair) for malfunctions with ideal

capacity of four containers based on workforce availability; and manual temperature parameter setup (PTI Set Up) involving technical workers and truck drivers connecting units to truck generators, processing one container at a time in arrival order.

- Washing zone: Prepares container interiors for clean cargo consolidation through water washing, adhesive removal, and odor elimination. The area accommodates 36 containers in four lines (three for reefer, one for dry), processing one line at a time with two containers simultaneously, beginning once four containers are arranged and maintaining safety gaps during operations.
- Block zone: Manages container handling and storage operations through lifting equipment and truck coordination. Container transfer operations (Truck Loading and Unloading) involve coupling or decoupling containers from trucks, with operators receiving precise instructions for truck identification and container destinations, processing one truck at a time while vehicles remain in designated spots. Storage management operations (Container Stacking and Unstacking) control container movement within the depot using lifting equipment for placement into designated storage blocks or processing areas and retrieval for removal or further handling, with each equipment handling one container at a time according to specific placement or retrieval instructions.
- The depot operations are supported by four specialized pieces of lifting equipment, each assigned to specific operational zones and container types. Lifting equipment 1 and 2 (LE1 and LE2, respectively) are responsible for handling dry containers, performing essential tasks such as truck loading and unloading operations alongside container stacking and unstacking activities within the dry area. Lifting equipment 3 (LE3) is dedicated exclusively to container maneuvers in the Workshop and PTI Areas, focusing solely on stacking and unstacking operations to support repair and inspection processes. Lifting equipment 4 (LE4) manages container operations in the Reefer and Washing Areas, handling both the reception and dispatch of refrigerated containers as well as performing specialized maneuvers at the washing station, including truck loading and unloading and container stacking and unstacking operations.

Lifting equipment operations follow established priority hierarchies to optimize efficiency and prevent bottlenecks. LE3 prioritizes arranging lines over picking up containers to maximize production efficiency by keeping operators continuously engaged, with Workshop and PTI priorities alternated to prevent exclusive occupation of one busy area. Lifting equipment 4 (LE4) in the Washing and Reefer Areas prioritizes truck operations (loading/unloading) above arranging and picking up washing lines to prevent queue formation and bottlenecks within the depot's street network, as truck processing delays could compromise overall site performance by blocking access to storage blocks and processing areas.

The depot operates two daily shifts (8:10 a.m.–3:30 p.m. and 3:40 p.m.–10:45 p.m.) with operational constraints due to residential proximity. Reefer operations must cease by 8:00 p.m. for noise reduction, affecting lifting equipment for Workshop, PTI, Washing, and Reefer dispatching that work continuously during the second shift until 8:00 p.m. without standard breaks, while Gate, Inspection, Gate-Out, and dry sector operations maintain full two-shift schedules. Truck arrivals halt 20 min before breaks (11:20 a.m., 6:50 p.m. for reefers, 7:50 p.m. for dry containers), creating active arrival windows of 705 min for dry containers and 550 min for reefers. Contractor operations follow distinct schedules with Workshop repairs operating 8:00 a.m.–1:00 p.m. and 2:00 p.m.–5:00 p.m., and Washing extending until 11:00 p.m. due to minimal noise generation, though lifting equipment serving contractor areas maintain depot standard schedules to ensure operational continuity within the 8:00 p.m. constraint.

4.2. Operational Flows Definition

The operational flow within the ECD follows distinct pathways depending on container type and operational purpose. These flows encompass the complete lifecycle of containers from arrival to departure, including all intermediate processing steps required to ensure containers meet operational standards before dispatch. The following subsection details the specific operational flows for dry containers, reefer containers, container returns, and container requests, highlighting the sequential processes and LE-facilitated movements that characterize depot operations.

As depicted in Figure 3, the dry container flow begins with the container's arrival at the depot on a truck, followed by inspection. After waiting for lifting equipment availability, the container is unloaded from the truck and stacked in a storage block. Depending on its condition and specific requirements (such as structural repair or washing), the container is placed in either an operational or non-operational block. Once all necessary procedures are completed, the container is stacked in an operational block. Based on a request from an external or internal client, the container is unstacked, loaded onto a truck, processed through Gate-Out procedures, and exits the depot. All container movements between storage blocks and processing areas are carried out by lifting equipment.

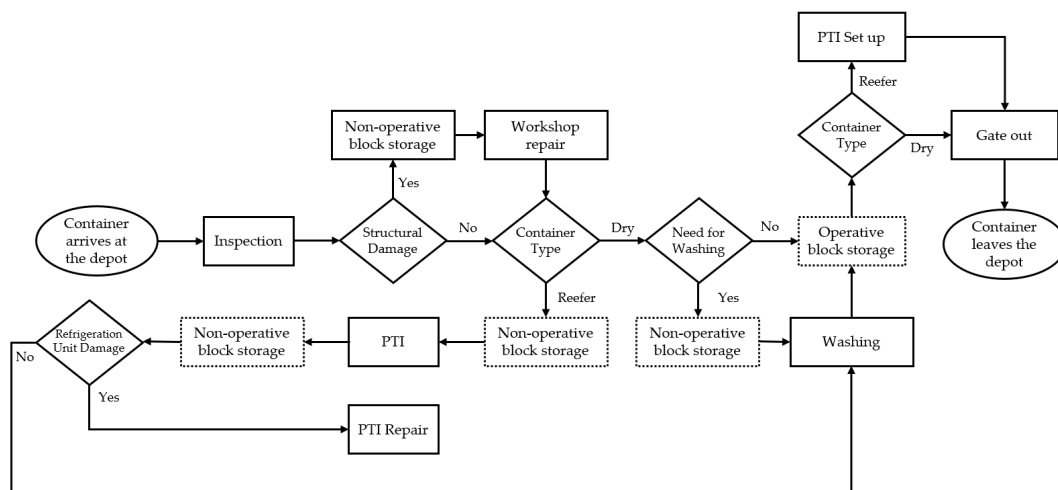


Figure 3. Container flowchart—dry and reefer.

The reefer container flow, detailed in Figure 3, involves additional steps compared to dry containers. After initial inspection, the container is unloaded and stacked in a non-operational block. Any necessary structural repairs are conducted at the Workshop, after which the container is placed in a non-operational block while awaiting Pre-Trip Inspection (PTI) and mandatory washing. If PTI reveals refrigeration unit damage, the container returns to the PTI line for repairs. Once PTI and any required repairs are completed, the container moves to a non-operational block while awaiting washing. After washing completion, the container is stacked in an operative block. Based on a request from an external or internal client the container is unstacked and loaded onto a truck. Before departing, the refrigeration unit is set to the required temperature, and the container passes through Gate-Out procedures before exiting the depot. All container movements between storage blocks and processing areas are carried out by lifting equipment.

As illustrated in Figure 4, the returning container flow begins with trucks entering the depot, where structural inspection is performed while containers remain mounted. Trucks then proceed to assigned storage blocks and wait for lifting equipment to unload containers. Once unloaded, trucks exit the depot without requiring additional procedures.

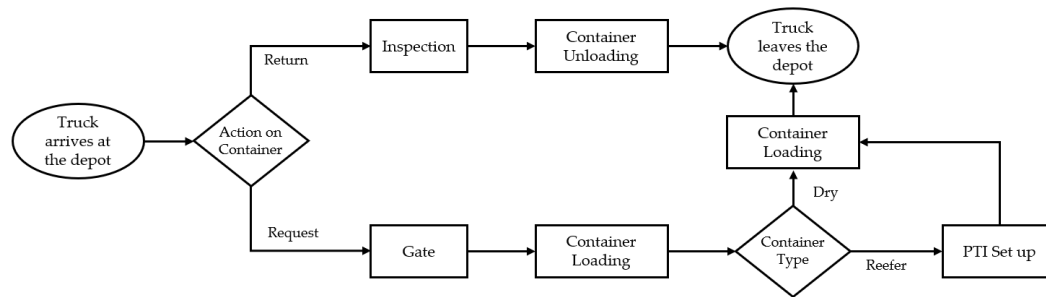


Figure 4. Truck’s return and request flowchart.

Figure 4 outlines the container requests flow, starting with trucks entering and passing through the gate. Trucks proceed to designated storage blocks for specific containers (operative dry or reefer), wait for lifting equipment availability, and have containers loaded. If the container is a reefer unit, it undergoes PTI setup after loading. Finally, trucks proceed through Gate-Out processing and exit the depot.

4.3. Data Gathering: Analysis and Statistical Modelling

The operational processes within the empty container depot exhibit varying temporal characteristics and behavioral patterns that reflect the complexity and nature of each activity. Table 2 summarizes the descriptive statistics for all measured processes, revealing distinct performance profiles across gate operations, maintenance activities, and container handling procedures.

Table 2. Descriptive statistics for processes and operations.

Process Time	Unit	Average	Median	STD	Min.	Max.	IQR.	Outliers
Gate (Internal trucks)	Seconds	7.120	5.00	9.26	0.00	43.00	6.750	10.5%
Gate (External trucks)	Seconds	82.80	49.5	111.94	18.00	539.0	30.75	14.0%
Inspection	Seconds	152.5	133.0	78.20	70.00	582.0	45.75	10.0%
Gate-Out	Seconds	142.0	125.0	53.34	83.00	335.0	62.00	6.00%
Workshop repair	Hours	0.650	0.580	0.570	0.020	3.170	0.330	6.70%
Washing	Minutes	22.14	20.39	8.270	41.89	10.75	0.000	0.00%
PTI Repair	Hours	5.940	5.450	3.690	0.500	17.00	4.470	4.50%
PTI Setup	Seconds	287.2	269.0	169.41	87.00	656.0	265.8	0.00%
Truck Loading	Seconds	35.83	35.0	11.30	15.00	70.00	10.00	10.00%
Truck Unloading	Seconds	27.33	26.0	8.160	16.00	47.00	9.750	3.33%
Container Stacking	Seconds	40.40	37.0	14.96	13.00	72.00	18.50	0.00%
Container Unstacking	Seconds	41.43	41.5	8.450	21.00	58.00	10.50	0.00%
Driving Speed LE	km/h	5.90	6.12	1.050	3.140	7.820	1.320	0.00%
Driving Speed Truck	km/h	12.58	12.75	0.920	10.43	14.80	1.120	0.00%

Gate operations exhibit distinct behavioral patterns between internal and external trucks. Internal truck processing demonstrates relatively fast operations with moderate variability, while external trucks require significantly longer processing times with high variability, indicating more complex documentation or verification procedures. Inspection processes demonstrate the longest durations with substantial variability, reflecting the thorough nature of container examinations. Gate-Out operations maintain stable processing times with moderate variability, suggesting standardized exit procedures. All gate processes show positive skewness, indicating occasional extended processing times that are likely to reflect complex cases or operational bottlenecks.

Workshop repair operations display high variability, indicating diverse repair complexities ranging from minor fixes to major interventions. PTI repair processes show longer

durations with moderate variability, depending on problems associated with the repairs. PTI setup operations are considerably shorter but exhibit high variability, suggesting different preparation requirements based on container specifications. The positive skewness in all repair processes indicates that while most operations follow standard timeframes, complex cases occasionally require extended attention.

Container handling operations present efficient and uniform performance patterns. Loading and unloading show moderate variability with slight positive skewness, indicating standardized procedures with occasional variations. Stacking operations exhibit similar patterns, suggesting well-established operational procedures. Driving speeds for both lifting equipment (5.9 km/h) and trucks (12.58 km/h) demonstrate tight clustering around median values with minimal variability, indicating strict adherence to safety protocols and operational guidelines within the terminal environment.

Table 3 presents the best-fit probability distributions for all measured processes, determined through rigorous statistical testing and goodness-of-fit criteria.

Table 3. Probability distributions fitted to operational processes in the ECD.

Process Time	Unit	Probability Distribution
Gate (Internal trucks)	Seconds	Lognormal ($\mu = 6.28, \sigma = 0.87$)
Gate (External trucks)	Seconds	Johnson SB ($\gamma = 0.5, \delta = 0.65, \theta = 17.20, \sigma = 90.04$)
Inspection	Seconds	Lognormal ($\mu = 128.69, \sigma = 0.23$)
Gate-Out	Seconds	Johnson SB ($\gamma = 0.59, \delta = 0.68, \theta = 81.61, \sigma = 228.14$)
Workshop repair	Hours	Weibull ($\lambda = 0.7, k = 1.25$)
Washing	Minutes	Johnson SB ($\gamma = 0.68, \delta = 0.76, \theta = 10.2, \sigma = 35.78$)
PTI Repair	Hours	Gamma ($\alpha = 2.55, \theta = 2.33$)
PTI Set up	Seconds	Johnson SB ($\gamma = 0.47, \delta = 0.48, \theta = 85.89, \sigma = 663.87$)
Truck Loading	Seconds	Johnson SB ($\gamma = 5.48, \delta = 2.78, \theta = 0, \sigma = 281.88$)
Truck Unloading	Seconds	Lognormal ($\mu = 26.20, \sigma = 0.29$)
Container Stacking	Seconds	Triangular ($a = 8.59, b = 77.65, c = 34.83$)
Container Unstacking	Seconds	Johnson SB ($\gamma = -0.46, \delta = 2.07, \theta = 0, \sigma = 74.97$)

5. Simulation Model Development and Experimental Design

The model was developed using Simulation software Simio version 15 to accurately replicate the physical depot layout with precise scaling of processing areas and storage blocks, as shown in Figure 2. All elements, including shapes, sizes, and distances, were meticulously reproduced based on CAD specifications given by the terminal.

5.1. Infrastructure Modelling

The model incorporates a comprehensive street network that replicates the depot's road infrastructure, including accurate lengths and directional specifications as depicted in the original CAD layout. A critical design consideration involves the implementation of separate street networks for different vehicle types, recognizing that while depot roads are predominantly double-lane and bidirectional, operational patterns vary significantly between trucks and lifting equipment. Trucks adhere to conventional double-lane traffic rules, whereas lifting equipment typically traverse along street centers, effectively occupying both lanes regardless of directional designations.

The intersection of truck and lifting equipment networks creates overlapping zones at specific junctions, as illustrated in Figure 5. The model incorporates these critical intersection points for detailed safety analysis. A strategically positioned roundabout between storage blocks B1 and B2 facilitates efficient container return traffic flow within the truck network. This roundabout enables trucks servicing block B1 to execute turning maneuvers and navigate toward the dedicated exit route between the two blocks, while trucks returning to block B2 can access this exit directly without using the roundabout.

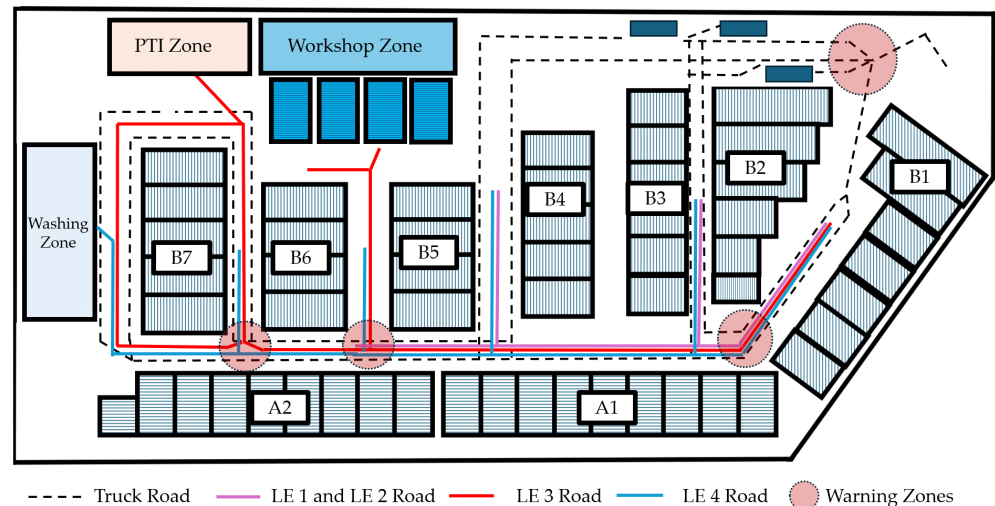


Figure 5. EDC warning zones and road networks for trucks and lifting equipment.

Storage blocks, which feature multiple access points along their full length in reality, are represented through a single-node approach where all operations converge at one designated point positioned on adjacent streets near each block's estimated center of mass. This center is determined based on TEU capacity distribution, with irregular-shaped blocks having centers positioned closer to areas of highest TEU concentration. For processing areas such as Workshop, PTI, and Washing zones, single nodes are placed at the estimated center of mass within each sector rather than on adjacent streets, reflecting the direct lifting equipment–container interaction patterns in these operations.

5.2. Entities and Resource Modelling

The model incorporates three container types (1 TEU Dry, 2 TEU Dry, and 2 TEU Reefer), four truck classifications (Request/Return for both Dry and Reefer containers), and four specialized lifting equipment (LE1 to LE4). The four lifting equipment are differentiated by operational zones and responsibilities: LE1 and LE2 handle dry container operations, LE3 manages Workshop and PTI area maneuvers, and LE4 oversees Reefer and Washing area operations.

5.3. Operational Logic and Special Considerations

The simulation model is constructed by incorporating all processes documented in preceding chapters, with their real-world time parameters and operational logics appropriately adapted. The logic and some special considerations associated with the operations are presented in Appendix A.

5.4. Experimental Design

The experimental design considers three truck arrival frequencies (Low, Regular and High) with two reefer-to-total container ratios (Low and High), creating six scenarios that systematically test depot performance under varying demand conditions based on historical data. Inter-arrival times are assumed to follow exponential distributions with rate parameters expressed as trucks per minute, calculated from the expected number of vehicles and respective operating hours for dry trucks and for reefer trucks. The exponential distribution rate parameters are presented in Table 4.

Table 4. Rate parameters (λ) for exponential inter-arrival time distributions across experimental scenarios, differentiated by truck type and operational purpose.

Scenario		λ Rate Parameter for Inter-Arrival Time Distribution (Trucks Per Minute)			
Arrival Frequency	Reefer Ratio	Request		Return	
		Dry	Reefer	Dry	Reefer
Low	Low	0.05390	0.01818	0.04539	0.01455
Low	High	0.04113	0.03455	0.03404	0.02909
Regular	Low	0.10496	0.03455	0.11206	0.03818
Regular	High	0.08085	0.06545	0.08652	0.07091
High	Low	0.17021	0.05818	0.18582	0.06364
High	High	0.13050	0.10909	0.14326	0.11818

The experimental design systematically evaluates depot performance by manipulating two critical operational factors: truck arrival intensity and reefer container proportion. This factorial approach captures realistic demand variations from low-traffic periods to high-volume scenarios with substantial refrigerated-container processing requirements. The design enables identification of performance bottlenecks and safety trade-offs across the full spectrum of expected operational conditions, providing comprehensive insights into how varying demand patterns affect truck turnaround times, equipment utilization, and collision risks.

6. Results

This study employs a comprehensive analytical framework combining quantitative statistical evaluation with qualitative contextual interpretation to examine simulation outcomes and derive actionable insights for operational enhancement. The analysis utilizes ANOVA for statistical significance testing to evaluate mean differences between scenario groups, enabling robust comparison of performance indicators across different operational conditions. Additionally, Poisson regression analysis investigates the effects of truck turnaround time (TTT) and lifting equipment travel distance (DCLE) on collision occurrence, with model construction based on backward elimination feature selection and model fit assessed using McFadden's pseudo R-squared. This integrated approach transforms simulation data into practical insights for collision risk assessment and operational efficiency evaluation at critical terminal intersections.

The results address key research objectives: (1) examining relationships between arrival frequency and operational conditions in performance indicators; (2) exploring the effect of TTT and DCLE on the number of potential collisions; (3) transforming simulation data into actionable insights for terminal layout optimization.

6.1. Results for ANOVA Analysis

6.1.1. Truck Turnaround Time Analysis

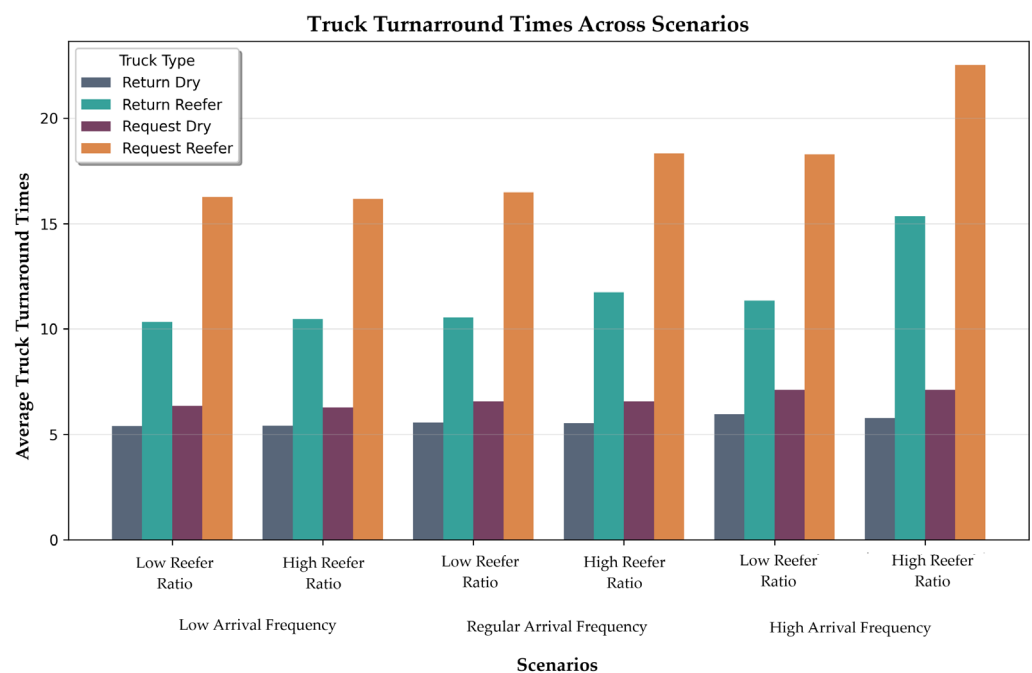
The TTT analysis across four truck categories reveals systematic performance differentials, with dry operations demonstrating higher efficiency compared to reefer operations. This disparity reflects the inherent complexity of refrigerated container processing requirements. Performance variations intensify under operational stress, with reefer categories exhibiting greater sensitivity to changing operational parameters than dry categories. The confidence intervals for the mean are presented in Table 5.

Table 5. Confidence interval for truck turnaround time (in minutes) by arrival frequency, reefer ratio, and truck category.

Arrival Frequency	Reefer Ratio	Return Dry	Request Dry	Return Reefer	Request Reefer
Low	Low	5.398 ± 0.063	6.357 ± 0.076	10.332 ± 0.334	16.273 ± 0.507
	High	5.426 ± 0.075	6.285 ± 0.077	10.477 ± 0.349	16.163 ± 0.419
Regular	Low	5.563 ± 0.061	6.578 ± 0.066	10.547 ± 0.283	16.484 ± 0.523
	High	5.538 ± 0.075	6.581 ± 0.070	11.744 ± 0.420	18.335 ± 0.588
High	Low	5.955 ± 0.076	7.114 ± 0.104	11.34 ± 0.234	18.276 ± 0.549
	High	5.775 ± 0.061	7.123 ± 0.121	15.345 ± 0.592	22.52 ± 0.842

Arrival frequency exhibits the strongest influence on TTT variations across all categories, with statistical analysis confirming significant differences between arrival frequency groups for each truck type and reefer ratio setting (p -value < 0.05). Dry operations exhibit moderate progressive increases between frequency levels. For return and request trucks in low reefer ratio settings, escalations are 3.06% and 7.04%, and 3.48% and 8.15% across low-to-regular and regular-to-high frequency transitions, respectively. In high reefer ratio scenarios, return and request trucks show escalations of 2.06% and 4.27%, and 4.71% and 8.24% across the same frequency transitions, respectively.

Reefer operations demonstrate substantially higher sensitivity to arrival frequency variations compared to dry operations. In low reefer ratio settings, return and request trucks show escalations of 2.08% and 7.49%, and 1.30% and 10.87% across low-to-regular and regular-to-high frequency transitions, respectively. Under high reefer ratio scenarios, sensitivity intensifies substantially, with return and request trucks exhibiting escalations of 12.10% and 30.66%, and 13.42% and 22.82%, respectively, across the same frequency transitions. This increased sensitivity under high reefer ratio conditions suggests that specialized container processing creates operational constraints when combined with higher arrival frequencies, as illustrated in Figure 6.

**Figure 6.** Truck turnaround times across the scenarios (in minutes).

ANOVA statistical analysis reveals significant differences in reefer ratio effects depending on arrival frequency intensity. Under low arrival frequencies, ratio impacts remain

minimal across all categories (<2% variation). At regular frequencies, reefer trucks (return and request) show substantial increases of approximately 11% when transitioning from low to high ratios, while dry trucks remain unaffected. Under high arrival scenarios, these effects intensify, with increases of 35.33% for reefer return and 23.21% for reefer request operations.

The TTT analysis reveals that arrival frequency serves as the primary driver of performance variations across all truck categories, with dry operations consistently outperforming reefer operations due to specialized processing requirements. While dry operations exhibit moderate, predictable increases in frequency levels, reefer operations show higher sensitivity, particularly under combined high stress conditions. Specifically, reefer operations experience high performance reduction under peak stress scenarios, compared to minimal variations under low arrival frequencies, showing critical operational thresholds that require specialized capacity planning strategies to prevent system-wide bottlenecks during peak periods.

6.1.2. Distance Covered by Lifting Equipment Analysis

The lifting equipment travel distance analysis reveals distinct operational patterns aligned with their specialized functions and priority hierarchies. LE1 and LE2, dedicated to dry container operations, show progressive increases in daily travel distances with arrival frequency, ranging from approximately 1.6–3.2 km under low frequency conditions to 5.2–7.8 km under high frequency scenarios. These units demonstrate moderate sensitivity to reefer ratio variations, with LE2 consistently traveling greater distances than LE1 across all operational conditions.

LE3, serving the Workshop and PTI Areas with priority given to scheduled operations, maintains relatively stable travel distances of around 24 km regardless of operational parameters, indicating consistent movement requirements between repair and inspection facilities. LE4, managing the Reefer and Washing Areas with truck operation prioritization, exhibits the most variable travel patterns, with distances increasing from approximately 24.6 km under low-demand conditions to 33.2 km under high arrival frequency and high reefer ratio scenarios.

ANOVA analysis reveals significant differences in lifting equipment sensitivity to operational parameters, with distinct patterns emerging across equipment types (Table 6). LE1, LE2, and LE4 demonstrate significant sensitivity to arrival frequency variations under both low and high reefer ratio conditions, while also showing significant responses to reefer ratio changes across all arrival frequency levels. In contrast, LE3 exhibits no significant sensitivity to either parameter, confirming its operational independence from traffic density and reefer activity variations.

Table 6. Confidence interval for distance covered by each lifting equipment (in km) by arrival frequency and reefer ratio.

Arrival Frequency	Reefer Ratio	LE 1	LE 2	LE 3	LE 4
Low	Low	2.151 ± 0.208	3.205 ± 0.155	23.975 ± 0.654	24.591 ± 0.652
Low	High	1.612 ± 0.156	2.567 ± 0.172	24.545 ± 0.565	26.605 ± 0.866
Regular	Low	4.146 ± 0.249	6.192 ± 0.364	24.379 ± 0.697	26.556 ± 0.628
Regular	High	3.327 ± 0.261	5.028 ± 0.316	24.392 ± 0.577	29.874 ± 0.922
High	Low	6.918 ± 0.291	9.713 ± 0.451	24.331 ± 0.641	28.445 ± 0.634
High	High	5.221 ± 0.319	7.773 ± 0.297	24.197 ± 0.479	33.241 ± 0.579

As shown in Figure 7, LE4 has a critical role in preventing bottlenecks through truck prioritization, with travel distances escalating significantly when both arrival frequency

and reefer processing demands intensify simultaneously. The heatmap reveals significant utilization imbalance, with LE1 and LE2 operating at low travel distances (under 10 km daily) while LE3 and LE4 maintain consistently high operational demands (20–33 km daily), indicating potential optimization opportunities through workload redistribution.

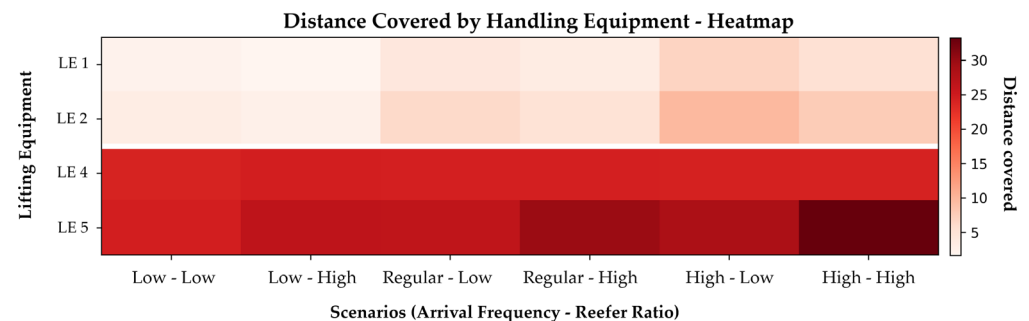


Figure 7. Heat map for distance covered by each lifting equipment (in km) across the scenarios (in minutes).

6.1.3. Potential Collisions Analysis

The collision analysis reveals distinct safety patterns across four identified conflict zones within the depot's operational layout (see Figure 8). ANOVA statistical analysis confirms significant differences in collision sensitivity patterns across the sites (Table 7). Figure 8 shows the average number of potential collisions across four identified conflict zones within the depot's operational layout. Site 1 is located in the Dry sector at the B2-B3-A2 intersection, Site 2 is positioned at the Dry/Reefer intersection zone between B5-B6 blocks, Site 3 is situated in the Reefer zone encompassing B6-B7 and A2 blocks, and Site 4 is located at the Gate sector intersection between B1-B2 blocks. Sites 1, 2, and 4 demonstrate significant sensitivity to arrival frequency variations, indicating that traffic density is the primary driver of collision risk at these locations. However, their responses to reefer ratio changes vary considerably: Site 1 shows no significant sensitivity to reefer ratio variations, while Site 2 exhibits significant sensitivity only under high arrival frequency conditions, and Site 4 demonstrates significant ratio sensitivity exclusively under regular arrival frequency scenarios. Site 3 maintains operational independence from both parameters, suggesting its collision patterns are driven by factors beyond the analyzed operational variables.

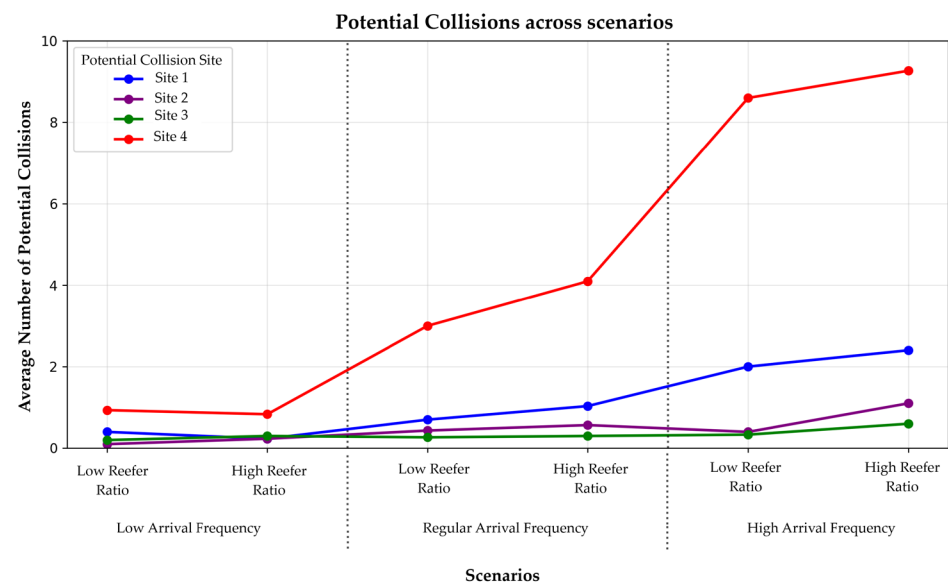


Figure 8. Number of potential collisions in each conflictive site by arrival frequency and reefer ratio.

Table 7. Confidence interval for the number of potential collisions by arrival frequency and reefer ratio.

Arrival Frequency	Reefer Ratio	Site 1	Site 2	Site 3	Site 4
Low	Low	0.400 ± 0.232	0.100 ± 0.114	0.200 ± 0.181	0.933 ± 0.353
Low	High	0.233 ± 0.161	0.233 ± 0.188	0.300 ± 0.200	0.833 ± 0.355
Regular	Low	0.700 ± 0.440	0.433 ± 0.212	0.267 ± 0.194	3.000 ± 0.672
Regular	High	1.033 ± 0.268	0.567 ± 0.272	0.300 ± 0.174	4.100 ± 0.710
High	Low	2.000 ± 0.449	0.400 ± 0.270	0.333 ± 0.204	8.600 ± 1.095
High	High	2.400 ± 0.609	1.100 ± 0.408	0.600 ± 0.304	9.267 ± 1.225

The collision analysis reveals distinct safety patterns across these sites. Site 1 represents a low-impact zone with minimal collision frequencies across all operational scenarios. Site 2 demonstrates the lowest absolute occurrence rates but shows sensitivity to operational stress during peak conditions. Site 3 exhibits moderate collision activity with increases under high operational stress. Site 4 shows the highest collision frequencies with no-table increases under high traffic density conditions, representing the primary operational challenge where traffic converges and requiring enhanced management procedures.

6.2. Regression Analysis to Explain the Number of Potential Collisions

Poisson regression was employed to analyze the effects of truck turnaround time (TTT) and distance covered by lifting equipment (DCLE) on the number of potential collisions. This analysis examines whether longer TTTs and greater DCLEs increase collision risk, and whether traditional efficiency metrics can predict collision likelihood at critical intersections. Table 8 presents the significant variables and goodness-of-fit measures for Poisson regression models explaining the number of potential collisions at conflict zones.

Table 8. Poisson regression models for potential collision Sites 1–4 and the sum of all PC: significant predictors and model performance. (✓) indicates statistically significant variables included in each model (p -value < 0.05); (×) indicates non-significant variables. Pseudo R-squared values calculated using McFadden’s formula.

Independent Variable	PC Site 1	PC Site 2	PC Site 3	PC Site 4	All PC
TTT Return Dry	X	X	X	X	X
TTT Request Dry	X	X	X	✓	✓
TTT Return Reefer	✓	X	✓	X	X
TTT Request Reefer	X	X	X	✓	✓
DCLE 1	X	X	X	✓	✓
DCLE 2	✓	X	X	✓	✓
DCLE 3	X	X	X	X	X
DCLE 4	X	✓	X	✓	✓
Pseudo R-Squared	0.17390	0.08334	0.01884	0.40050	0.4217
LLM p -value	<0.005	<0.005	<0.05	<0.005	<0.005

The model developed to explain the number of collisions at Site 1, located at the intersection of blocks handling dry containers, shows a moderate fit ($R^2 = 0.1739$). One of the statistically significant variables for this model is DCLE1 ($\beta = 0.1905$), which is associated with container handling equipment in this zone. This establishes a directly proportional relationship. As the distance traveled by the lifting equipment (LE) increases, there is a tendency toward a higher number of potential collisions.

However, another statistically significant variable is TTT of trucks requiring reefer containers ($\beta = 0.1485$). This finding indicates that the number of potential collisions tends to increase as the residence time of this type of container in the system increases. It is important to note that these trucks represent those that spend the longest time in ECD.

Consequently, any increase in their TTT generates increased congestion in specific sectors, particularly in the corridor between areas A1 and A2.

The TTT of trucks requiring reefer containers constitutes the only statistically significant variable in the model developed for Site 3 ($\beta = 0.1269$). However, the model fails to adequately fit the number of potential collisions observed at this point ($R^2 = 0.01884$). A similar pattern emerges in the results obtained for Site 2, where the only variable showing statistical significance is DCLE4 ($\beta = 0.1622$). This equipment is directly associated with the intersection sector in question. Similarly, satisfactory results are not obtained in terms of model fit ($R^2 = 0.08334$).

Both results strongly suggest that it is necessary to consider the incorporation of specific safety indicators in the comprehensive evaluation of CDS layouts. These would function as a complement to traditional TTT and DCLE metrics.

In contrast, the model associated with Site 4 exhibits the best fit among all analyzed models ($R^2 = 0.4005$). In particular, TTT variables associated with both dry ($\beta = -0.4347$) and reefer ($\beta = 0.0518$) container requirements demonstrate statistical significance for the model. Similarly, the distances traveled by lifting equipment DCLE1 ($\beta = 0.1725$), DCLE2 ($\beta = 0.1588$), and DCLE4 ($\beta = 0.0797$) are significant. Consequently, most of the variables incorporated in the analysis are relevant for explaining the behavior of potential collisions at PC4.

It is essential to observe that Site 4 is strategically located in the Gate zone. This is an area where vehicular congestion manifests as a direct result of the convergence of most operational processes associated with the ECD. Under this same conceptual logic, the total number of collisions, considering all identified conflict sites, faithfully reproduces the same behavior observed at Site 4. This confirms its representativeness as a comprehensive system indicator.

Managerial Insights

The analysis of three key performance indicators has identified significant inefficiencies, workload imbalances, and safety risks throughout the depot's operations. Based on this, we propose some recommendations to address these critical challenges.

The Reefer area operates with single lifting equipment for both truck servicing and container maneuvers. Deploying additional lifting equipment would distribute these dual responsibilities and provide performance alignment with dry area operations. Task redistribution should include reallocation of workshop operations or container maneuvers to maintain resource utilization across operational areas.

The current layout generates congestion during operations. Relocating PTI setup processes from the Reefer area would reduce truck processing times. Street network and block configuration optimization should address the traffic conflicts and processing delays through dedicated traffic lanes and improved sight lines.

The depot entrance at Site 4 requires traffic pattern reconfiguration with improved lane directionality and flow management. Automated traffic management systems including traffic signals and motion sensors would provide systematic traffic regulation throughout the facility.

Finally, manual gate processes impact truck operations, particularly trucks that request containers. Automating gate entry and exit procedures would streamline workflows and reduce processing times. This automation would provide consistent service delivery across varying traffic volumes.

Based on the findings and recommendations from this research study, the terminal has initiated a comprehensive layout modification project to address the identified operational inefficiencies and safety concerns. The terminal management has begun implementing

structural changes to optimize traffic flow patterns, redistribute equipment allocation, and reconfigure critical operational areas to enhance overall performance and reduce processing bottlenecks throughout the facility.

7. Conclusions

This study addressed three critical research objectives in container terminal operations: examining relationships between arrival patterns and operational conditions with performance indicators, analyzing the effect of truck turnaround times and equipment travel distances on potential collision frequency, and exploring how efficiency metrics explain collision risk while transforming simulation insights into actionable optimization strategies.

The operational analysis reveals significant disparities between dry and reefer container operations. TTT analysis demonstrates superior efficiency in dry truck operations due to streamlined processing requirements, with minimal efficiency losses under increasing arrival frequencies. Conversely, reefer operations exhibit escalating inefficiencies under high-demand conditions, requiring targeted capacity optimization strategies. The simulation model confirms this resource imbalance, showing reefer-dedicated equipment operates 3–4 times the travel distance of dry-dedicated equipment, highlighting intensive operational requirements and optimization opportunities.

From a safety perspective, the collision analysis examined four conflict zones with distinct risk profiles. Site 1 at the gate intersection shows the highest collision frequencies that increase under high traffic density conditions, while other sites demonstrate varying sensitivities to operational parameters. Site 4 requires management protocol enhancements as the primary traffic convergence point, while Sites 1–3 require targeted interventions based on their specific operational dependencies.

The Poisson regression analysis reveals that different conflict zones respond to distinct operational factors with varying predictive strength. Site 4 shows the strongest explanatory power with multiple significant predictors, while Sites 2 and 3 exhibit poor model fits, indicating that traditional efficiency metrics inadequately predict collision occurrence at these locations. Notably, TTT for reefer request trucks emerges as a significant predictor across multiple sites, demonstrating that reefer operations generate systemic congestion effects throughout the depot.

The poor model performance at several conflict zones challenges the adequacy of conventional efficiency metrics for comprehensive safety assessment. This finding emphasizes that effective ECD layout evaluations must integrate specific safety indicators alongside traditional efficiency metrics.

Based on these findings, four critical recommendations emerge: optimizing lifting equipment allocation to address reefer operation bottlenecks while redistributing tasks to prevent overloading; redesigning physical layout and traffic flow by relocating PTI processes and optimizing street networks; implementing enhanced safety measures focused on high-risk areas through automated traffic management systems; and automating administrative gate operations to eliminate processing delays. These integrated strategies provide a comprehensive framework for achieving balanced resource utilization, improved operational efficiency, and enhanced safety protocols.

The convergence of these findings establishes a comprehensive DES-Framework for terminal layout evaluation that prioritizes both operational efficiency and safety performance.

Current research is extending this framework along two complementary directions. First, the simulation model is being adapted to evaluate real-world layout modifications currently under implementation by the partnering maritime terminal. Based on this study's recommendations and additional operational requirements, the terminal has developed a comprehensive redesign proposal encompassing container type relocations, gate infras-

tructure modifications, service facility repositioning, and traffic flow optimization. These modifications are being systematically assessed through enhanced versions of our simulation framework to quantify individual and synergistic effects on both operational efficiency and safety performance.

Second, we are developing an integrated mathematical optimization model for dynamic space allocation within ECD operations. This model addresses the strategic positioning of container segregations according to shipping line ownership, container specifications (reefer/dry), and maintenance requirements (damaged/undamaged). Given that segregation placement significantly influences internal traffic patterns, equipment workload distribution, and potential collisions, the simulation framework is being enhanced to incorporate space allocation decisions and evaluate their effects on overall yard performance. These ongoing developments will enable more comprehensive evaluation of ECD layout alternatives and their operational implications.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Operational Logic in Simulation Model Development

The logic associated with the operations is as follows:

- **Gate:** The process employs sequential probabilistic decisions to determine container request types: trucks are first classified for dry or reefer container requests, with dry container requests further differentiated between 1 TEU and 2 TEU units. Storage block allocation follows probabilistic distribution, with dry containers having a 1/5 probability of visiting any of five operational blocks and reefer containers having a 1/2 probability of accessing either of two operational blocks, contingent upon container availability. All probability parameters remain manually adjustable to facilitate scenario testing under varying operational conditions.
- **Inspection:** The process accommodates up to two trucks simultaneously and employs probabilistic decision mechanisms to determine container return classifications and routing. The model sequentially categorizes containers as dry or reefer, with dry containers further differentiated between 1 TEU and 2 TEU units. Container condition assessment follows probabilistic logic: structurally damaged dry containers have a 1/2 probability of assignment to either of two designated non-operative storage blocks, while operative dry containers have a 1/5 probability of allocation to any of five operative blocks contingent upon space availability. Reefer containers follow simplified routing: damaged units are directed to the designated non-operative reefer block, while operative containers proceed to the PTI-pending block based on space availability. All probability parameters remain manually adjustable to enable scenario testing under diverse operational conditions.

- Gate-Out: The process operates with single-truck capacity and functions as the terminal step in the depot workflow. Unlike other processes, this station involves no additional decision-making mechanisms or probabilistic routing, serving solely as a validation checkpoint before truck departure. Upon completion of this process, trucks conclude their depot journey and are directed to the sink, representing their exit from the simulation system.
- Workshop Repair: The Workshop Repair process operates through Regular and Extended Repair stages using four repair lines with 12-container capacity each. Regular repair processes fully loaded lines with a maximum of two concurrent operations, following Weibull distribution for repair times (see Table 3). Upon completion, probabilistic decisions determine whether containers require extended repair (second cycle with temporary placement at block B6) or proceed to post-repair allocation. Dry containers have 1/5 probability of assignment to operative storage blocks, while reefer containers are directed to the PTI-pending block (B7), with all probability parameters manually adjustable for scenario testing.
- Washing: The process uses four 9-container lines: three for reefer containers, one for dry containers. Operations require a minimum of four containers per line, processing two simultaneously with one active line at a time. Safety protocols maintain a two-container gap between active washing and pending containers. Post-washing allocation is probabilistic: dry containers distribute equally among five storage blocks (1/5 probability each), reefers distribute between two designated blocks (1/2 probability each), subject to space availability.
- PTI and PTI Repair: The processes operate on four 11-container reefer lines with shared capacity, beginning operations when three lines are fully arranged (33 containers total) to simulate real-world processing efficiency while reducing variability. During container pickup, probability-based damage identification determines if containers require repair, with damaged units temporarily moved to non-operative block B6 before reallocation to empty PTI lines for processing. PTI Repair takes longer than regular PTI but uses the same line capacity, and the three-line operational requirement includes both regular PTI and repair containers. Repaired containers completing early remain blocked until entire line clearance since they are positioned at line start, requiring full line disarrangement for lifting equipment access. Upon completion, all containers (PTI and PTI Repair) transfer to non-operative block B7 for washing queue with no return to PTI area required, and all probability parameters remain adjustable for scenario testing.
- PTI Setup: The process handles one truck at a time, simulating real-world operator interaction with reefer container setup panels. The process involves no additional decision-making steps, with trucks proceeding directly to Gate-Out upon completion.
- Truck loading and unloading: The processes handle container transfers using lifting equipment as secondary resources. Loading uses a combinator server to merge trucks and containers into loaded trucks, while unloading uses a separator server to split loaded trucks into unloaded trucks and containers. The process involves no additional decision-making steps.
- Container stacking and unstacking: The processes simulate real-world container transfers using lifting equipment with detailed timing distributions. Stacking occurs after the truck unloading or after unstacking from other blocks. Unstacking occurs before truck loading or before transfer to other blocks. No entity synchronization required.

Appendix A.1. Special Considerations

To enhance the simulation model's ability to replicate real-world depot dynamics, several special considerations were incorporated that address practical operational aspects not explicitly detailed in standard processes. These additional features provide an adaptable framework for tracking operational behaviors, managing resource constraints, and identifying safety risks that significantly impact depot performance and efficiency.

Storage Block Capacity Counter: Each storage block utilizes dual counters to track allocated TEUs and remaining capacity, enabling real-time determination of space availability for container placement or retrieval. Dry container blocks employ separate servers for 1 TEU and 2 TEU containers with capacity calculated by adding single TEU units plus twice the number of double TEU containers, while reefer blocks manage exclusively 2 TEU containers with allocated capacity computed as twice the stored container count. Complex blocks handling multiple container types feature specialized configurations with separate servers for different container categories, requiring adjusted capacity equations to accommodate their unique storage arrangements.

Overstock and Understock Exits: The system employs capacity counters to validate truck operations through add-on processes at Gate and Inspection stations, verifying container availability for request trucks and space availability for return trucks before proceeding with normal workflows. When validation fails, trucks are immediately redirected to designated Understock sinks (insufficient containers) or Overstock sinks (insufficient space), providing quantitative tracking of depot capacity imbalances and operational inefficiencies at simulation completion.

Truck per street constraint: Road network nodes incorporate counting mechanisms that monitor truck density on pathways, restricting entry when three or more trucks occupy the same route regardless of lane configuration or traffic direction. This field observation-based approximation ensures adequate space for loading operations and storage block access while preventing roadway congestion, though it introduces potential variability in simulation results by directly impacting truck workflow timing throughout the depot.

Truck Stopper: Stopper nodes positioned one truck length from storage block attacking centers on both road lanes enforce safety protocols by halting truck movement during active lifting equipment operations involving container loading, unloading, stacking, or unstacking activities. This design replicates real-world operational safety practices observed in the field, ensuring sufficient workspace for lifting equipment operations while preventing vehicle interference with critical container handling processes.

Potential Collisions: Four high-risk intersections identified by depot personnel are monitored through dual counter systems that track current vehicle occupancy and cumulative potential collision events, with incidents recorded when two or more vehicles occupy the same intersection simultaneously. These critical safety zones, including the depot entrance where entering and departing trucks cross paths, are marked by structural layouts with blind spots and historical incident records, providing quantitative risk assessment data for operational safety analysis and mitigation planning.

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