FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Synchromodal Transport for Seamless Port–Hinterland Connectivity: Towards More Sustainable and Responsive Global Supply Chains

Francisco Maria de Borges Afonso



Master in Mechanical Engineering

Supervisor: Prof. Drª. Catarina Moreira Marques

Co-Supervisor: Prof. Dr. Jorge Pinho Sousa

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Abstract

Container terminals must reconcile two flows of work that draw on the same handling equipment. On the seaside, vessel calls impose concentrated and time-critical workloads and on the landside external trucks generate a dispersed and highly variable demand. At Terminal XXI of the Port of Sines the competition between the two flows for the same pool of yard cranes is visible as congestion at the terminal gate.

This dissertation evaluates how the dimensioning of the yard crane fleet and the coordination between the two flows affect landside performance, and at what cost. A discrete-event simulation model of the terminal is developed in FlexSim, following the seven-step approach proposed by Law, representing at the level of individual trucks, containers and cranes the gate procedures, the storage of containers unloaded from vessels, the relocation of obstructing containers and the retrieval operation itself. To represent this, two models were built. The first reproduces the current operation, in which the appointment limit of 30 pickups per hour applies uniformly throughout the day. The second represents an appointment system aware of the berthing schedule, reducing that limit to 20 pickups per hour while the storage of containers unloaded from vessels is in progress. Each model was tested with fleets of five, seven and ten cranes, over thirty independent replications of one week of operation.

The results show that the baseline fleet operates at 93% utilisation, with trucks waiting on average more than two and a half hours. Under the current rules, the first capacity increment removes only 12% of that wait, while the full expansion to ten cranes removes 79% for 11 million euros of additional investment. Coordinating truck arrivals with the berthing schedule removes 43% at no capital cost, and, combined with a moderate expansion to seven cranes, reaches the service level of the largest fleet for 40% of its investment, at the cost of serving 14% to 19% fewer trucks per hour. The configurations evaluated therefore form a set of compromises, in which capacity expansion and coordination measures are evaluated.

Keywords: container terminal; yard cranes; truck appointment system; discrete-event simulation; landside congestion; cost–performance trade-off

Resumo

Os terminais de contentores têm de conciliar dois fluxos que recorrem ao mesmo equipamento de movimentação de contentores. Do lado marítimo, as chegadas dos navios impõem cargas de trabalho concentradas e com prazos exigentes e, do lado terrestre, os camiões externos ao porto geram uma procura dispersa e muito variável. No Terminal XXI do Porto de Sines, a competição entre os dois fluxos pelo mesmo conjunto de *yard cranes* manifesta-se sob a forma de congestionamento à entrada do terminal.

Esta dissertação avalia de que modo o dimensionamento da frota de *yard cranes* e a coordenação entre os dois fluxos afetam o desempenho do lado terrestre, e a que custo. É desenvolvido em FlexSim um modelo de simulação do terminal, seguindo a abordagem em sete passos proposta por Law, que representa ao nível de cada camião, contentor e grua os procedimentos na portaria, a arrumação dos contentores descarregados dos navios, a remoção dos contentores que obstruem o solicitado para levantamento e a própria operação de recolha. Para o efeito, foram construídos dois modelos. O primeiro reproduz a operação atual, na qual o limite de 30 recolhas por hora se aplica de modo uniforme ao longo do dia. O segundo representa um sistema de marcações sensível à chegada de navios, reduzindo esse limite para 20 recolhas por hora enquanto decorre o armazenamento de contentores recém-chegados. Cada modelo foi testado com frotas de cinco, sete e dez gruas, ao longo de trinta replicações independentes de uma semana de operação.

Os resultados mostram que a frota de referência opera a 93% de utilização, com os camiões a esperar, em média, mais de duas horas e meia. Sob as regras atuais, o primeiro aumento de capacidade elimina apenas 12% dessa espera, enquanto a expansão completa para dez gruas elimina 79%, com um investimento adicional de 11 milhões de euros. Coordenar as chegadas com as chegadas de navios elimina 43% sem qualquer investimento e, combinada com uma expansão moderada para sete gruas, atinge o nível de serviço da maior frota por 40% do seu investimento, ao custo de servir menos 14% a 19% de camiões por hora. As configurações avaliadas constituem, assim, um conjunto de compromissos, nos quais são avaliadas medidas de expansão de capacidade e de coordenação.

Palavras-chave: terminal de contentores; *yard cranes*; sistema de marcação de camiões; simulação de eventos discretos; congestionamento; compromisso custo–desempenho

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Francisco Afonso

"Practice isn't the thing you do once you're good.
It's the thing you do that makes you good."

Malcolm Gladwell

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Abbreviations

INESC TEC	Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência
PRR	Recovery and Resilience Plan
IoT	Internet of Things
AI	Artificial Intelligence
TAS	Truck Appointment System
RFID	Radio Frequency Identification
OCR	Optical Character Recognition
AGVs	Automated Guided Vehicles
EDI	Electronic Data Interchange
WSNs	Wireless Sensor Networks
FCFS	First Come, First Served
EDD	Earliest Due Date
CO_2	Carbon Dioxide
MILP	Mixed-Integer Linear Programming
IP	Integer Programming
SD	System Dynamics
DES	Discrete Event Simulation
ABM	Agent-Based Modelling
TEU	Twenty-foot Equivalent Unit
ZH	Hydrographic Zero
aRTG	Automated Rubber-Tyred Gantry Crane
KPI	Key Performance Indicator
SMEs	Subject-Matter Experts

Chapter 1

Introduction

This introductory chapter aims to present the subject of study, using for that four subsections. Firstly, in section 1.1, the context and motivation of the study are given, framing the operational difficulties that arise when the storage of containers unloaded from vessels and their retrieval by external trucks compete for the same yard cranes. The goals of this dissertation, together with the research question that guides it, are described in section 1.2, while a brief summary of the methodology and scientific approach adopted is provided in section 1.3. Finally, the document structure is presented in section 1.4.

1.1 Context and Motivation

Maritime transport sustains the greater part of international trade, and seaports have, consequently, evolved from simple points of cargo transfer into critical nodes whose performance conditions the efficiency of entire supply chains. Container terminals occupy a complex position within this network, as they should reconcile two flows governed by different logics. On the **seaside**, the arrival of vessels imposes large, concentrated and time-critical handling workloads, as the cost of berth occupation and the contractual obligations toward shipping lines make rapid loading and unloading a priority. On the **landside**, the arrival of external trucks generates a more dispersed but highly variable demand, shaped by the preferences and constraints of road carriers. Both flows ultimately depend on the same finite pool of internal handling equipment, and it is in the management of this shared dependency that much of a terminal's operational difficulty resides.

The **yard cranes** are the resource through which this dependency becomes most acute. They are required both to support vessel operations, by placing containers in their assigned slots in the storage yard, and to serve external trucks, by retrieving the containers requested for onward transport to the hinterland. When vessel handling and truck service are planned in isolation, the demand they place on these cranes overlaps in time, producing contention that neither activity can resolve on its own. The visible symptom of this contention is **congestion at the gate**. When

seaside-flow workload absorbs the yard cranes' capacity, incoming trucks accumulate upstream of the terminal. This generates queues, prolonged waiting times, additional pollutant emissions and degrades service across the surrounding road network. Conversely, during quieter periods the same resources may remain underused, revealing an imbalance between demand and capacity rather than an absolute shortage of equipment.

To address these problems was created the NEXUS project, an initiative funded through the Recovery and Resilience Plan (PRR) of the European Union. This project integrates the investment in Mobilising Green Agendas/Alliances for Business Innovation, from Component 05 – Capitalisation and Business Innovation, of the Resilience dimension of the PRR. NEXUS is directed at the digital and low-carbon transformation of the logistics network that serves the Port of Sines, seeking operations that are at once more efficient, better coordinated and environmentally sustainable [3].

This dissertation, developed within the Master's in Mechanical Engineering at the Faculty of Engineering of the University of Porto (FEUP) and carried out as part of the NEXUS project, examines operational challenges at Terminal XXI, the main container facility of the Port of Sines. The study presented in this document is centred on the yard cranes, the resource at which landside and seaside demands converge, and aims to support decision on the dimensioning of the yard crane fleet. The main objective is to determine the trade-offs across scenarios, considering that increasing the availability of handling equipment can relieve congestion and improve the service provided to trucks, but requires an investment that should be justified by the operational benefit obtained. To answer this question, this dissertation reviews the state of the art in the field and then develops a simulation-based approach to evaluate alternative yard crane fleets and policies across a set of scenarios, quantifying their impact on truck service levels, vessel handling performance and resource utilisation.

1.2 Objectives and Research Question

The general objective of this dissertation is to evaluate how the dimensioning and coordination of the yard cranes at Terminal XXI affect the two handling tasks these resources should perform: storing containers unloaded from vessels and retrieving containers for delivery to the hinterland. Because both tasks draw on the same crane capacity, the workload generated by the storage of vessel arrivals determines how much capacity remains available to serve trucks and it is this competition that conditions the performance perceived on the landside. The study therefore focuses on the container yard, where containers are stored and on the process through which trucks retrieve them, rather than on the scheduling of any single flow in isolation.

The objective of this work, however, extends beyond identifying a single optimal configuration. Instead, it seeks to evaluate multiple operational scenarios and resource allocation strategies that may improve the performance of landside operations, analysing the trade-offs between the costs associated with increasing resource availability and the operational benefits obtained in

terms of reduced congestion, improved truck turnaround times and enhanced coordination with vessel operations.

This concern gives rise to the research question that guides the work:

What operational scenarios and resource allocation configurations enable more sustainable and efficient container terminals operations?

From this question, the following specific objectives are derived:

• to characterise the current operation of the terminal, describing the activities involved in the way vessel handling and container collection share the yard cranes and the constraints that shape their joint performance, so as to establish a reference baseline;

• to build a model that represents the interaction between container arrivals and truck arrivals and the contention they create for internal handling resources, capturing the variability of both flows;

• to use this model to evaluate the operational and economic effects of alternative resource configurations and coordination strategies, in terms of congestion, truck turnaround time and resource utilisation;

• to identify configurations that offer a favourable balance between performance gains and the cost of additional resources, thereby supporting decisions on the dimensioning of landside operations.

The aim is therefore to assess the operational impacts of varying the number of available resources, not only in terms of reducing congestion at the terminal entrance and lowering truck turnaround times, but also in terms of the economic implications of deploying additional equipment, thereby supporting informed decision-making regarding the optimisation of landside operations.

1.3 Methodological Approach

The methodology is organised as a series of phases. The first phase comprises a review of the literature on port logistics, on the digitalisation of port operations and on the modelling approaches used to study terminal performance, with emphasis on the representation of seaside and landside flows and on the methods used to evaluate and improve the allocation of handling resources. This review delimits the theoretical ground on which the study is built and supports the modelling choices that follow.

The second phase consists of the analysis of the case study and its operations. This phase describes the operation of Terminal XXI, examines the current process and identifies its critical points. This analysis also establishes the baseline as a reference for subsequently evaluating alternative operational configurations.

The third phase concerns the definition and characterisation of the problem to be addressed. Building on the insights gained in the previous phase, the boundaries of the system, the decision variables, the sources of variability and the performance measures of interest are formally established, so that the problem is stated in terms suitable for modelling.

The fourth phase develops the simulation modelling. Simulation is chosen because the phenomenon under study is dynamic and stochastic, as the arrival of vessels and trucks, the variability of handling times and the resulting competition for the yard cranes cannot be captured adequately by a static formulation. The simulation model reproduces the joint operation of the two flows, allowing alternative resource configurations and coordination strategies to be examined under realistic variability. This approach makes it possible to quantify the trade-offs between cost and performance.

The final phase comprises the testing of the simulation model and the comparative evaluation of multiple scenarios to support decision-making. Each scenario is assessed against the baseline in terms of congestion, service to trucks and the associated investment cost. By allowing different scenarios to be tested, the simulation approach provides the decision-maker with the information required to make an informed choice regarding the dimensioning and coordination of the terminal's resources.

1.4 Document Structure

The dissertation is organised as follows. The present chapter has introduced the context and motivation of the work, the objectives and the methodological approach. The second chapter reviews the relevant literature, covering the role of ports in international trade, the digitalisation of port operations and the simulation approaches used to study terminal performance and the interaction between seaside and landside flows.

The third chapter characterises the problem in the specific context of Terminal XXI, describing its infrastructure and resources, the current operation and the entities involved, with particular attention to the yard cranes and to the arrival of vessels. The fourth chapter presents the development of the model, detailing the assumptions, parameters and logic through which the interaction between the two flows and their competition for resources are represented. The fifth chapter reports and discusses the results obtained for the different scenarios and resource configurations, comparing them against the reference baseline. The final chapter draws together the main conclusions, considers the limitations of the work and identifies directions for future research.

Chapter 2

Literature Review

This chapter presents a review of the scientific literature underpinning the study of truck scheduling and landside operations in container terminals. Section 2.1 examines the dynamics of port logistics and global supply chains, highlighting the strategic role of maritime transport, the operational structure of container terminals and the growing relevance of the Port of Sines within the national and international logistics landscape. Section 2.2 explores the technological transformation of port systems, focusing on the digitalisation of terminal operations and the emergence of the smart port paradigm, supported by Industry 4.0 technologies such as IoT, AI, Digital Twins and automated gate systems. In Section 2.3, the literature on Truck Appointment Systems (TAS) is reviewed in detail, identifying their main operational challenges, the evolution from traditional scheduling rules to advanced optimisation approaches and the increasing use of mathematical models, heuristics and metaheuristics to manage truck arrivals efficiently. Finally, Section 2.4 discusses the role of simulation modelling in the analysis of port systems, comparing the main simulation paradigms and emphasising the predominance of Discrete Event Simulation in studies addressing container terminal operations.

2.1 Port Logistics and Supply Chain Dynamics

Globalisation has opened most countries to trade with distant regions. Supply chains have therefore become critical, since national economic resilience depends on their effectiveness. This growing logistical demand has led to an increase in the volume of goods transported across all modes of transport (road, rail, maritime and air) [54]. Given the essential role of logistics in everyday life, research interest in optimising resources in this field has naturally grown. This aligns with the fundamental definition of logistics, which is to facilitate the transportation of goods as efficiently as possible, that is, ensuring fast delivery at low cost, while meeting deadlines and quality constraints [33].

It is within this context that maritime transport emerges as the primary logistical mode, given its higher cargo capacity than that of other modes and a lower cost per tonne-kilometre. Consequently, it is responsible for approximately 80% of the volume of international trade in goods

[55].

Considering data on port logistics, Portuguese ports handled approximately 82 million tonnes of cargo in 2025. Among them, the Port of Sines stands out at the national level, handling around 42.1 million tonnes, thus representing the largest logistics platform in the country [9]. These figures highlight the strategic importance of maritime freight transport for the national economy, as well as the significance of the Port of Sines within this context.

The efficiency of supply chains critically depends on logistical nodes, namely ports. From an operational perspective, a container terminal can be divided into five main, interdependent areas [15]:

- **Berth** — the section of water alongside the terminal where vessels moor while they are being loaded and unloaded.
- **Quay** — the adjacent stretch of platform on which the quay cranes operate, transferring containers between the vessel and the terminal.
- **Transport Area** — the space through which containers are moved between the quay and the storage yard, usually by internal vehicles such as terminal tractors, straddle carriers or automated guided vehicles.
- **Storage Yard** — the area where containers are stacked and held temporarily between their arrival and their departure to the hinterland, and where yard cranes perform the storage and retrieval operations.
- **Gate** — the point of entry and exit for external trucks, where the documentation, inspection and registration of containers take place before they are admitted to or released from the terminal.

The berth and the quay are considered part of the maritime side, while the storage yard and the gate belong to the landside. The transport area is the interface between the two. Figure 2.1 illustrates these areas on a container terminal layout.

Regarding port operations, a berth is assigned to each vessel arriving at the terminal; after mooring, quay cranes unload the containers, which are then moved to the storage yard by internal transport vehicles, such as automated guided vehicles or manned tractors [35]. Depending on their final destination, containers may be transshipped onto another vessel or dispatched through the terminal gate for onward transport to the hinterland by truck or rail.

In summary, the evolution of logistics requirements points toward a systemic integration in which ports act as critical nodes within the overall operation, whose sustainability and operational efficiency are essential for a country's economic stability and growth.

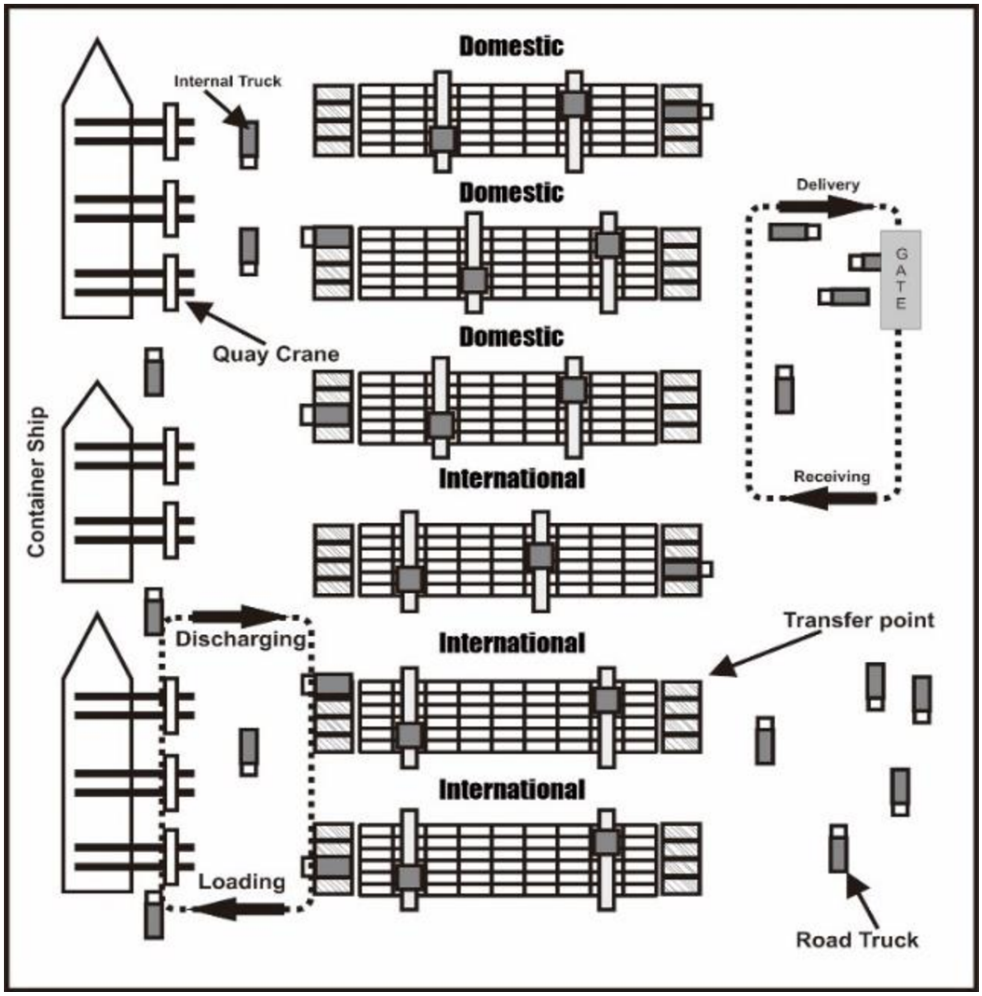


Figure 2.1: Example of a Layout of a Container Terminal [42]

2.2 Technology Applied to Port Logistics

As discussed in the previous section, trade has become increasingly globalised, marked by the decentralisation of production and the rise of large-scale manufacturing systems. This leads supply chains to face increased pressure to seek and implement solutions that enhance their levels of efficiency and flexibility. This demand for improved performance in this area is intrinsically connected to the evolution of industrial and logistics paradigms, being driven forward through the application of Industry 4.0 principles [40] [39]. In this context, traditional ports, which still exhibit low levels of digitalisation and a predominance of manual processes, show increased difficulty in responding in a timely and sustainable manner to the dynamics of global trade [29]. The lack of coordination among the various stakeholders in the logistics chain and the insufficient sharing of information between them often result in congestion, prolonged waiting times and a deterioration of operational efficiency, especially during peak activity periods [20].

To address these limitations, the concept of the **smart port** emerges, representing a more advanced generation of ports supported by technological solutions that enable ports, their users and

their workforce to improve the efficiency of their activities, generating benefits across the entire supply chain [51]. This concept essentially reflects the incorporation of Industry 4.0 digital technologies into the port domain: technologies such as the **internet of things** (IoT), big data, artificial intelligence (AI), **digital twins** and blockchain enable port operations to become driven by real-time data [51]. Their implementation facilitates interoperability between logistics platforms and multi-stakeholder collaboration, allowing more efficient resource allocation, the anticipation of operational constraints and improved management [6]. To support these new capabilities, several data collection and management technologies are employed, such as Radio Frequency Identification (RFID), Optical Character Recognition (OCR), Automated Guided Vehicles (AGVs), Electronic Data Interchange (EDI) and Wireless Sensor Networks (WSNs), which play a structural role in the logistical modernisation of container terminals [44].

Another application of technology in this port process is the implementation of the so-called **smart gates**, which replace manual inspection with automated verification processes. These rely on smart-lane signaling, automatic license plate and container code recognition, self-service kiosks, damage inspection systems and biometric identification equipment for drivers [44] [28]. Additionally, smart scheduling systems can be used to manage the flow of truck arrivals based on the real-time availability of terminal resources, including container location in the yard, vessel berthing schedules and crane availability [35]. The effectiveness of these systems is maximised when they are integrated into a Smart Mobility Management ecosystem that coordinates landside and seaside flows in a holistic manner [35].

Digital transformation at the port level can also involve the use of Digital Twins, which, when applied to a port as in the context of this case study, can be defined as a system of models and algorithms that describe the complex interaction of various port processes and operations. This enables the identification of historical inefficiencies, provides a comprehensive view of the current state and generates forecasts through the simulation of hypothetical scenarios, such as the implementation of changes to port processes [34].

The digitalisation of port terminals not only increases the efficiency of maritime logistics processes but also represents a step toward sustainability, as demand forecasting and the reduction of truck idling time while waiting directly contribute to lowering greenhouse gas emissions [4].

Thus, the application of technology to traditional ports and the transition toward smart ports is not merely a technological upgrade, but rather a necessary paradigm shift to maintain the competitiveness of port infrastructures, both in terms of the challenges of the green transition and the resilience requirements of modern supply chains [6].

2.3 Truck Appointment Systems

Given the sustained growth in containerised maritime transport and the pressing need to increase the productivity of port terminals, the planning of heavy vehicle arrivals has emerged as one of the most critical issues in landside logistics. Truck arrivals are irregular, port resources limited and

time windows rigid. Without effective coordination, this combination leads to congestion, long waiting times and systemic inefficiency [17].

From an operational perspective, container terminals interface with the external environment through two distinct dimensions: the maritime side and the landside. With regard to the latter, the primary objective is to ensure a uniform distribution of arrivals throughout the day, thereby reducing truck turnaround times and ensuring compliance with container delivery deadlines [35]. In this context, the storage yard plays a critical role as a buffer zone between quay operations and landside activities and its occupancy rate should remain below 80% in order not to compromise the performance of handling equipment [15]. Over the past decades, several approaches have been explored to regulate access flows, ranging from interventions in gate infrastructure to the implementation of congestion information systems. More recently, digital access control platforms, particularly appointment systems, have emerged and have dominated the scientific research landscape over the past decade [35].

Traditional arrival management methodologies are based on simple deterministic rules such as First Come, First Served (FCFS) or Earliest Due Date (EDD), which have proven to be insufficient to meet the demands of modern terminals. By disregarding the terminal's effective capacity and failing to promote a balanced distribution of demand over time, these approaches lead to resource allocation imbalances and peak periods characterised by high congestion [26]. The strict application of the FCFS rule in terminals with operational constraints results in the formation of long queues, whereas introducing greater flexibility into this rule yields immediate operational improvements [21]. In line with these findings, studies show that FCFS performs worse than well-synchronised time-window systems in terms of transit times and CO_2 emissions, highlighting the unsustainability of such practices in the current context [46].

By virtue of these limitations, the literature has highlighted **Truck Appointment Systems** (TAS) as an effective solution to promote a balanced distribution of demand and enhance the overall efficiency of container terminals [58]. These systems allow logistics operators to book specific time slots in advance for container pick-up or delivery operations, thereby introducing greater predictability into operational management. A systematic review by Lange et al. [35] found that 67% of the analysed studies employed appointment systems to achieve their objectives, most of which were based on the allocation of individual slots per operation. Im et al. [32] further demonstrated that the effectiveness of these systems increases when combined with penalty policies for non-compliance. Additionally, the strict definition of time windows and the control of entry rates per time interval help to prevent overloads in critical resources such as yard cranes [16].

More recently, research has explored dynamic allocation mechanisms that enable real-time rescheduling, particularly in response to disruptions such as vessel arrival delays [57]. The integration of digital pre-booking platforms with real-time operational data paves the way for proactive vehicle flow management, mitigating the impact of simultaneous arrivals and optimising the utilisation of handling equipment [24]. The emerging paradigm in the literature points toward bilaterally negotiated time windows, where the adopted solution seeks to maximise the joint benefit

of terminals and trucking companies [35].

The optimal resolution of the truck–time window allocation problem requires mathematical models capable of capturing the complexity of the involved variables, including container locations, crane availability and trucking companies' preferences [10] [41]. These problems are typically formulated as Mixed-Integer Linear Programming (MILP) or Integer Programming (IP) models, which allow discrete decision-making under multiple simultaneous constraints. However, their combinatorial nature classifies them as NP-hard, making their exact solution computationally intractable as problem size increases [59]. Interdependent decisions, such as time window assignment, coordination with quay operations and verification of equipment availability, make the solution space grow exponentially. Solving such problems therefore requires approximate methods that deliver high-quality solutions within acceptable computational times[13].

In this context, heuristics have emerged as key tools for obtaining feasible solutions efficiently, being particularly suited to environments that require high operational responsiveness [30]. The concept dates back to the 1950s, having originated in the field of artificial intelligence to address complex problems without guaranteeing optimality, yet with recognised practical efficiency. In truck scheduling contexts, methods such as greedy algorithms, first-fit strategies, or variants based on priority rules, such as request flexibility or remaining time until due date, are commonly employed. For larger-scale and more complex problems, metaheuristics, such as Simulated Annealing, Genetic Algorithms, Tabu Search and Ant Colony Optimisation enhance the exploration of the solution space, enabling escape from local optima and the simultaneous consideration of multiple criteria, such as emission reduction and waiting time minimisation [52, 27]. These techniques, consolidated since the 1990s, have been widely applied in the port context. The most recent trend points toward hybrid approaches that combine heuristics with machine learning, with the aim of producing increasingly adaptive and scalable solutions [19, 50]. Machine learning is used either to generate predictions that the decision procedure treats as parameters, or to guide the search within the solution algorithm itself, while the heuristic remains responsible for producing feasible solutions within the response times that real-time operation requires.

2.4 Simulation Modelling

2.4.1 Simulation as a Tool for the Analysis of Real Systems

Simulation modelling constitutes a widely adopted methodological approach for the study of complex systems. Simulating the behaviour of a real system over time involves creating an artificial history of that system, which can then be observed to draw conclusions regarding the operational characteristics of the real system [11]. The need to resort to simulation arises when direct experimentation on the real system is infeasible, excessively costly, or disruptive to ongoing operations [36]. Simulation is also applied when prototyping or experimenting with the real system is impossible or economically prohibitive [14].

The fundamental distinction between analytical models and simulation models lies in the treatment of time and complexity. Analytical models produce results that depend functionally on a set of input parameters, becoming insufficient when an analytical solution does not exist or is difficult to obtain, or when the temporal dynamics of the system are critical to understanding the problem [36]. Simulation, by contrast, captures the evolution of the system state over time, representing both continuous and discrete processes and revealing emergent behaviours resulting from the simultaneous interaction of multiple components [14].

The usefulness of any simulation model is conditioned by its validity, that is, by the degree to which it constitutes a sufficiently accurate representation of the real system to achieve the specific objectives of the study, with the appropriate level of detail depending on the intended use and on the costs of developing the model [36].

On the other hand, a model is credible when the decision-maker and the other stakeholders in the project accept it as correct [36]. The two properties are independent, as a valid model may fail to be credible simply because its fundamental assumptions are not understood or accepted, while a model may be perceived as credible on the strength of an impressive animation and still rest on incorrect assumptions. Regular interaction with the decision-maker throughout the project is therefore important, both to ensure that the correct problem is being addressed and that the underlying assumptions are understood and accepted, and to reinforce the model's credibility as the work progresses [36].

2.4.2 Simulation Paradigms

The literature identifies three major simulation paradigms: **System Dynamics** (SD), **Discrete Event Simulation** (DES) and **Agent-Based Modelling** (ABM), each being suited to different levels of abstraction and different types of research questions [14].

Beginning with System Dynamics, this paradigm was developed with the objective of studying the information feedback characteristics of industrial activity and the manner in which organisational structure, policies and time delays influence the performance of complex systems [14]. The SD paradigm represents real-world processes in the form of stocks, flows between those stocks and variables that determine flow values, adopting an aggregated and policy-oriented perspective [25]. The SD paradigm operates at the highest level of abstraction: system elements are treated as continuous quantities, without individuality or distinction between items within the same stock [25]. This approach is particularly suitable for understanding macro-level trends, long-term policy dynamics and global causal dependencies [14]. The limitation of SD lies in this abstraction: by not considering individual entities and events, it is generally inadequate for capturing the operational complexity of systems where the individual behaviour of each actor has direct relevance to the outcomes [18].

On the other hand, Discrete Event Simulation formalises a modelling approach based on the concepts of entities, resources and process flowcharts [14]. In DES, the state variables of the model only change at discrete points in time corresponding to the occurrence of events, with activity durations and delays affecting the sequence of those events. Entities may compete for system

resources, forming queues and each event updates the system state while releasing or occupying resources [11]. DES operates at a low to intermediate level of abstraction and is particularly suited to systems where processes are inherently sequential, event-driven and resource-constrained [18]. The quality of discrete event simulation models depends strongly on the quality of the input data, with compatibility between data sources and the simulation model being a critical factor for successful modelling [48].

Agent-Based Modelling, in turn, is the most recent of the three paradigms to achieve practical maturity and its distinguishing characteristic is its decentralised nature [14]. ABM is particularly useful for understanding real systems in which the representation or modelling of multiple individuals with autonomous behaviours is determinant, offering new and relevant possibilities for production systems and supply chains [43]. Unlike SD and DES, where the global system logic is centrally defined, ABM distributes behavioural rules among the individual agents themselves and collective behaviour emerges from the interactions between those agents within a shared environment [14]. An important advantage of ABM is that it enables the construction of models even in the absence of knowledge regarding the global dependencies of the system: provided that the individual behaviour of participants is understood, it becomes possible to build the model and observe the resulting emergent global behaviour [14]. The focus of ABM lies in the simulation of entities and their interactions, where each agent possesses its own thread of control [43]. Furthermore, ABM is applied across all levels of abstraction, ranging from highly detailed physical models to high-level strategic models, distinguishing it from the SD and DES paradigms, whose natural domains of application are more restricted [14].

2.4.3 Application of Simulation in Logistics and Port Systems

The application of simulation to container terminal operations has a well-established tradition in the academic literature, with the use of simulation models in the development of ports and container terminals proving demonstrably beneficial over the past 50 years [18]. As a more recent example, simulation is present in around 24% of scientific publications on Truck Appointment Systems (TAS) [35], which demonstrates the continued relevance of this tool.

Since port activity is event-driven and constrained by terminal process resources, where vessels, trucks, cranes and yard equipment interact simultaneously under uncertain conditions, the DES paradigm has consistently emerged as the dominant modelling paradigm in this domain [18, 13]. This logic naturally fits terminal operations, in which activities such as truck arrivals, crane assignment and gate releases are inherently sequential and resource-dependent [7].

2.5 Summary

To summarise, the literature reviewed in this chapter establishes the theoretical and methodological foundations upon which this dissertation is built, providing the necessary context to frame the problem of truck scheduling and landside operations at container terminals.

Section 2.1 demonstrated that maritime transport plays a central role in global supply chains, where ports operate as critical logistical nodes whose operational efficiency directly influences the performance of the entire supply chain. This underscores the importance of studying issues related to port operations to enhance overall efficiency, particularly given the growing strategic relevance of logistics for global economic competitiveness and sustainability.

Section 2.2 examined the technological transformation underway in port systems, driven by the principles of Industry 4.0 and reflected in the emergence of the smart port paradigm. The role of smart scheduling systems and digital pre-booking platforms is particularly relevant to this work, as these tools enable the coordination of truck arrivals with terminal resource availability.

Section 2.3 reviewed the literature on Truck Appointment Systems (TAS), which constitutes the primary operational mechanism for regulating landside access at container terminals. The mathematical complexity of the underlying optimisation problems was highlighted, thereby justifying the use of heuristic and metaheuristic methods, as well as simulation-based approaches, to obtain high quality solutions within acceptable computational times.

Finally, Section 2.4 examined the role of simulation modelling in the analysis of port systems. The three major simulation paradigms were compared and the comparison showed a predominance of Discrete Event Simulation in container terminal studies, due to its alignment with the sequential, event-driven and resource-constrained nature of terminal operations. The importance of model validity and credibility was also emphasised, reinforcing the methodological rigour required for the development of the simulation model.

These weaknesses and gaps justify and motivate the research undertaken in this dissertation, which seeks to address the identified challenges through a simulation-based analysis of resource allocation and truck scheduling dynamics.

Chapter 3

Context and Problem Characterisation

This chapter presents the problem that motivates the study of landside performance, using Terminal XXI of the Port of Sines as a case study. Section 3.1 outlines the broader context in which the problem emerges, emphasising the growing pressure on port–hinterland connectivity, the structural imbalance between truck arrivals and terminal processing capacity and the resulting congestion at the gate. Section 3.2 provides a formal characterisation of the problem, describing the terminal's physical layout, the interdependence between the quay, yard and gate subsystems and the operational constraints that shape container retrieval activities. Section 3.3 presents the As-Is process, detailing the sequence of activities currently implemented for truck access, verification and container pickup, as well as the decision points that govern the flow of operations. Finally, Section 3.4 characterises the key entities involved in the process, namely the gate, the container yard, the yard cranes and the vessel arrival patterns, providing the structural and operational parameters required for the development of the simulation model.

3.1 Problem Context

International maritime freight transport forms the backbone of the global economy and, despite the significant benefits it provides to economies and communities, it also generates complex challenges in the management of ports and container terminals. A central issue is the variability of external truck arrival times [22]. Peaks over-utilise terminal resources, while troughs leave the same resources idle. This phenomenon creates a particularly challenging operational management scenario, further aggravated by the fact that port operators tend to prioritise maritime operations, generating a structural imbalance in the allocation of available resources for serving external trucks [13].

During peak periods, the excess number of trucks can cause congestion, increased pollutant emissions and long queues, while during periods of lower activity operational efficiency is compromised due to the underuse of available resources.

The port's resources therefore require careful management to serve both trucks and trains transporting cargo to the hinterland, as well as the vessels arriving with new containers to be placed in the appropriate yard locations. This resource management should be aligned with intelligent scheduling systems that regulate truck inflows. Such systems distribute demand across time windows and match it to the terminal's actual capacity. With this more rational and anticipatory management of access schedules, the goal is not only to mitigate truck congestion upstream of the gate, thus reducing urban traffic around the port, but also to promote more sustainable and safer practices, in line with the principles of modern logistics [13, 10].

In the specific context of Terminal XXI at the Port of Sines, the scheduling process is carried out mainly according to the preferences of road transport companies, resulting in insufficient coordination with terminal resources. This approach leads to an unbalanced distribution of arrivals throughout the day, causing long waiting times for trucks and operational inefficiencies in the process. The situation has become increasingly critical, with congestion extending from the gate to the Vale Marim roundabout, generating delays, greenhouse gas emissions and systemic logistical inefficiencies [44]. A satellite image of the terminal is shown in Figure 3.1, identifying the gate, the Vale Marim roundabout and the location of the future pre-gate.



Figure 3.1: Satellite Image of the Gate Access and the Future Pre-Gate Area [44]

Additionally, the study by Pereira et al. [44] documents structural weaknesses in the current yard access process, namely excessive reliance on paper-based procedures, lack of integration between information systems, inadequate infrastructure and interoperability challenges.

In response to these issues, the Port Authority of Sines and the Algarve, in collaboration with other entities, has been developing an **intelligent pre-gate** solution upstream of the terminal. Implementing this system aims to redirect truck traffic and modernise terminal entry. Compared with the existing manual setup, the new process is faster and more efficient, thereby reducing gate queues, waiting times and environmental impacts [44].

3.2 Problem Characterisation

The case study under analysis occurs at Terminal XXI, located in the Port of Sines. This is the largest container terminal in Portugal and one of the most relevant in the Iberian Peninsula [8], operated by PSA Sines, S.A.. In terms of capacity, the infrastructure currently comprises a quay measuring 1,150 + 200 metres in length, equipped with 10 post-Panamax cranes and 2 super post-Panamax cranes. Additionally, it includes a storage area of 42 hectares and an annual handling capacity of 2.7 million TEU. Its maritime infrastructure features natural depths of up to 17 metres relative to hydrographic zero (ZH), enabling the reception of large container vessels operating on intercontinental routes[5].

Within the container yard, the yard cranes at the Port of Sines currently total more than 35 units, following the recent introduction of six aRTGs [45]. These cranes move cargo within the storage yard, storing containers upon arrival and subsequently retrieving them for onward transport to the hinterland by road or rail. This set of equipment positions Terminal XXI as a critical logistics hub, whose performance has a direct impact on the entire supply chain it serves.

Regarding the layout of the Port of Sines, Terminal XXI follows the conventional structural organisation of container terminals, being functionally divided into three interdependent subsystems. The berth system constitutes the maritime interface, where ship-to-shore cranes transfer containers between vessels and the terminal. The yard system is responsible for the storage, handling and internal movement of containers, managed by yard cranes operating over organised stacks. Finally, the gate system serves as the interface between the terminal and the hinterland, functioning as the entry and exit point for external trucks. Figure 3.2 illustrates the spatial configuration of Terminal XXI, highlighting the distribution of yard sectors and their relative position to both the quay and the gate.



Figure 3.2: Scheme of the Yard Layout of Terminal XXI

The main operational challenge emerges within this last subsystem, in the management of

container pickup and delivery operations at the interface between the terminal and the hinterland. Coordinating maritime, rail and road access in alignment with internal yard operations constitutes a complex task. The primary difficulty arises from the absence of effective coordination mechanisms, particularly in the road transport domain, which leads to overlapping activities, inefficient utilisation of available resources and recurrent congestion within the terminal.

This structural imbalance between truck arrivals and internal resource availability is what motivates the objectives and research question set out in Section 1.2 and what the simulation model developed in the following chapter is designed to investigate.

3.3 "As-Is" Container Pickup and Appointment Process

Understanding the current operational process is essential prior to developing any simulation model capable of evaluating alternative scenarios or supporting informed decision-making. For this reason, the present section characterises the As-Is process, what is currently implemented at Terminal XXI for the management of container pickup appointments and the corresponding retrieval operations, that is, the sequence of activities that begins with the submission of a pickup request by a transport operator and ends with the departure of the container from the yard on an external truck. The characterisation details this sequence, the interaction between the landside and yard subsystems and the constraints that shape operational performance, establishing the reference baseline against which alternative resource allocation strategies and scheduling policies are assessed in the following chapters. Figure 3.3 presents a schematic representation of this process, capturing the main operational flows and decision points that should be incorporated into the simulation model.

The truck collection process begins with the submission of a request to pick up a specific container, for which a determined time window is suggested. The terminal should then verify whether this request complies with the established requirements, namely whether the proposed time window falls within the terminal's operating hours and whether it occurs before the maximum authorised pickup deadline for that specific container. In this As-Is process, there is a maximum limit of 30 pickups per time window, meaning that any requests submitted after this limit has been reached are automatically rejected.

Once the appointments have been scheduled, trucks begin arriving at the queue upstream of the gate during their assigned time window, exhibiting variability in their arrival times. Trucks wait in the queue until they reach the gate, where verification and control procedures are carried out. After completing this process, they are granted access to the terminal to collect the container associated with their request, as soon as a yard crane becomes available to handle it. Once this condition is met, the truck proceeds to the yard sector where the requested container is stored and completes the pickup operation.

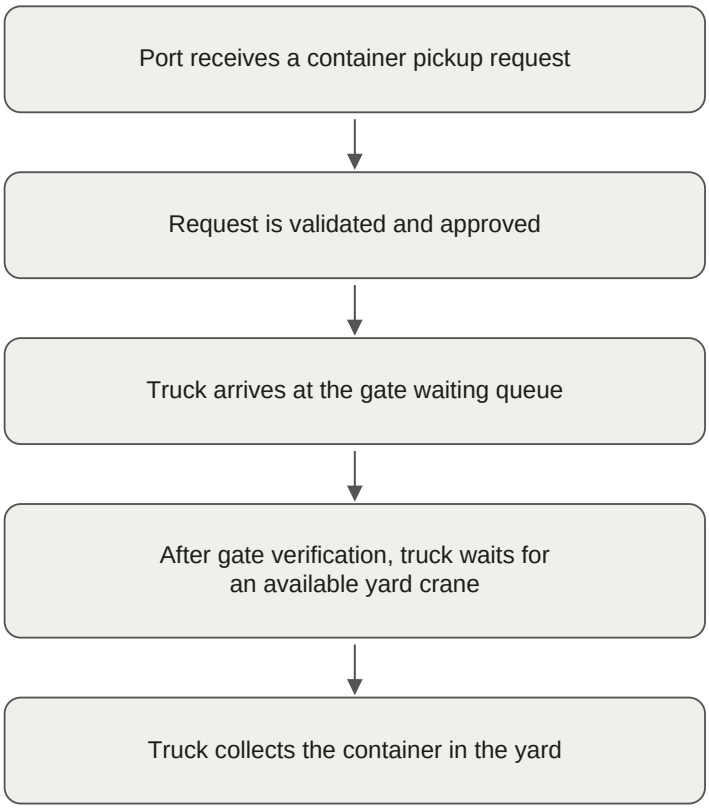


Figure 3.3: Diagram of the Process "As-Is" Stages

3.4 Characterisation of the Entities in the Process

3.4.1 Access to the Terminal

An essential component of the process concerns the access granted to trucks entering the terminal to collect containers, a procedure managed by the gate subsystem. Container collection is restricted to the port's operating hours, which extend from 08:00 to 22:59, with scheduled breaks for lunch (12:00–12:59) and dinner (20:00–20:59). Within this operating period, activities are organised into one-hour time slots and container pickup requests are allocated accordingly.

To perform a collection, a truck should hold a valid **pickup request**, meaning that it has secured a designated time window. The truck should also comply with the authorised **pickup deadline** associated with the respective container, as a failure to meet this deadline results in the container being blocked within the terminal, thereby preventing its retrieval. Once a valid request is confirmed, the driver should wait at the gate until access to the terminal is authorised. During this stage, identity verification is conducted, the access request is validated and the required documentation for the pickup is completed.

After completing the documentation and control procedures, the truck may enter the terminal only if a yard crane is available to service the request. Access is therefore contingent upon internal resource availability, reinforcing the interdependence between gate operations and yard handling

capacity.

3.4.2 Container Yard

Following the operational flow of the port system, attention now shifts to the container yard, where containers are stored after their arrival at the terminal and remain until they are dispatched to the hinterland.

This subsystem is organised into **blocks** of containers, which are rectangular storage areas comprising several rows of containers stored side by side and on top of one another. Each block is further structured into **bays**, **stacks** and **tiers**, as illustrated in Figure 3.4. A bay is a cross-section of the block taken perpendicular to its longitudinal axis, corresponding to the set of storage positions that the crane can reach without moving along the block. A stack is the vertical pile of containers held at a given position within a bay, while a tier denotes the vertical level occupied by a container within that stack, numbered from the ground upwards. A **storage slot** is therefore uniquely identified by the combination of block, bay, stack and tier to which the container is assigned.

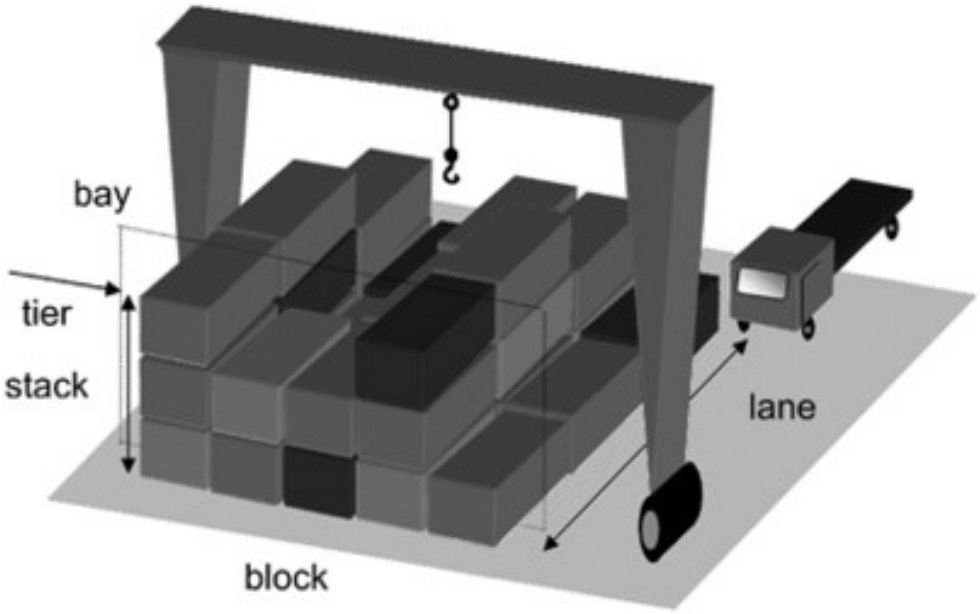


Figure 3.4: Description of a Block of Containers
[38]

3.4.3 Yard Cranes

Yard cranes constitute the central component of the system, since they both store the containers unloaded from vessels and retrieve those requested by external trucks. Their relevance lies in their ability to handle containers through both vertical and horizontal movements, making them indispensable in the port context. These resources stand out primarily due to their high lifting capacity,

axial mobility and, notably, their ability to handle containers of different sizes and weights. Additionally, these cranes improve operational safety and maintain the processing speed required for efficient terminal operations.

A yard crane is composed mainly of the gantry and the trolley, as shown in Figure 3.5. The gantry is the crane's main supporting structure, consisting of two vertical A-shaped legs connected by a horizontal beam. It rests on fixed rails laid on the ground, the gantry tracks, along which the whole structure travels longitudinally. This movement, known as gantry motion, positions the crane along the length of the block, allowing it to serve any bay within its working zone. The trolley is the carriage mounted on the horizontal beam, which travels transversely along it. This perpendicular movement, known as trolley motion, positions the load over any stack within the selected bay. Together, the two motions allow the crane to reach any point in the horizontal plane of the block. The load, in this case a container, is suspended from the trolley by a rope, whose hoisting and lowering give access to the different tiers of a stack.

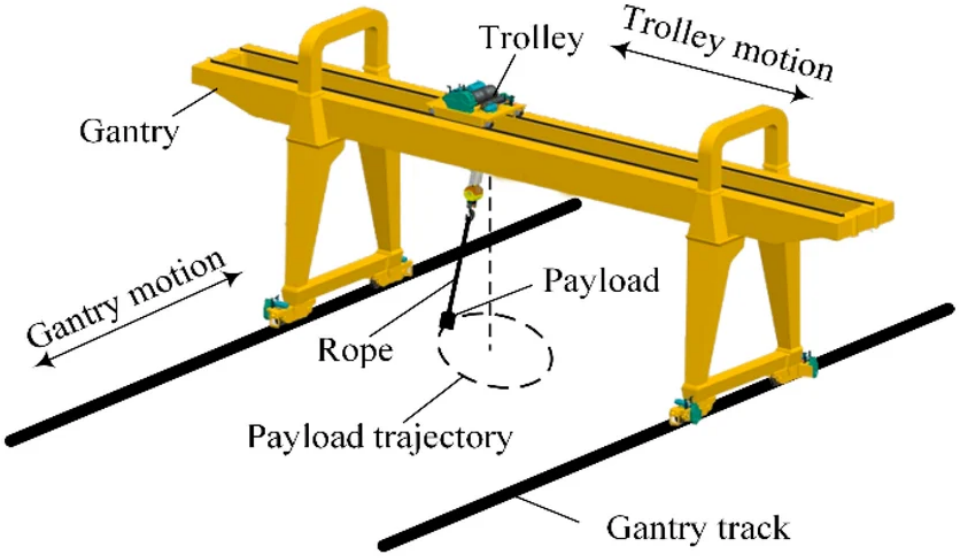


Figure 3.5: Structural Components of a Yard Crane
[49]

Regarding the technical capabilities of the yard crane, the model considers the values presented in Table 3.1 for acceleration and speed, according to the different scenarios to which the crane may be subjected, based on [53, 37].

Table 3.1: Yard Crane Technical Specifications

Speed	**Value**
Loaded/empty gantry travel	220 m/min
Loaded/empty trolley move	120 m/min
Loaded/empty hoisting/lowering	75 m/min
Acceleration/Deceleration	**Value**
Gantry	0.4 m/s^2
Trolley	0.4 m/s^2
Hoisting/Lowering	0.35 m/s^2

Beyond their technical performance, yard cranes should also be characterised in terms of cost, since each additional unit represents a substantial fixed investment. In January 2023, PSA Sines awarded Konecranes a contract for six fully electric automated Rubber-Tyred Gantry cranes (aRTG), delivered in the first quarter of 2024 as part of the Phase III expansion of Terminal XXI [2]. However, as is common practice in this sector, the value of the order was not disclosed, making it necessary to estimate a unit cost from comparable market references.

A conventional Konecranes RTG of similar specification was priced at approximately 1.75 million euros per unit in the 2019 Georgia Ports Authority order [1], a value consistent with the 1.8 to 2.0 million euros reported by port operators for this equipment class [23]. Based on data gathered from port operators, Gattuso and Pellicanò estimate that automation adds 8% to 10% to the purchase cost of the crane itself, pricing an aRTG at approximately 2.2 million euros [23].

3.4.4 Ship Arrival

In the port context, the arrival of vessels constitutes one of the most critical stages of the entire operational system, as they are responsible for transporting the containers that supply the terminal and, in many cases, for dispatching goods to other destinations. Since ports receive several categories of vessels, which differ in size and consequently in cargo-handling capacity, this section compiles, in Table 3.2, data describing these characteristics for each vessel type. The information is expressed in TEUs (Twenty-Foot Equivalent Units), following the classification presented in [56].

Table 3.2: Cargo-handling Capacity for Each Type of Vessel

Type of Vessel	**Cargo-handling Capacity (TEUs)**
Small feeder	Up to 1,000
Feeder	1,000 to 2,000
Feedermax	2,000 to 3,000
Panamax vessels	3,000 to 5,000
Post Panamax vessels	5,000 to 10,000
New Panamax vessels	10,000 to 14,500
Ultra Large Container Vessel (ULCV)	14,500 and above

These values are expressed in TEUs, a widely adopted unit of measurement in the port and maritime logistics sectors, as it provides a straightforward representation of cargo-handling capacity. This convention stems from the fact that containers typically have either a 20-foot or a 40-foot length, corresponding respectively to 1 TEU and 2 TEUs.

3.5 Summary

This chapter established the operational foundations of the dissertation by characterising the problem under study and detailing the processes and entities that shape landside performance. The structural imbalance between truck arrivals and terminal processing capacity was first contextualised, highlighting how insufficient coordination between gate operations, yard handling resources and vessel-driven inflows generates recurrent congestion and extended truck turnaround times.

The As-Is process description then provided a sequential view of truck appointment scheduling, gate verification procedures and container retrieval operations, identifying the decision points and constraints that govern system behaviour. Finally, the characterisation of the main operational entities supplied the structural information necessary to represent the terminal in a computational environment.

Together, these elements form the conceptual basis for the simulation model developed in the following chapter. By translating the operational logic, constraints and resource interactions described in this chapter into a formal modelling framework, the simulation enables the systematic evaluation of alternative resource configurations and scheduling strategies.

Chapter 4

Simulation Model

This chapter presents the simulation model developed to represent the operation of a port and to evaluate the alternative resource configurations that address the research question stated in Chapter 1.

Section 4.1 describes the framework adopted, following the seven-step approach proposed by Law, and defines the performance measures used to compare the configurations under study. Section 4.2 discusses simulation as a modelling approach, justifying its suitability for a system characterised by stochastic arrivals, resource interdependencies and dynamic queue formation. Section 4.3 introduces FlexSim, the discrete-event simulation software in which the model was implemented, together with its Process Flow module. Section 4.4 defines the entities that compose the model, namely the gate, the yard, the vessel arrivals and the task executers that operate within the terminal, specifying the structural and operational parameters assigned to each of them. Section 4.5 details the process flows that implement the operational logic, covering the placement of the initial containers, the arrival of vessels and the storage of their containers, and the collection of containers by external trucks. Finally, Section 4.6 presents the two models developed. Model 1 reproduces the current operation of the terminal and provides the baseline, while Model 2 makes the rate of truck arrivals conditional on the state of the crane pool, representing an appointment system aware of the berthing schedule and providing a demand-side alternative to the capacity-based scenarios.

4.1 Simulation Framework

Since a simulation model is a surrogate for experimentation with the actual terminal, any conclusion drawn from it is only as reliable as the model itself. The design of the model therefore followed the seven-step approach proposed by Law [36].

The first step is the formulation of the problem, which fixes the objectives of the study, the specific questions the model should answer and the performance measures used to evaluate the alternative configurations. Without this specification it is not possible to decide on an appropriate level of detail. In the present study, the problem derives directly from the research question stated

in Section 1.2, namely the balance between the service offered to each of the two competing flows and the cost of the yard cranes that serve them. The performance measures adopted to compare the alternative configurations are the following:

- the turnaround time of the external trucks, measured from their entrance to their exit from the terminal;
- the length of the queue upstream of the gate and the waiting time within it;
- the utilisation rate of the yard cranes, separated by the flow that generated each task;
- the number of trucks served per hour, taken as the throughput of the system.

The second step is the collection of information and data and their consolidation into a written assumptions document, which constitutes the conceptual model of the terminal. This document states, in non-computational terms, the entities represented, the sequence of activities each of them follows, the resources they compete for and the distributions that describe the duration of every activity. The data available conditioned the strategy adopted, as where operational records are unavailable, the conceptual model draws on the study of the Sines container terminal published in [44], on the technical specifications of the equipment and on the values reported in the literature on yard crane cycle times [37, 53]. The parameters that describe the terminal's activities are defined as probability distributions rather than fixed values, which allows the model to represent the inherent variability of port operations.

The third step assesses the validity of these assumptions, before any implementation takes place. The assumptions are first confronted with the values reported in the literature and then reviewed with the project manager and subject-matter experts, being corrected wherever inconsistencies are found.

The fourth step is the implementation of the conceptual model in simulation software and its verification. The assumptions document is translated into a FlexSim model, in which the 3D layout reproduces the physical arrangement of the yard and the Process Flow logic reproduces the sequence of activities and the competition for the yard cranes. Verification consists of confirming that this implementation reproduces the assumptions document faithfully, which was carried out by tracing individual entities through the flow, by inspecting the statistics of the sampled distributions against their theoretical parameters and by running the model under simplified conditions whose outcome can be determined analytically.

The fifth step is the validation of the implemented model. The outputs of the baseline configuration are compared with the behaviour of the terminal described in Chapter 3 and with the reference values available in the literature, and the results are reviewed for reasonableness together with the project manager and subject-matter experts. Only once the baseline is judged to represent the current operation with sufficient fidelity can the model be used to draw conclusions about configurations that do not yet exist.

The sixth step is the design and analysis of the experiments. Each scenario is run under identical conditions, namely the same simulated horizon, the same warm-up period discarded from

the statistics and the same number of independent replications, so that the performance measures are estimated with confidence intervals rather than from a single run.

Finally, the seventh step presents and discusses the results, comparing each scenario against the baseline in terms of the performance measures defined in the first step.

4.2 Simulation as a Modelling Approach

Simulation has become a crucial approach for analysing complex logistical systems, particularly those characterised by stochastic behaviour, resource interdependencies and operational variability. Container terminals exemplify such environments, with the incorporation of multiple subsystems that interact dynamically, fluctuation of processing times and the propagation of operational constraints across the quay, yard and gate. Under these conditions, analytical models often become intractable, as they require simplifying assumptions that fail to capture the true behaviour of the system. Simulation, by contrast, enables the representation of detailed process logic, the incorporation of randomness and the evaluation of alternative operational scenarios under controlled and repeatable conditions.

In the context of this dissertation, simulation provides a structured means of examining the interactions between truck arrivals, gate processing capacity, yard crane availability and vessel-driven container inflows. As demonstrated in the literature on Discrete Event Simulation and port logistics, this approach is suited to systems in which entities compete for limited resources, queues form dynamically and performance depends on the sequencing and timing of events. By modelling the As-Is process and testing alternative resource configurations, simulation enables the identification of bottlenecks, the quantification of operational trade-offs and the assessment of strategies aimed at reducing congestion and improving landside performance.

The simulation model developed in this dissertation was implemented in FlexSim and aims to replicate the operational logic of Terminal XXI at the level of individual trucks, containers and yard cranes. This specific software can incorporate the structural characteristics of the gate, yard and vessel arrival processes, as well as the stochastic distributions governing processing times and arrival patterns. Through the construction of a model, it becomes possible to evaluate the impact of varying resource levels, modifying scheduling policies and testing alternative operational scenarios on KPIs, such as truck turnaround times, queue lengths, yard crane utilisation and overall system throughput.

4.3 FlexSim

FlexSim is a discrete-event simulation package, used to model a system as a sequence of events that change its state at separate instants in time and leave it unchanged between those instants, which suits production and logistics systems governed by queues, processing times, transport delays and resource availability. A model is built by connecting objects from a predefined library and editing the parameters of each object to define processing times, capacities and routing rules. Each

parameter accepts either a fixed value or a statistical distribution, which lets the model reproduce the variability of a real facility. FlexScript, an interpreted language with C++ syntax, handles the logic that the library objects do not cover.

A FlexSim model has two complementary layers. The 3D model holds the physical representation of the system, namely the objects that occupy space and the items that move between them, while the Process Flow module holds the logic that governs their behaviour, expressed as a flowchart of activities. The two layers are linked, in the sense that the logic defined in Process Flow can create, move and destroy the objects of the 3D model, and events occurring in the 3D model can in turn trigger activities in the flow.

4.3.1 The 3D Model

The items that circulate through the 3D model are called flowitems. A flowitem is a discrete unit that moves through the system and carries data with it, and in the present model it represents either a container or a truck. Each flowitem carries labels, which are named fields attached to the item and used to store its attributes, such as the identifier of a container, its storage position or the instant at which the truck that came to collect it entered the terminal.

The objects that occupy fixed positions in the layout are known as fixed resources, such as:

- the **source**, which introduces flowitems into the model according to a certain frequency, either an inter-arrival distribution, a predefined schedule or an explicit instruction from the logic layer;
- the **queue**, which holds flowitems while they wait for a downstream resource to become available, and whose contents give the length of the waiting line at any instant;
- the **processor**, which retains a flowitem for a given duration, representing an operation performed upon it;
- the **rack**, which stores flowitems in addressable positions organised into bays and levels, and which is used here to represent the storage slots of the yard;
- the **sink**, which removes flowitems from the model once they have completed their route, marking the end of their path through the system and the instant at which their time in the system is recorded.

The mobile resources are called task executers. Unlike fixed resources, a task executer travels through the layout and performs task sequences, which are ordered lists of elementary instructions such as travelling to a location, loading a flowitem, unloading it or waiting for a given duration. This class includes operators, transporters and cranes, for example. A task executer is a finite resource, so that it is unavailable to any request while it is executing a task sequence.

4.3.2 Process Flow

The Process Flow module expresses the logic of the model as a flowchart. The entity that travels through this flowchart is called a token, and it is the logical counterpart of the flowitem. A token does not occupy space in the layout and is not necessarily visible, its purpose being to carry the state of a process as it advances through the sequence of activities. A token may be bound to a flowitem, in which case the two move in step and the token drives the behaviour of the physical item, or it may be purely abstract and represent an order, a request or an event that has no physical embodiment. Like flowitems, tokens carry labels, which is how information is passed from one activity to the next.

The blocks of the flowchart are the activities, such as:

- the **source** activities, which create tokens, either at intervals drawn from a distribution, at instants fixed by a schedule or in response to an event occurring elsewhere in the model;
- the **delay**, which holds a token for a given duration, drawn from a distribution when the duration is variable, and which is used to represent the time consumed by an operation;
- the **acquire resource** and **release resource** activities, which respectively request and return a unit of a shared resource. A token that reaches an acquire activity when no unit is available waits there until one is released;
- the **decide**, which routes a token along one of several outgoing connectors according to a condition evaluated at that instant;
- the **assign labels**, which writes or updates the data carried by the token;
- the **sink**, which destroys the token once its process is complete.

Two further mechanisms support the exchange of information between the different parts of the model. A list is a shared structure onto which tokens or flowitems are pushed and from which they are later pulled, optionally according to a query that selects the entry best matching a given criterion. A global variable, in turn, is a single value accessible from anywhere in the model, which any activity may read or modify, and which serves to make the state of one flow visible to another.

4.3.3 Experimentation and Statistics

During a run, the software collects the performance measures defined, reporting them through dashboards and exportable tables. Because the model is stochastic, the result of a single run is one realisation among many, and conclusions require repeated execution. The Experimenter automates this, running each configuration for a defined number of independent replications and reporting the performance measures as means accompanied by confidence intervals. It also allows a warm-up period to be specified, during which the model runs but no statistics are collected, so that the measures reflect the steady state of the system rather than the transient that follows an empty start.

4.4 Model Entities

This section defines the entities that compose the model and the data that parametrise each of them. For every entity, such as the gate, the container yard, the arriving vessels and the task executers that operate within the terminal, namely the external trucks and the yard cranes, the structural characteristics and the operational parameters adopted in the simulation are specified. These parameters translate into the simulation environment the characterisation of the terminal presented in Chapter 3 and, where operational records were unavailable, draw on the technical specifications of the equipment and on the values reported in the literature, as described in Section 4.1. Together, they establish the quantitative basis upon which the operational logic of the model, presented in the following section, is executed.

4.4.1 Gate

In the simulation model, trucks arriving during their assigned time window join a queue upstream of the gate, where they wait for processing. To represent truck arrivals, the model uses a Weibull distribution with parameters (1.66, 0.742) minutes. These parameters produce a mean equivalent to 30 arrivals per hour, which corresponds to the limit imposed by the Port of Sines. This distribution also reflects the variability observed in real inbound flows and captures their fluctuations, based on the study by Pereira et al. [44].

Once in the queue, trucks wait for their turn at the gate. There, they undergo the verification stage, which includes identity checks, validation of the access request and completion of the required documentation. The model represents this stage as a combination of deterministic and stochastic components, using a fixed processing time of 7.58 minutes, supplemented by a Weibull (5.2, 1.6) minutes component. This formulation, also defined based on the study by Pereira et al. [44], uses a Weibull distribution to capture the variability inherent in the administrative procedures.

4.4.2 Yard

The simulation model has to specify the spatial and structural parameters required to reproduce yard operations. To do so, for the case under study, each storage slot measures 12.10 metres in length, 2.50 metres in width and 2.50 metres in height. These dimensions were considered as they slightly exceed those of a standard forty-foot container, providing the required operational clearance.

In addition, each container block consists of 13 bays, 6 stacks in width and a maximum of 5 tiers in height. These parameters establish the physical configuration of the yard in the simulation environment. They also provide the structural basis for modelling container placement, container removal and the occurrence of relocation movements.

In the simulation model, 300 containers are also placed at instant zero, randomly distributed across the terminal. This initial condition accounts for the containers already stored at the port before the arrival of any vessel.

4.4.3 Vessel Arrival

The model represents vessel arrivals as a stochastic phenomenon, reflecting the inherent uncertainty of maritime traffic. Container vessels arrive at the Port of Sines at a mean rate of 967 container vessels per year [12], which translates to around 2.65 vessels per day. For this study, a slightly higher rate of 3 vessels per day was established, which corresponds to a mean inter-arrival time of 8 hours. Accordingly, the time between consecutive vessel arrivals follows an exponential distribution with a mean of 8 hours, which corresponds to a Poisson arrival process with a rate of three vessels per day. This approach allows the model to reproduce both periods of concentrated seaside workload and intervals of reduced activity, rather than imposing a deterministic and therefore unrealistic arrival pattern.

The simulation model also assumes a fixed workload of 500 TEUs per vessel arrival. This standardised volume represents an average scenario, even though the terminal accommodates vessels ranging from small feeders to Ultra Large Container Vessels. The model explicitly defines the physical dimensions of the containers, as each forty-foot unit measures 12.03 m in length, 2.40 m in width and 2.39 m in height, aligned with standard ISO specifications. Under the conventional equivalence in which one forty-foot unit corresponds to 2 TEUs, this workload converts to 250 forty-foot containers, the operational quantity used in the simulation.

4.4.3.1 Trucks

Within the simulation environment, external trucks are represented as task executer entities responsible for entering the terminal, travelling to the yard sector where the requested container is stored and completing the pickup operation.

Regarding travel behaviour, the model considers a maximum speed of 30 km/h for all trucks, a value that is consistent with the speed limits commonly enforced within container terminals [44], where the circulation of heavy vehicles is deliberately restricted for safety reasons, given the coexistence of trucks, handling equipment and internal transport vehicles within the same operational space. In addition to the speed limit, the model sets truck acceleration and deceleration at 1.00 m/s^2.

These parameters govern the time required for trucks to traverse the distance between the gate and the assigned yard block, thereby influencing the truck turnaround time, one of the KPIs evaluated in this study.

4.4.3.2 Yard Cranes

The yard cranes are represented in the simulation model as task executer entities responsible for both the storage of containers arriving by vessel and the retrieval of containers requested by trucks, thereby constituting the shared resource around which the contention between the two flows develops. In order to reproduce their movement within the yard, the model assigns the cranes a set of kinematic parameters, in accordance with the technical specifications presented in Chapter 3.

Regarding travel behaviour, the cranes travel at a maximum speed of 120 m/min. Since the simulation environment applies a single travel speed to the overall movement of the crane, rather than distinguishing between gantry, trolley and hoisting motions, this value was adopted as an effective aggregate speed. This value corresponds exactly to the rated trolley speed presented in Table 3.1.

In addition to the speed limit, the acceleration and deceleration of the cranes were both defined as 0.40 m/s^2, also in direct correspondence with the values reported in Table 3.1 and backed by the literature on yard crane cycle-time modelling. These comparatively low values reflect the considerable mass of gantry crane structures and the need to limit payload sway during container handling, which prevents this class of equipment from performing abrupt changes in velocity.

Beyond their travel kinematics, the cranes were assigned a fixed handling time of 2 minutes per load and unload operation. By condensing these sub-operations into a single deterministic service time, the model captures the fixed component of the crane cycle that is incurred at every handling task, independently of the travel distance covered between consecutive positions.

Together, these parameters govern both the time required for the cranes to reposition between consecutive handling tasks and the duration of the handling operations themselves, thereby influencing the rate at which containers are stored in the yard and the waiting time experienced by trucks until a crane becomes available.

4.5 Process Flow

The objects of the 3D model represent the physical structure of the terminal. They define where the blocks stand, the distance a truck travels between the gate and a block, how many containers a stack holds and the speed at which a crane moves. They do not, however, allow the logic behind the process to be defined. It is not possible, for instance, to associate a pickup request with a truck, to define which crane should serve each request, or to define the criteria that govern the relocation of the containers.

The model therefore relies on Process Flow to implement these decisions. This module of FlexSim expresses the logic of a model as a flowchart of activities. Tokens travel through that flowchart and a token is the entity that triggers the logic of each activity it crosses. Unlike the items of the 3D model, a token has no physical representation, as it can correspond to a container, to a request, an order, or a decision that does not exist physically in the terminal.

An activity can create tokens continuously, according to a statistical distribution that defines the time between successive creations and this is how the model reproduces a flow of arrivals subject to variability. It can, alternatively, create tokens according to a schedule defined in a table, when the instants of creation are known in advance. It can also create tokens in response to an event that occurs in the 3D model, such as the entry of an item into an object or the completion of an operation, which links the flowchart to the physical model. Finally, an existing token can create further tokens along its path, which allows a task to be decomposed into the subtasks that compose it.

Each token created carries labels, which store the information that distinguishes it from the others and which the activities consult along the path. A label can hold the identifier of the associated container, the time window assigned, the pickup deadline or the state of the request. Through these labels the state of the system is attached to the entities themselves rather than residing solely in global variables and an activity identifies the object of the 3D model on which it should act.

The logic of the model is organised into three flows, presented below:

- Initial containers, which populates the yard before the operation begins, so that the first trucks find containers to collect;
- Vessel arrival, which converts each vessel call into containers and places them in the yard, consuming the crane capacity that the placement requires;
- Container pickup, which governs the arrival of a truck, its processing at the gate, the relocation of the containers that obstruct the requested one and the retrieval itself.

The three flows do not call one another. They communicate through a list on which the containers stored in the yard are published, so that the first two flows supply the list and the third draws from it. Figure 4.1 presents the process flow of the model, and the following subsections describe each flow in turn.

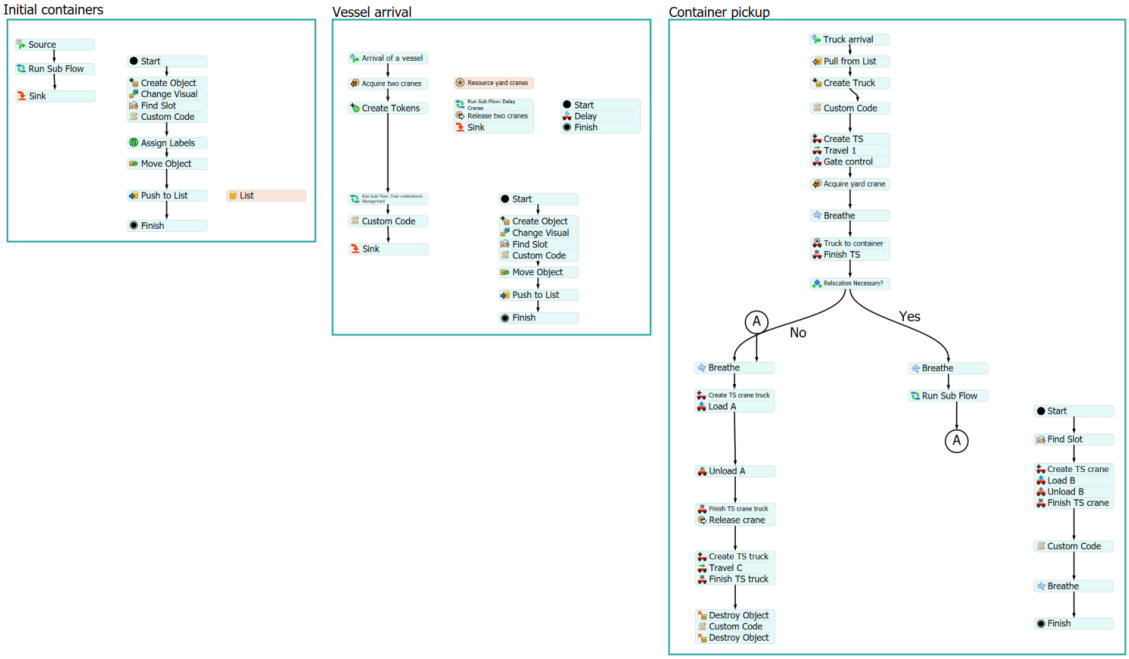


Figure 4.1: Overview of the Three Process Flows Implemented in the Model

4.5.1 Initial Containers

The model starts with an empty yard, a state that the terminal does not present, since containers unloaded before the period under study remain stored and are collected during it. This flow populates the yard before the operation begins, so that the first trucks find containers to collect and the

results do not reflect an initial condition that the terminal never exhibits. Figure 4.2 presents the activities of this flow.

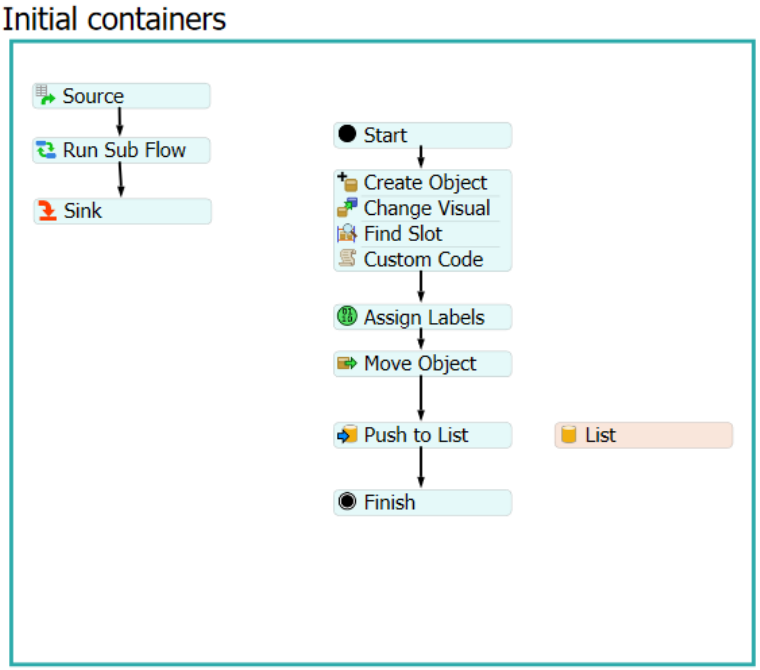


Figure 4.2: Process Flow for the Placement of the Initial Containers

A source creates one token at the start of each simulation run. The Run Sub Flow is defined to generate 300 tokens, the established number of containers in instant zero. Each token is sent to a sub flow that performs the placement. The sub flow begins by creating the flow item that represents the container and by setting its visual properties, namely the shape and the dimensions stated in Section 4.4.3. It then queries the storage system for an available slot and a custom code activity saves the information related to each container, the item id and its location in the yard, in the global table.

The token then associates the label of the container location to the token id. The container is then moved into its slot and published on the list of containers stored, which is the structure from which the pickup flow later draws. The sub flow ends, the token returns to the main flow and a sink destroys it once every container has been placed.

4.5.2 Vessel Arrival

This flow reproduces the seaside stream of work. It converts a vessel call into containers, assigns each of them a position in the yard and occupies the equipment that the placement consumes. Figure 4.3 presents it.

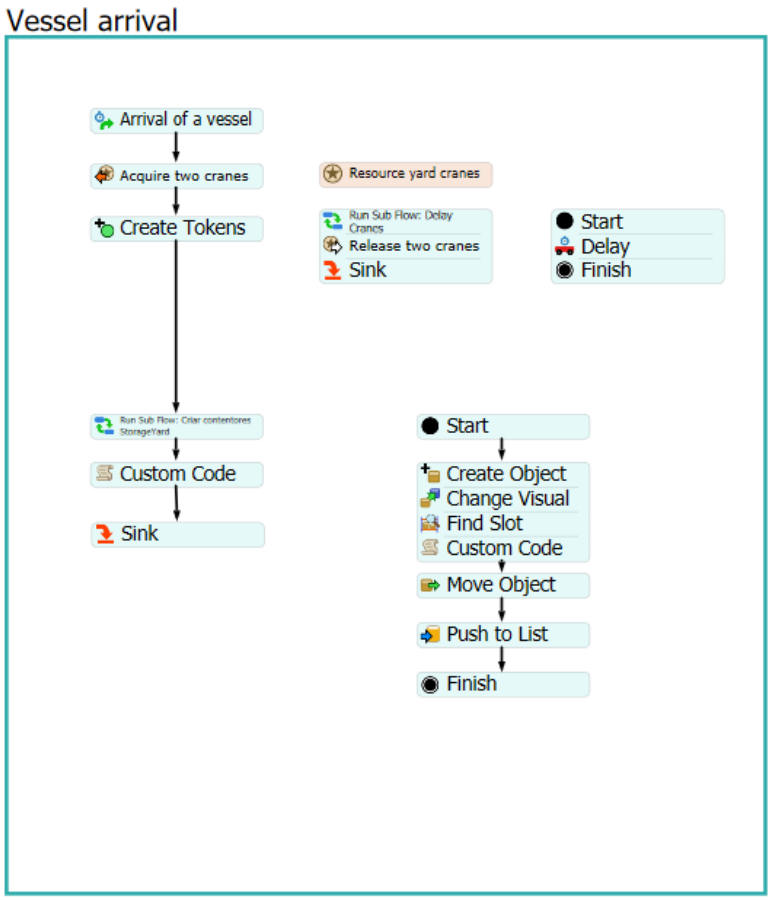


Figure 4.3: Process Flow for the Arrival of a Vessel and the Storage of its Containers

The flow begins with the arrival of a vessel, whose times between successive arrivals follow the distribution stated in Section 4.4. The token created at the arrival acquires two yard cranes, which are held for the duration of the call and are therefore unavailable to serve trucks while the unload proceeds. This acquisition is the point at which the seaside workload reaches the pool of equipment that the two flows share.

Since this dissertation addresses the yard and the collection of containers by trucks rather than the operation at the quay, the flow represents the discharge at a lower level of detail than the collection. The containers are assigned to available slots drawn at random and the two cranes are held busy for the time that their placement would consume, rather than performing each move individually. The model represents this time by a normal distribution with a mean of 4.17 hours and a standard deviation of 1 hour, which corresponds to a mean of 2 minutes per container move. This value stands at the upper end of the interval of 95 to 120 seconds that the literature reports for the cycle time of a yard crane [31]. Two cranes are held rather than one so that the discharge of a call is completed, on average, before the following vessel arrives.

The token then creates one token for each container of the call and each of these tokens follows a sub flow that places its container in the yard. The sub flow reproduces the sequence described

for the initial containers, as it creates the flow item, sets its visual properties, queries the storage system for an available slot, executes the custom code that records the identifier of the container and its address in the global table. The container is then published on the list of containers stored, which is the structure from which the pickup flow later draws.

A second sub flow runs in parallel and holds the equipment. It comprises a single delay, whose duration is drawn from the distribution stated above and represents the interval during which the two cranes remain busy with the placements of the call. When the delay ends, the two cranes are released and become available to the pickup flow again and a sink destroys the token that represented the call.

4.5.3 Container Pickup

This flow reproduces the landside stream of work, from the arrival of a truck at the terminal to its departure with the container. It is the longest of the three, since it comprises the gate procedures, the acquisition of a crane, the relocation of the containers that obstruct the requested one and the retrieval itself. Figure 4.4 shows the container pickup flow and its activities.

The flow begins with the arrival of a truck, whose times between successive arrivals follow the distribution stated in Section 4.4.3.1. The token created at the arrival draws a container from the list published by the two preceding flows, which is the activity that associates a physical container with the request that the truck carries.

The token then creates the task executer that represents the truck and assigns it a first task sequence, which comprises the travel to the gate and the verification performed there. The duration of this verification combines the fixed and the random components stated in Section 4.4.1

The truck does not enter the yard at the end of the verification. It waits instead until a yard crane becomes available, which reproduces the dependence of the gate on the internal handling capacity. A crane held by a vessel call is unavailable at this point and the queue that forms upstream of this activity is the congestion that the study measures. Once a crane is available, the truck travels to the block that holds the requested container.

The flow then examines whether the requested container is accessible. A container stored on the top tier of its stack can be retrieved directly and a container stored below others requires that the obstructing containers be moved first. This test governs the two paths that follow and it is evaluated again after each relocation, so that a container buried under several others generates as many relocations as the stack requires.

When a relocation is required, the sub flow performs it. It queries the storage system for a free slot nearby its current position with the lowest tier, assigns the crane a task sequence that lifts the obstructing container and places it in that slot and executes the custom code that updates the slot address of the moved container in the global table. The flow then returns to the test described above.

When the requested container is accessible, the crane loads it and transfers it to the truck. The crane is then released and returns to the pool of equipment, that is the point at which it becomes available to a vessel call or to another truck. The truck receives a final task sequence that carries

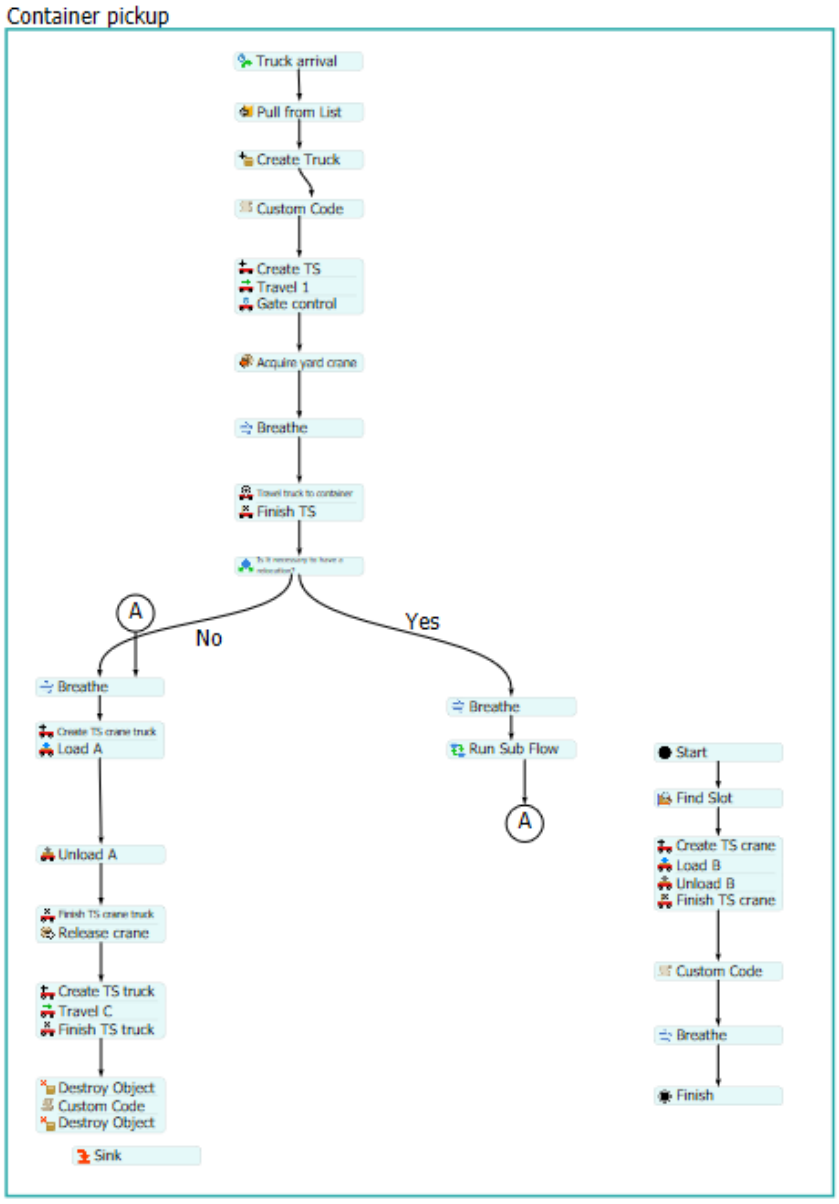


Figure 4.4: Process Flow for the Collection of a Container by an External Truck

it to the exit and the flow destroys the objects that represented the truck and the container before a sink destroys the token. The instant of this destruction closes the measurement of the turnaround time that began at the arrival of the truck.

4.6 Simulation Models

Two models are developed in this work. Both share the same entities, the same 3D layout and the same Process Flow structure, described in the previous sections, and differ solely in the rule that governs the rate of truck arrivals. Model 1 reproduces the current operation of the terminal, while Model 2 introduces an appointment system that is aware of the berthing schedule. Keeping every

other element unchanged ensures that any difference in the results can be attributed solely to the modulation of the truck arrival rate.

4.6.1 Model 1 — Base Model

Model 1 reproduces the As-Is process characterised in Chapter 3. The appointment limit of 30 pickups per time window is applied uniformly throughout the operating day, irrespective of the activity taking place on the seaside. The time between successive truck arrivals follows a Weibull distribution with parameters $(1.66, 0.742)$ minutes, as stated in Section 4.4.1, whose mean of approximately 2 minutes corresponds to the limit of 30 arrivals per hour.

Truck arrivals are therefore generated at the same rate whether or not a vessel is being discharged, and the two flows meet the shared pool of yard cranes without any form of coordination. This model provides the baseline against which the alternative configuration is assessed.

4.6.2 Model 2

The competition for the yard cranes does not result only from an absolute shortage of equipment, but from the coincidence in time between the storage of newly arrived containers and the peaks of truck arrivals. A response based solely on additional equipment addresses the symptom by enlarging the capacity available during those coincidences, at the cost of leaving that capacity idle for the remainder of the operating time. An alternative response is to act on the demand rather than on the capacity, steering truck arrivals away from the periods in which part of the crane fleet is committed to the discharge of a vessel.

Model 2 therefore represents an appointment system that is aware of the berthing schedule. When a vessel call begins and its cranes are seized, the terminal offers fewer pickup slots per time window, and the inbound truck flow is correspondingly thinner until the discharge is completed and the cranes are released.

The inter-arrival distribution of the container pickup flow thus becomes conditional on the state of the crane pool. Whenever at least one vessel call is holding cranes, the inter-arrival time is drawn from a Weibull distribution with parameters $(2.5, 0.742)$ minutes, corresponding to a mean of approximately 3 minutes and to a reduction of the appointment limit from 30 to 20 pickups per time window. The shape parameter is kept at 0.742, so that the relative variability of the arrival process is preserved. When no cranes are allocated to vessel operations, the distribution reverts to the one used in Model 1.

The modification relies on the Process Flow structure described in Section 4.5 and requires no change to the 3D model. A global variable records the number of yard cranes currently allocated to the placement of containers brought by vessels, being incremented when the vessel arrival flow acquires the cranes and decremented when they are released at the end of the storage delay. The inter-arrival time of the truck arrival activity is then replaced by an expression that evaluates this counter at each draw and selects the corresponding distribution.

4.7 Summary

This chapter translated the operational characterisation of the terminal into a computational model. The construction followed the seven-step approach proposed by Law, which fixed the objectives and the performance measures before any implementation took place, consolidated the available data into an assumptions document and subjected that document to review before it was translated into software. The performance measures adopted, namely the turnaround time of the external trucks, the queue upstream of the gate, the utilisation of the yard cranes and the number of trucks served per hour, define the terms in which the alternative configurations are later compared.

The choice of simulation was justified by the nature of the system under study, in which entities compete for limited resources, queues form dynamically and performance depends on the sequencing and the timing of events. The concepts of FlexSim used throughout the model were then introduced, distinguishing the 3D layer, which holds the physical representation of the terminal, from the Process Flow layer, which holds the logic that governs its behaviour.

The entities of the model were subsequently parametrised. The gate, the yard, the vessel arrivals, the external trucks and the yard cranes were each assigned the structural characteristics and the operational parameters that reproduce the terminal described in Chapter 3, with probability distributions rather than fixed values wherever the underlying process is variable. The operational logic was then organised into three flows, which populate the yard at the start of the run, convert each vessel call into stored containers and govern the collection of a container by an external truck. The three flows communicate through the list of containers stored in the yard, and it is at the acquisition of a yard crane that the seaside and landside streams of work meet.

Two models were finally defined. Model 1 reproduces the current operation, in which the appointment limit is applied uniformly throughout the day, and provides the baseline. Model 2 makes the rate of truck arrivals conditional on the state of the crane pool, reducing the number of pickup slots offered while a vessel call holds cranes. Since the two models share every other element, any difference between their results can be attributed to the arrival rule alone. The next chapter presents the scenarios tested with these models and discusses their results.

Chapter 5

Experiments and Results

This chapter presents the experiments conducted with the simulation model developed in Chapter 4 and the analysis of the results obtained. Section 5.1 describes the experimental design, defining the scenarios under evaluation, the number of replications per scenario and the length of the simulation and warm-up periods. Section 5.2 analyses the results of the experiments for each of the KPIs defined in Section 4.1, the truck turnaround time, the waiting time and number of trucks in the queue, the utilisation rate of the yard cranes and the terminal's output per hour. Section 5.3 combines the operational results with the respective cost estimation to examine the trade-off between service performance and investment, comparing the response based on additional equipment with the response based on the variation of truck arrivals and Section 5.4 summarises the main findings of the chapter.

5.1 Experimental Design

The experiments were defined and executed through FlexSim's Experimenter tool, which allows alternative scenarios to be specified as combinations of model parameters, runs each scenario for a defined number of independent replications and reports the resulting performance measures previously defined together with their statistical summaries.

For this study, two models were evaluated. The Model 1, considered the Base Model, reproduces the As-Is process characterised in Chapter 3, a model whose truck arrivals were limited to 30 pickups per one-hour time window, gate verification combining a fixed and a stochastic component, vessel arrivals following the distribution stated in Section 4.4.3 and the competition for yard cranes between the placement of newly arrived containers and the retrieval of containers requested by trucks. The second model, Model 2, described in Section 4.6.2, applies a single change to this process. In this model, whenever a vessel discharge is in progress, the appointment limit is reduced from 30 to 20 pickups per time window, reducing the inbound truck flow precisely during the periods in which part of the yard crane fleet is already occupied positioning the new containers. All other elements of the process remain identical, so that any difference between the two models can be attributed solely to this variation of the arrival rate.

5.1.1 Definition of Scenarios

The decision variable of this study is the number of cranes serving the yard area of the terminal. This choice derives directly from the problem characterisation of Chapter 3, where the congestion observed upstream of the gate is the visible symptom of the unavailability for the yard cranes to reach all the solicitations, and the research question asks which resource configurations best reconciles the service offered to both flows with the investment in equipment necessary for each scenario. Model 2 adds a second perspective to the problem, allowing the effect of resource capacity to be compared with that of demand variability and the effect of both combined.

Six scenarios were defined and are presented in Table 5.1. For the Base Model, Scenario 1, with 5 yard cranes, establishes the baseline against which every alternative configuration is compared. Scenarios 2 and 3 increase the number of yard cranes available to 7 and 10 units, respectively, representing a moderate and a substantial expansion of the resource capacity. The remaining scenarios correspond to Model 2, following the same strategy. From Scenario 4 to 6, the same three fleet sizes were applied, so as to observe the effect of the truck arrival variation in isolation at each capacity level.

Table 5.1: Scenarios Considered for the Analysis

Model	Scenario	Yard cranes	Truck arrivals during discharge
1	1	5	30/hr
	2	7	30/hr
	3	10	30/hr
2	4	5	20/hr
	5	7	20/hr
	6	10	20/hr

The remaining parameters are common to all scenarios and correspond to the values defined in Chapter 4, so as to ensure that any difference observed in the performance indicators across scenarios results exclusively from the variation in the number of yard cranes and from the modulation of the truck arrival rate, and not from differences in the demand imposed on the system.

5.1.2 Number of Replications per Scenario

Since the inputs of the model are stochastic, as truck arrivals, gate verification times and vessel arrivals are all drawn from probability distributions, the outputs of a single simulation run constitute only one realisation of the random variables involved and cannot, on their own, be taken as a reliable estimate of the system's performance. Multiple independent replications of each scenario are therefore required, so that the mean, the standard deviation and confidence intervals can be computed for each KPI, allowing differences caused by the configuration of the system to be distinguished from differences caused by random variation in the inputs.

In this study, the number of replications performed for each scenario was 30. This value ensures that the estimates of the performance measures are sufficiently precise to support the comparisons made in Section 5.2, while keeping the total computational effort of the experiments

manageable. The Experimenter automates the execution of the replications and reports, for each performance measure, the mean value and the associated 95% confidence interval.

5.1.3 Length of the Simulation

The decisions that this study supports, the dimensioning of the yard handling capacity, involve planning the future of the terminal and a large capital expenditure. The results should therefore reflect operations of the terminal on a steady-state rather than transient effects caused by the initial conditions of the model. Considering this, each replication simulates one week of terminal operation, aligned with other port studies [47]. In addition, since the queues and the crane workload require some time to reach a behaviour representative of steady-state operation, a warm-up period of one day was defined in order to stabilise the model. During this period no data is collected and, therefore, the collection of the performance measures starts only after this period.

5.2 Analysis of Results

After the experimental design was concluded, the simulations were run in FlexSim for the six scenarios presented in Subsection 5.1.1, with 30 replications each. This section analyses the results obtained for each of the KPIs defined in Section 4.1. For each indicator, the values of the individual replications are presented in replications plots, which expose the variability of the results and the mean values with the respective 95% confidence intervals are summarised in a table.

5.2.1 Queue Waiting Time

The queue upstream of the gate is the principal indicator of the scarcity of yard cranes. It represents the impact on the quality of service provided to the trucks and on the congestion onto the surrounding road network. Trucks join this queue after completing the gate verification and remain in it until a yard crane becomes available to serve their request. Figures 5.1 and 5.2 present the replications plots for Model 1 and Model 2, respectively, and Table 5.2 reports the mean and 95% confidence interval for the average waiting time in the queue.

Table 5.2: Average Waiting Time in the Queue (in minutes) — Mean and 95% Confidence Interval

Model	Scenario	Cranes	Mean (95% CI)	Std. dev.	Min — Max
1	1	5	163.75 ± 13.18	35.30	83.14 — 278.11
	2	7	143.76 ± 18.42	49.34	26.39 — 263.20
	3	10	34.76 ± 8.01	21.44	3.70 — 88.01
2	4	5	93.30 ± 10.35	27.73	47.34 — 148.11
	5	7	36.90 ± 8.73	23.38	4.56 — 90.45
	6	10	4.07 ± 2.65	7.09	0.31 — 38.61

The results in Table 5.2 indicate that the availability of the yard cranes is the binding constraint of the As-Is operation, represented by Model 1. In Scenario 1, trucks wait on average 163.75 minutes, which translates to more than two and a half hours for an available crane, and the replications

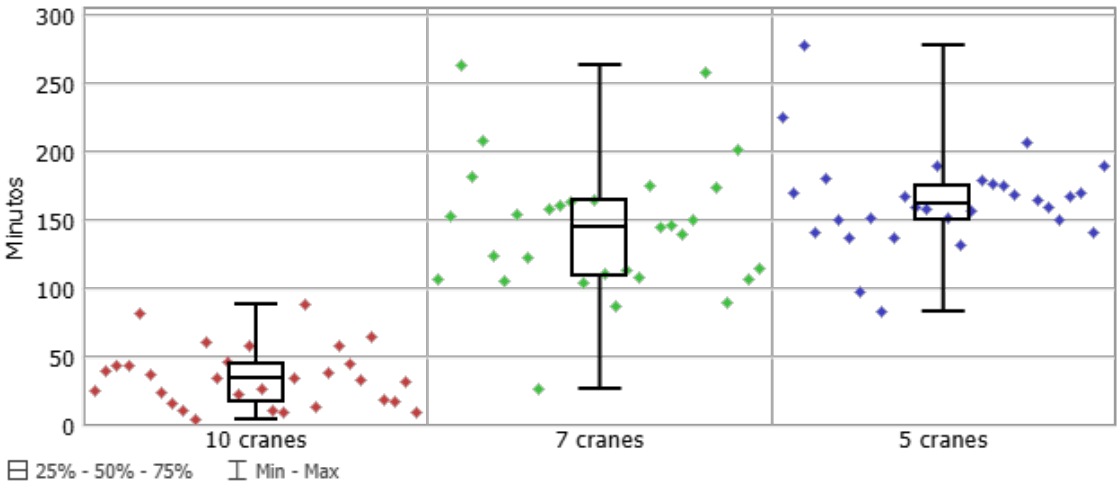


Figure 5.1: Model 1: Average Waiting Time in the Queue (in minutes) — Replications Plot

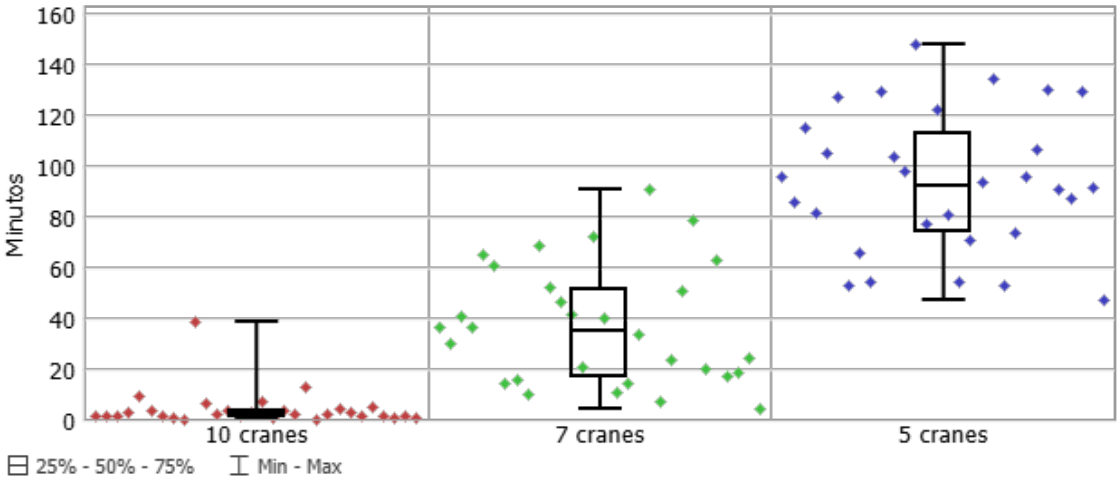


Figure 5.2: Model 2: Average Waiting Time in the Queue (in minutes) — Replications Plot

plot in Figure 5.1 shows a wide dispersion, from below one and a half hours up to more than four and a half hours across replications. This dispersion indicates that the congestion of the baseline is not a constant condition, but the result of the overlap between vessel discharges, which seize two of the five cranes each one, and the constant rate of truck arrivals, which overwhelms the current process. Replications in which vessel arrivals happened to concentrate produced substantially longer queues than those in which they were spread apart.

The response of this indicator to additional resource availability is, however, weaker than might be expected. The increase to 7 cranes in Scenario 2 reduces the average wait only to 143.76 minutes, a reduction of approximately 12% relative to the baseline. The dispersion across replications actually widens, with results ranging from 26 to 263 minutes, indicating that at 30 arrivals per hour a fleet of 7 cranes obtains substantial relief with favourable spacing between vessel arrivals but remains congested when discharges are more concentrated. Only with 10 cranes does the queue practically cease to depend on the vessel arrivals, with an average wait of 34.76 min-

utes, a reduction of approximately 79%. The residual queue waiting time reflects the momentary coincidence of many simultaneous requests rather than a structural shortage of equipment.

Model 2 shows that a substantial part of the same relief can be obtained by acting on the demand instead of the resource capacity. At the baseline fleet of 5 cranes, the reduction of the appointment limit to 20 pickups per hour during discharges lowers the average wait from 163.75 to 93.30 minutes, a reduction of approximately 43% obtained without any additional equipment and reduces the dispersion considerably, as the worst replication falls from 278 to 148 minutes. This zero-investment configuration presents a considerably better performance in comparison with the Scenario 2 on this indicator, despite the latter requiring two additional cranes.

The effect of the truck arrival variation does not cease to improve as more cranes are added. At 7 cranes the modulation reduces the average wait from 143.76 to 36.90 minutes, a level statistically indistinguishable from that of the 10-crane fleet in Model 1 (34.76 minutes, with overlapping confidence intervals) and at 10 cranes it brings the queue down to a negligible 4.07 minutes.

5.2.2 Truck Turnaround Time

The truck turnaround time measures the time each external truck spends inside the terminal, from its entry after the verification at the gate to its exit with the container bound for the hinterland. It therefore captures the internal travel, the possible relocation of obstructing containers and the handling operation itself, but not the waiting in the queue, which was analysed in the previous subsection. Figures 5.3 and 5.4 present the replications plots for Model 1 and Model 2, respectively, and Table 5.3 reports the mean and 95% confidence interval for the average truck turnaround time.

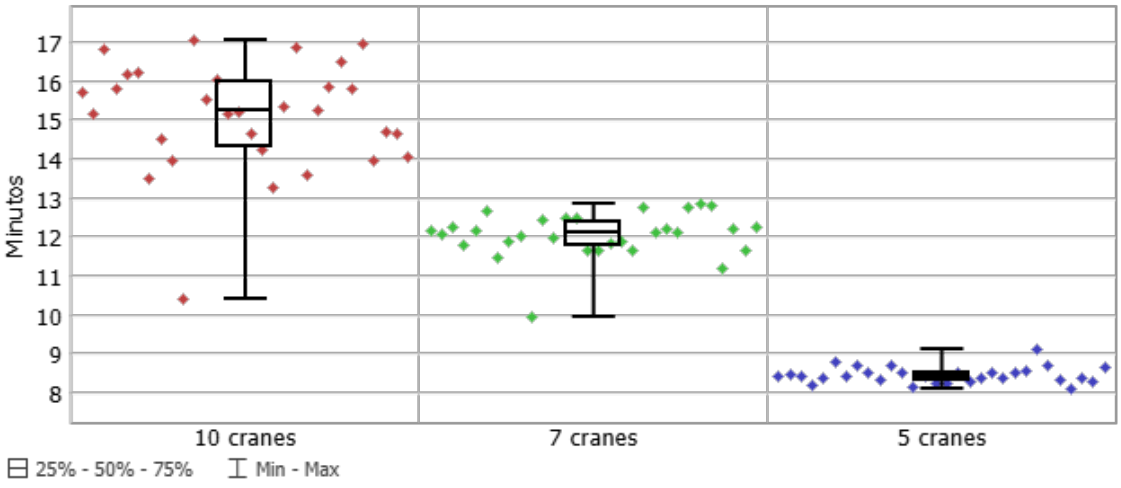


Figure 5.3: Model 1: Average Truck Turnaround Time (in minutes) — Replications Plot

The results in Table 5.3 show that when yard cranes are scarce, fewer trucks circulate inside the terminal at any moment, as they only enter the terminal when a yard crane is available to serve them, which facilitates the travel inside the terminal for both trucks and cranes. Trucks are served almost immediately upon reaching its block, so the internal time is short and stable (the standard deviation in Scenario 1 is only 0.21 minutes). When cranes are abundant, trucks are admitted in

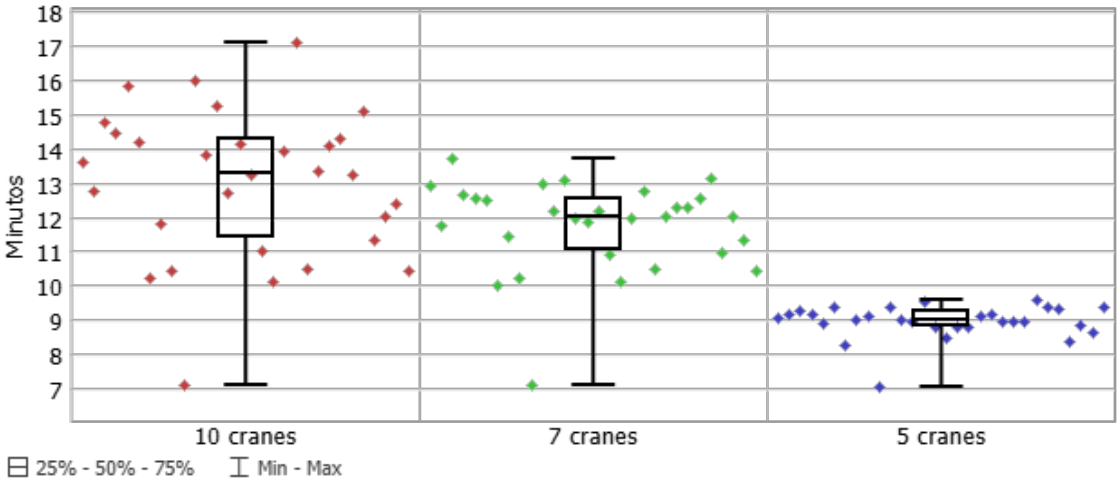


Figure 5.4: Model 2: Average Truck Turnaround Time (in minutes) — Replications Plot

Table 5.3: Average Truck Turnaround Time (in minutes) — Mean and 95% Confidence Interval

Model	Scenario	Cranes	Mean (95% CI)	Std. dev.	Min — Max
1	1	5	8.45 ± 0.08	0.21	8.11 — 9.09
	2	7	12.04 ± 0.21	0.57	9.96 — 12.86
	3	10	15.10 ± 0.52	1.39	10.40 — 17.03
2	4	5	8.96 ± 0.18	0.48	7.05 — 9.58
	5	7	11.76 ± 0.49	1.31	7.13 — 13.72
	6	10	12.99 ± 0.81	2.17	7.12 — 17.11

greater numbers, increasing the internal traffic and coinciding more often with other relocation movements.

Model 2 reproduces the same pattern at a slightly attenuated level, with the turnaround time ranging from 8.96 minutes at 5 cranes to 12.99 minutes at 10 cranes.

5.2.3 Number of Trucks in the Queue

The average number of trucks in the queue complements the waiting time analysed in Subsection 5.2.1. While the waiting time expresses the delay suffered by each individual truck, the queue length expresses the physical extent of the congestion. Figures 5.5 and 5.6 present the replications plots for Model 1 and Model 2, respectively, and Table 5.4 reports the mean and 95% confidence interval for the number of trucks in the queue.

The behaviour of this indicator is similar to that of the waiting time, as expected from the relation between both. In the baseline, the mean for the average queue length was equal to 82.69 trucks, with peaks above 140 trucks in the worst replications. Seven cranes leave the average queue essentially unchanged, reducing it by only approximately 5%, to 78.19 trucks, with the worst replication still reaching 140 vehicles. Only ten cranes produce a substantial contraction, of approximately 70%, to 25.24 trucks.

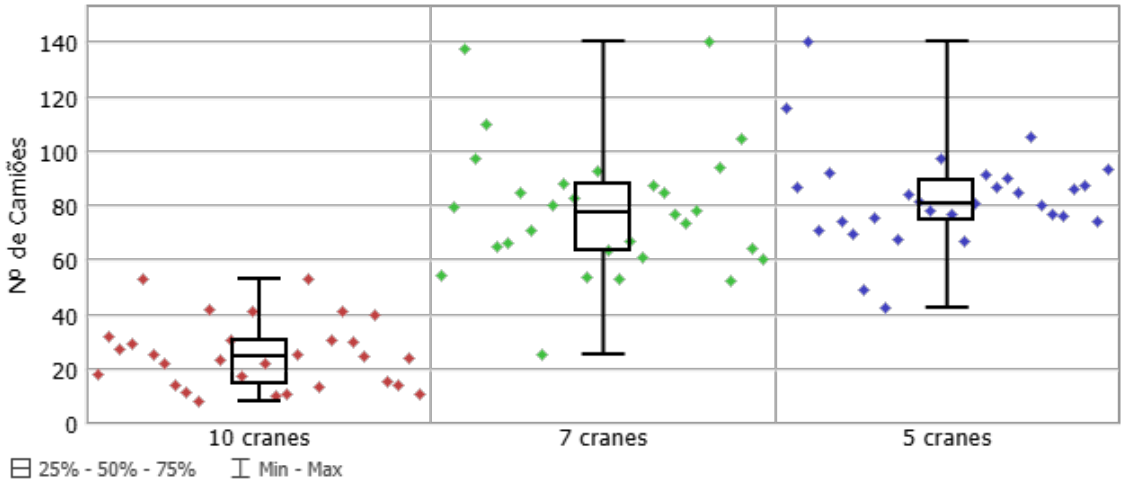


Figure 5.5: Model 1: Number of Trucks in the Queue — Replications Plot

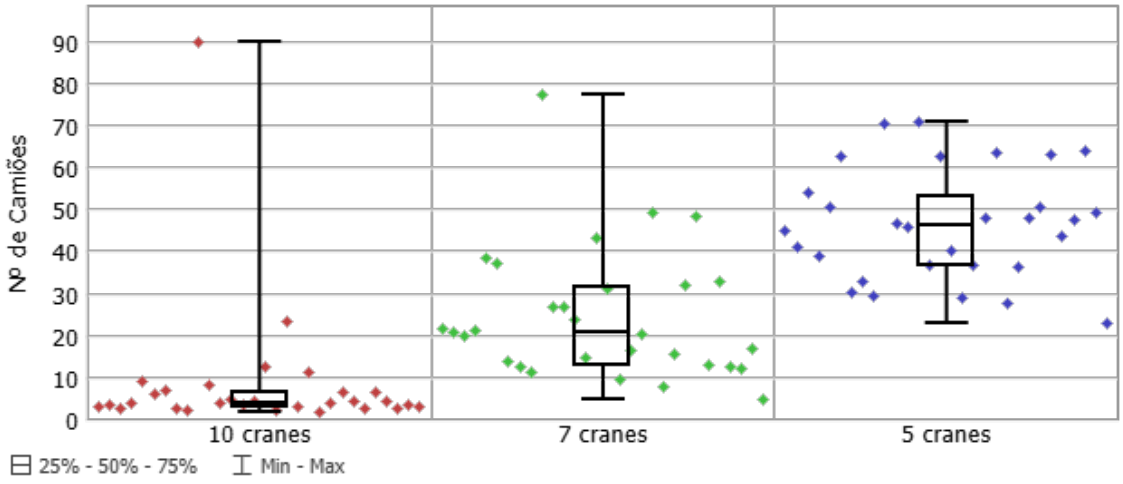


Figure 5.6: Model 2: Number of Trucks in the Queue — Replications Plot

Table 5.4: Number of Trucks in the Queue — Mean and 95% Confidence Interval

Model	**Scenario**	**Cranes**	**Mean (95% CI)**	**Std. dev.**	**Min — Max**
1	1	5	82.69 ± 6.73	18.02	42.36 — 140.29
	2	7	78.19 ± 9.08	24.31	25.11 — 140.27
	3	10	25.24 ± 4.64	12.42	8.08 — 53.21
2	4	5	46.24 ± 4.93	13.21	22.85 — 71.03
	5	7	24.37 ± 5.80	15.53	4.85 — 77.13
	6	10	8.18 ± 5.97	15.99	1.93 — 89.72

Model 2 is particularly effective on this indicator at low capacity, presenting, at 5 cranes, a cut in the average queue of approximately 44% (from 82.69 to 46.24 trucks) and, more notably, reduces the worst-case replication from 140 to 71 trucks, halving the extreme congestion episodes that most affect the surrounding road network.

5.2.4 Utilisation of the Yard Cranes

The utilisation rate of the yard cranes measures the percentage of the operating time in which the cranes are executing tasks generated by either flow, the storage of vessel-borne containers or the service of trucks, including the relocation of obstructing containers. This indicator complements the previous ones, as while the queue and the turnaround time express the quality of service offered, the utilisation rate expresses the cost side of the terminal, revealing whether the equipment added in each scenario is productively employed or remains idle. Figures 5.7 and 5.8 present the replications plots for Model 1 and Model 2, respectively, and Table 5.5 reports the mean and 95% confidence interval for the average crane utilisation.

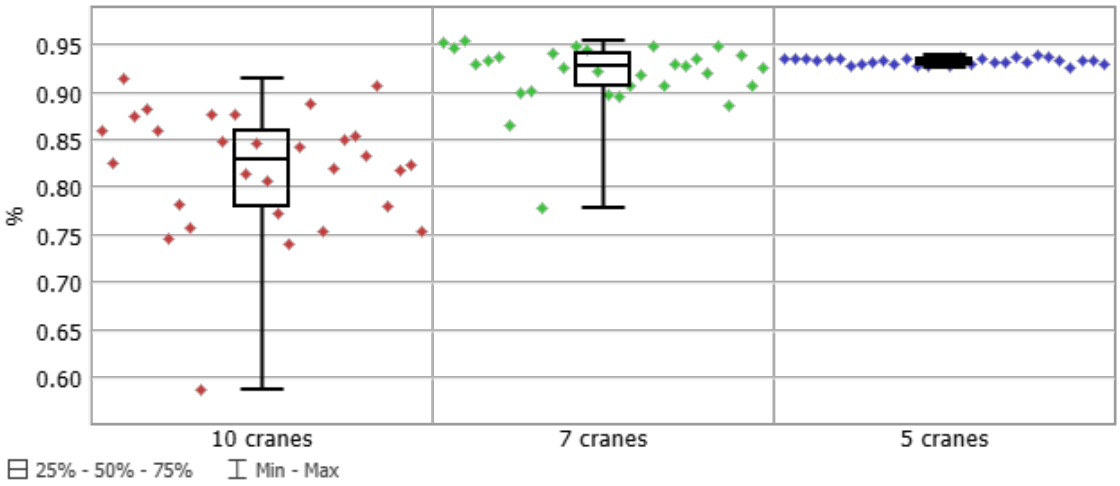


Figure 5.7: Model 1: Average Crane Utilisation (in percentage) — Replications Plot

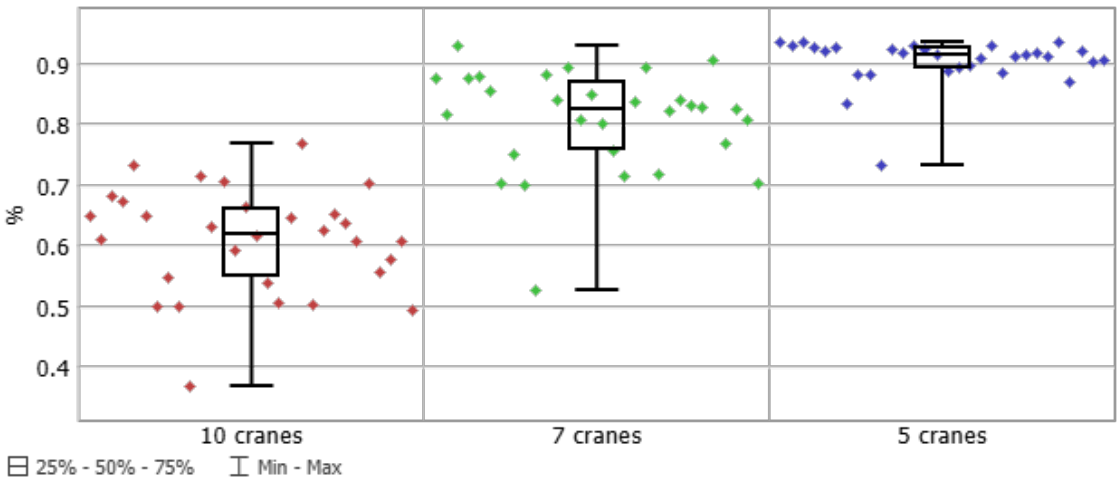


Figure 5.8: Model 2: Average Crane Utilisation (in percentage) — Replications Plot

As expected, the average utilisation per crane decreases as cranes are added, since the demand imposed on the system, the vessel calls and the truck requests, remains identical in every scenario. In Scenario 1 the cranes operate at approximately **93% utilisation**, a level at which practically

Table 5.5: Average Crane Utilisation (in percentage) — Mean and 95% Confidence Interval

Model	Scenario	Cranes	Mean (95% CI)	Std. dev.	Min — Max
1	1	5	93.2 ± 0.1	0.3	92.6 — 93.8
	2	7	91.9 ± 1.3	3.4	77.9 — 95.3
	3	10	82.0 ± 2.5	6.6	58.7 — 91.4
2	4	5	90.3 ± 1.5	4.0	73.2 — 93.6
	5	7	80.7 ± 3.2	8.4	52.5 — 92.9
	6	10	60.8 ± 3.3	8.7	36.7 — 76.8

no slack exists, which leaves the port more subject to the consequences of the process fluctuations. Any perturbation, such as two vessel calls in quick succession, propagates immediately to the queue at the gate, which explains both the length and the volatility of the baseline queue. Scenario 2 lowers the utilisation only marginally, to approximately 92%, which reveals that the two additional cranes are almost entirely absorbed by the demand admitted at 30 arrivals per hour and reveals that despite this resource increase it is not enough to support the truck arrivals rate imposed. Only in Scenario 3 does the utilisation fall to approximately 82%, a level that finally creates a margin behind the strong reduction of the queue, while still retaining a productive use of the equipment.

Model 2 presents lower utilisation than the Base Model at every fleet size (90% against 93% at 5 cranes, 81% against 92% at 7 and 61% against 82% at 10), reflecting the smaller workload admitted during discharges and the relief this produces. At 10 cranes, the combination of the enlarged fleet with the reduced arrivals rate leaves approximately 39% of the fleet's capacity idle, revealing that at this point the two measures overlap in the slack they create.

5.2.5 Output per Hour

The output per hour measures the number of trucks served by the terminal per operating hour and therefore expresses the throughput of the landside operation. It is an essential complement to the previous indicators when comparing the two models, because enables the measurement of the difference in the truck requests number caused by the variation during discharge, a cost that has also to be considered in the trade-off. Figures 5.9 and 5.10 present the replications plot for Model 1 and Model 2, respectively, and Table 5.6 reports the mean and 95% confidence interval for the average output per hour.

Table 5.6: Output per Hour — Mean and 95% Confidence Interval

Model	Scenario	Cranes	Mean (95% CI)	Std. dev.	Min — Max
1	1	5	29.71 ± 0.26	0.70	27.64 — 30.93
	2	7	29.37 ± 0.28	0.74	27.39 — 30.67
	3	10	29.77 ± 0.21	0.56	28.51 — 30.98
2	4	5	25.60 ± 0.23	0.62	24.35 — 26.94
	5	7	24.88 ± 0.24	0.64	23.35 — 25.85
	6	10	24.25 ± 0.21	0.56	23.20 — 25.48

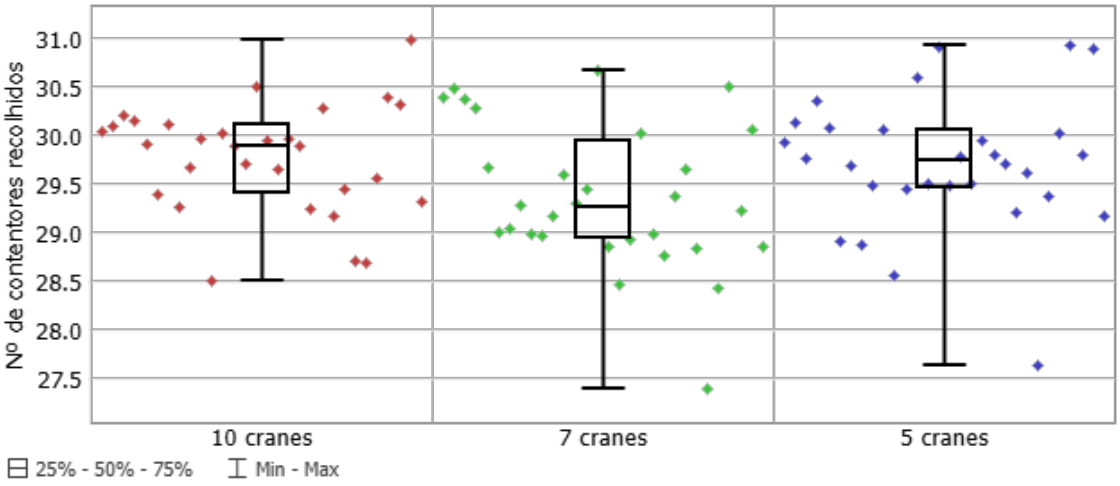


Figure 5.9: Model 1: Output per Hour — Replications Plot

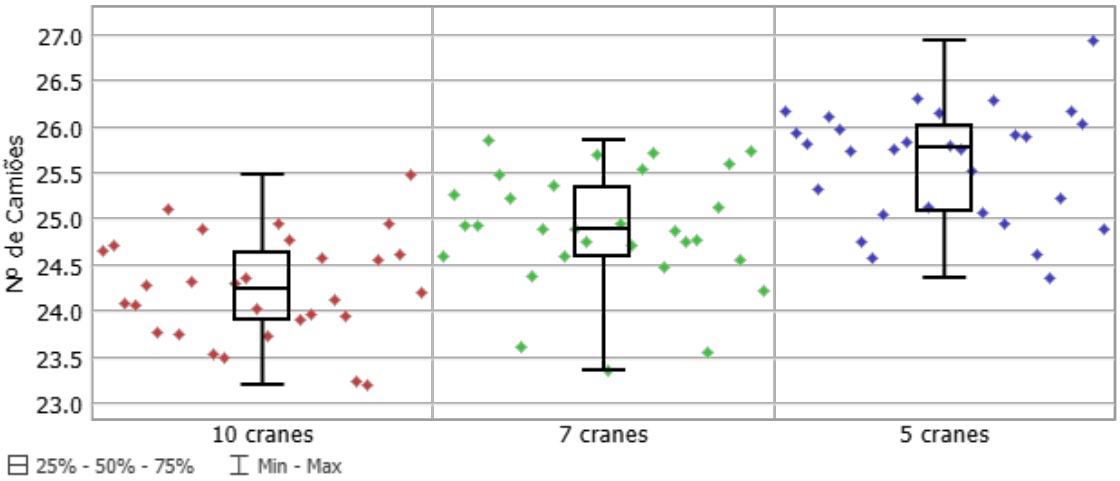


Figure 5.10: Model 2: Output per Hour — Replications Plot

In the Base Model, the output is essentially insensitive to the number of cranes, remaining between 29.4 and 29.8 trucks per hour in the three scenarios, close to the defined appointment limit of 30 arrivals per hour.

Model 2, by contrast, serves between 24.3 and 25.6 trucks per hour, which translates into a reduction of approximately 14% to 19% relative to Model 1. This is the direct consequence of the reduced appointment limit during discharges, as the requests not admitted in those periods are simply not served within the simulated horizon, relieving the terminal's congestion at the cost of throughput.

5.3 Cost–Performance Trade-Off

The analysis of the previous section characterised the operational effect of each configuration. This section sets that performance against what each configuration costs, using the unit value

of 2.2 million euros per aRTG established in Section 3.4.3 and compares the response based on equipment with the response based on the variation of arrivals. Table 5.7 summarises, for each scenario, the incremental investment relative to the baseline fleet and the gains and losses obtained in the main service indicators.

Table 5.7: Cost–Performance Comparison of the Scenarios Relative to the Baseline

Model	**Scenario**	**Additional investment [M]**	**Reduction in queue wait [%]**	**Reduction in queue length [%]**	**Output [trucks/hr]**
1	2	4.4	12.2	5.4	29.4
	3	11.0	78.8	69.5	29.8
2	4	0	43.0	44.1	25.6
	5	4.4	77.5	70.5	24.9
	6	11.0	97.5	90.1	24.3

Three observations emerge from this comparison. In Model 1, the first capacity increment is not significant. Scenario 2 removes only approximately 12% of the baseline queue waiting time for an investment of 4.4 million euros, approximately 4.5 minutes of average waiting time removed per million euros invested. The step from Scenario 2 to Scenario 3 costs a further 6.6 million euros and removes approximately 109 additional minutes, which transposes to approximately 16.5 minutes per million euros invested, more than three and a half times more cost-effective than the first step. The full expansion to 10 cranes delivers substantial reductions, around 79% in the queue waiting time and 70% in the queue length relative to the baseline, at an additional investment of 11 million euros.

At the existing fleet of 5 cranes, Scenario 4 removes approximately 43% of the baseline waiting time, 44% of the queue length and halves the worst-case congestion episodes. As this solution does not imply investment, the comparison of the reductions per euro invested is not possible. The cost, in this case, is a reduction in output, serving approximately 14% fewer trucks per hour. Part of the relief obtained therefore reflects a lighter admitted demand, and not only a better use of the same resources. The variation on truck arrivals is therefore best understood not as a mere substitute for the dimensioning of the fleet, but as an instrument that adapts the arrival of trucks to the availability of the resources, whose benefit should be weighed against the demand it displaces.

Scenario 5 delivers the same waiting time as Scenario 3 (36.90 against 34.76 minutes, with overlapping confidence intervals) for 4.4 million euros instead of 11 million, though serving approximately 16% fewer trucks per hour. Scenario 6 practically eliminates the queue, with an average wait of approximately 4 minutes. Once the arrivals are coordinated with the discharges, a moderate fleet expansion suffices to reach the service level that, in Model 1, only the largest fleet attains.

These six configurations identify a set of alternatives whose advantages and disadvantages can be weighed against one another. Evaluated on investment, queue waiting time and throughput, none of them is dominated by any other, as each buys an improvement in one dimension by conceding in another. The choice among them therefore depends on which dimension the terminal is

least willing to concede. If investment is the binding constraint, Scenario 4 delivers a substantial share of the available improvement at no capital cost. If throughput must be preserved in full, Scenario 3 is the configuration that reaches a lower waiting time without displacing demand, at 11 million euros of additional investment. If a moderate reduction in throughput is acceptable, Scenario 5 reaches essentially the same service level for 40% of that investment, removing approximately three quarters of the baseline congestion while keeping the fleet utilised at 81%.

5.4 Summary

This chapter evaluated the effect of the dimensioning of the yard crane fleet and of the modulation of truck arrivals during container storage, on the landside performance of Terminal XXI, using the simulation models developed in Chapter 4. Six scenarios were compared, using 5, 7 and 10 cranes, each in Model 1 and in Model 2, which reduces the appointment limit from 30 to 20 pickups per hour during discharges, with the performance measured through the queue formed at the gate, the truck turnaround time, the utilisation rate of yard cranes and the hourly output, considering an investment at 2.2 million euros per each aRTG added.

The results show that the congestion of the baseline is originated by the coincidence between vessel discharges, which seize two of the five cranes each vessel and peaks of truck arrivals. In Model 1, this congestion responds weakly to the first increment of capacity, to 7 yard cranes, which removes only approximately 12% of the waiting time and 5% of the number of trucks in the queue for an investment of 4.4 million euros, with the fleet remaining saturated at 92% utilisation, and the full expansion to 10 cranes removes approximately 79% of the waiting time for a total investment of 11 million euros. The variation of truck arrivals was an effective zero-investment measure at the existing fleet, removing approximately 43% of the waiting and halving the worst congestion episodes, at the cost of serving approximately 14% fewer trucks per hour and, combined with a moderate expansion to 7 cranes, reached the service level of the largest Model 1 fleet for 40% of its investment. The six configurations form a set of compromises rather than a ranking, since none of them is dominated by any other on investment, waiting time and throughput simultaneously.

Chapter 6

Conclusions and Future Work

This final chapter draws together the work developed throughout the dissertation. Section 6.1 revisits the objectives and the research question formulated in Chapter 1 and summarises the main conclusions supported by the results of Chapter 5. Section 6.2 discusses the limitations of the study, distinguishing those that come from the availability of data from those that stem from the modelling choices adopted. Finally, Section 6.3 identifies directions in which the work can be extended, both in the refinement of the model itself and in the operational questions it opens.

6.1 Main Conclusions

The two models tested in this dissertation represent two distinct responses to the same cause. The congestion observed at the gate does not arise from an absolute shortage of equipment, but from the coincidence in time between the storage of newly discharged containers and the peaks of truck arrivals. A response based on additional cranes addresses that coincidence by enlarging the capacity available when it occurs, and leaves that capacity idle for the remainder of the operating time. A response based on the appointment rule addresses it by reducing the demand in those periods, without any capital cost apart from serving less trucks. Model 1 and Model 2 therefore do not represent a good and a bad configuration of the same policy, but the supply-side and the demand-side treatment of the problem.

The results show a fleet saturated at 93% utilisation for the baseline scenario, in which trucks wait more than two and a half hours and more than 80 vehicles queue on average. The wide dispersion across replications confirms that the problem is driven by the overlap in time between vessel discharges and truck arrival peaks, which the current appointment process does nothing to prevent. Under those rules the congestion is insensitive to the first capacity increment, since the additional cranes are absorbed by the demand admitted at 30 arrivals per hour, and only yields to the full expansion to ten cranes and its 11 million euros of investment. Coordinating arrivals with discharges removes a substantial share of the same congestion at no investment and, combined with a moderate expansion to seven cranes, reaches the service level of the largest fleet for 40% of its cost, at the price of serving 14% to 19% fewer trucks per hour. Capacity and coordination

therefore act on different causes of the congestion and are more effective together than either is alone.

The configurations evaluated form a set of compromises, within which coordination consistently reduces the investment required to attain a given service level, at the price of the demand it displaces. Which compromise is preferable is not a technical question but one of terminal policy, depending on whether investment or served demand is the less acceptable concession.

6.2 Limitations

The conclusions above should be read in light of the limitations of the study, which fall into two groups.

The first group stems from the availability of data. Operational records of Terminal XXI were not accessible, so the parameters of the model were drawn from the published study of the Sines pre-gate [44], from the technical specifications of the equipment and from values found in the literature on yard crane cycle times. The truck arrival process, in particular, reproduces the appointment limit and the variability reported in that study and the vessel arrival process assumes a Poisson process with a standardised workload of 500 TEUs per call, whereas the real terminal receives vessels ranging from small feeders to Ultra Large Container Vessels, whose calls differ by more than an order of magnitude in workload. The absolute values reported in Chapter 5 of waiting times, queue lengths and throughputs, should therefore be interpreted as indicative of the behaviour of the system under the stated assumptions and the comparisons between scenarios, which share those assumptions, as more robust than the absolute values themselves.

The second group stems from modelling choices made to keep the model tractable and aligned with the focus of the study. The discharge of a vessel is represented in aggregate, by seizing two cranes for a fixed duration, rather than by simulating each individual placement. The number of cranes allocated to a discharge is fixed at two, whereas a real terminal adjusts this allocation to the size of the call and to the schedule of the yard cranes. Containers are assigned to random storage slots, so the model does not capture the specific storage strategies that the port uses as a rule. The crane movement uses a single aggregate speed rather than distinguishing gantry, trolley and hoisting motions. The solicitations for yard cranes from the rail flow and the transshipment flow are outside the model, which considers only the truck-bound containers. The cost analysis considers only the acquisition cost of the equipment, excluding operating and maintenance costs as well as the prevented costs of the truck waiting time avoided.

None of these limitations, however, has implications for the main findings, the persistence of the saturation of the yard crane fleet under the current arrival rules up to intermediate fleet sizes and the complementarity between coordination and capacity in relieving the congestion, as they are structural properties of the process modelled.

6.3 Future Work

The work developed in this dissertation can be extended in several directions. The first concerns the calibration and validation of the model with real data. Access to the operational records of the terminal, such as gate transaction logs, yard crane task logs and the berthing schedule would allow the input distributions to be fitted empirically, the outputs of the baseline to be validated against observed waiting times and the credibility of the model with the decision-makers to be reinforced.

A second idea is related to the appointment system itself. The modulation studied here involves a simple appointment system, with a uniform reduction of the truck pick-up rate during discharges, a normal rate pushed to the limit of the terminal and not considering periods of lower demand. More generally, the definition of the pick-up limit per time window can be formulated as an optimisation problem, in line with the Truck Appointment System literature reviewed in Chapter 2 and solved with the heuristic and metaheuristic methods discussed there, using the simulation model as the evaluation function of the candidate solutions. Such an iterative simulation–optimisation loop would extend the present scenario analysis into a systematic search of the coordination policies that maximise service at a given demand.

A third vector concerns the allocation of the yard cranes. The model under study holds fixed at two the number of cranes seized by each discharge. The possibility of making this allocation dynamic, proportional to the size of the vessel, or coordinated with the length of the truck queue, would maximise the yard cranes utilisation by occupying the idle time reinforcing the storage of the new containers. Relatedly, replacing the random assignment of storage slots with specific stacking strategies would offer a model more closely aligned with what actually happens in the terminal.

Finally, the evaluation framework can be broadened. The cost side can be further explored, incorporating the operational and maintenance costs of the cranes to understand the investment in the long run and the cost saved by reducing truck waiting time. On the performance side, gains such as reduced truck-idling emissions and demand growth from better service should also be considered. The recent implementation of the pre-gate infrastructure, including the intelligent pre-gate, can evolve the scope of the model, studying its interaction with the yard crane fleet and the possibility of defining their schedule in advance.

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