Simulation-Based Layout Optimization and Operational Dock-Door Assignment Modeling in a Cross-Docking Warehouse

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Abstract

Freight forwarders operate in a highly competitive, low-margin environment where operational efficiency in warehousing is increasingly decisive. Within the cross-docking warehouse of Garland Transport Solutions (GTS) in Maia, decisions regarding dock-door assignment and storage allocation have historically relied on empirical experience rather than systematic analytical criteria, creating an opportunity to leverage granular operational data accumulated since the Warehouse Management System (WMS) implementation in 2024. The cross-docking literature identifies dock-door assignment and storage allocation as the primary levers for reducing internal travel distance and improving operator productivity, yet most analytical models do not reflect the real freight-forwarding complexity. This dissertation proposes a data-driven analytical framework to optimize warehouse operations in a single-sided cross-docking facility, where inbound and outbound operations compete for the same dock perimeter.

WMS records for 2025, covering over 220000 pallet movements, were extracted, cleaned, and integrated to develop a high-fidelity Discrete-Event Simulation (DES) model in *AnyLogic*, calibrated using on-site measurements and WMS-derived dwell-time thresholds, and validated iteratively with the warehouse management team. A baseline scenario quantified current performance across 43 storage locations and 32 dock doors, establishing the reference for comparison.

Two alternative configurations were evaluated against a baseline of approximately 16900 km total internal travel distance and average productivity of approximately 19 and 20 pallets per operator-hour, for inbound and outbound, respectively. Scenario 1 introduced a proximity-based dock-door assignment policy on the existing layout, with dock selection for cross-docking pairs driven by outbound storage locations at the request of the operational management team, reducing total travel by approximately 31% and raising productivity to approximately 32 (inbound) and 30 (outbound) pallets per operator-hour. Scenario 2 combined the same logic with a spatial redesign into seven destination-country zones across 1143,75 m^2, achieving a 32% travel reduction with outbound productivity reaching 38 pallets per operator-hour. In cross-docking environments, outbound efficiency is critical as delays directly impact customer service levels. The results confirm that the largest driver of inefficiency is not the physical layout but the absence of a systematic spatial criterion in dock-door allocation. Scenario 2 was the one with the strongest structural impact on outbound flow efficiency and total distance reduction. The model is intended as a decision-support tool for comparing configurations rather than an absolute performance predictor.

A *Visual Basic for Applications* (VBA)-based *Excel* prototype was developed using the Scenario 2 layout to automate daily dock allocation, embedding cross-docking pair identification, service-specific door constraints, and a 24-hour occupancy grid for conflict detection. This research provides a scalable methodology for integrating WMS data into tactical decision-making, offering a foundation for future warehouse automation and digital twin architectures.

Keywords: Cross-Docking, Storage Allocation, Dock-Door Assignment, Discrete-Event Simulation, WMS

Resumo

Os transitários operam num ambiente altamente competitivo e de margens reduzidas, onde a eficiência operacional em armazém é cada vez mais determinante. No armazém de cross-docking da Garland Transport Solutions (GTS) na Maia, as decisões de alocação de portas de cais e distribuição de carga têm assentado em conhecimento empírico em vez de critérios analíticos sistemáticos, criando uma oportunidade para explorar os dados operacionais acumulados desde a implementação do Software de Gestão de Armazéns (WMS) em 2024. A literatura sobre cross-docking identifica a atribuição de portas e a alocação de armazenamento como os principais factores de eficiência, contudo a maioria dos modelos analíticos não reflecte a complexidade real dos transitários. Esta dissertação propõe uma abordagem analítica baseada em dados para otimizar as operações num armazém de cross-docking de lado único, onde as operações de entrada e saída competem pelo mesmo perímetro de cais.

Registos do WMS de 2025, que abrangem mais de 220000 movimentos de paletes, foram extraídos, tratados e integrados para desenvolver um modelo de simulação de eventos discretos em *AnyLogic*, calibrado com medições no local e limites de permanência derivados do WMS, e validado com a equipa de gestão do armazém. Um cenário base foi construído para avaliar o desempenho atual do armazém com 43 localizações de armazenamento e 32 portas de cais.

Duas configurações alternativas foram avaliadas face ao cenário base de aproximadamente 16900 km de distância total e produtividade média de entrada de 19 paletes e de saída de 20 por hora-operador, aproximadamente. O Cenário 1 introduziu uma política de atribuição de portas por proximidade, com seleção orientada pelas localizações de saída em caso de cross-docking a pedido da gestão operacional, reduzindo a distância total em cerca de 31% e aumentando a produtividade de entrada para 32 paletes e de saída para 30 por hora-operador, aproximadamente. O Cenário 2 conjugou a mesma lógica com uma reconfiguração em sete zonas orientadas pelo destinos das cargas numa área de 1143,75 m^2, alcançando uma redução de 32% com a produtividade de saída a atingir 38 paletes por hora-operador. Em ambientes de cross-docking, a eficiência de saída é crítica pois atrasos afectam directamente os níveis de serviço ao cliente. Os resultados confirmam que o principal factor de ineficiência não é o layout físico mas a ausência de um critério espacial sistemático na atribuição de portas. O cenário 2 foi o que obteve maior impacto na eficiência do fluxo de saída e a maior redução na distância total. O modelo destina-se ao apoio à decisão por comparação relativa de cenários.

Foi desenvolvido um protótipo em *Visual Basic for Applications* (VBA) no *Microsoft Excel* com o layout do Cenário 2 para automatizar a alocação diária de portas, incorporando identificação de pares de cross-docking, restrições por tipo de serviço e uma grelha de ocupação de 24 horas. Este estudo propõe uma metodologia escalável para integrar dados granulares do WMS no apoio à decisão tática, constituindo uma base para a automatização futura do armazém e arquiteturas de gémeo digital.

Palavras-chave: Cross-Docking, Alocação de Armazenamento, Atribuição de Portas de Cais, Simulação de Eventos Discretos, Software de Gestão de Armazéns

UN Sustainable Development Goals

This dissertation proposes a data-driven framework to optimize internal warehouse flows and dock-door assignment at a cross-docking facility. As highlighted in the UNESCO report *Engineering for Sustainable Development* (UNESCO, 2021), engineering innovations in data analytics, smart logistics and infrastructure optimization are key enablers for achieving the Sustainable Development Goals. The contributions of this work align with three SDGs, as detailed in the table below.

SDG	Goal	Contribution	Performance Indicators and Metrics
8	Target 8.2: Achieve higher levels of economic productivity through diversification, technological upgrading and innovation.	Engineering is recognized as an essential enabler of economic growth (UNESCO, 2021). This dissertation applies a DES model, warehouse data engineering and decision-support methods to automate dock-door allocation decisions previously based on manual experience, increasing operational productivity and improving resource utilization.	Inbound productivity increased from 19,7 to 32,1 pallets/operator-hour (+63%) in Scenario 1. Total operator hours were reduced by 35,7% in Scenario 1 and 38,6% in Scenario 2 compared with the baseline.
9	Target 9.4: Upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.	The results demonstrate that significant efficiency gains can be achieved through improved dock-door assignment and storage allocation logic. The VBA-based decision-support tool translates simulation findings into operational practice, supporting innovation in logistics management and warehouse operations.	Internal travel distance was reduced by approximately 31% in Scenario 1 and 32% in Scenario 2 relative to the baseline. The prototype supports daily allocation decisions across 32 dock doors and 18 storage subzones.

SDG	Goal	Contribution	Performance Indicators and Metrics
11	Target 11.6:Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	The UNESCO report highlights the role of engineering, data analytics and efficient transportation systems in creating more sustainable cities (UNESCO, 2021). By reducing unnecessary internal movements, the proposed framework contributes to more resource-efficient logistics operations and lower energy requirements for internal transport activities.	In scenario 2, total internal travel distance was reduced by approximately 5 400 km (32%) across the simulated period. Average inbound travel distance decreased from 38,90 m to 28,49 m, while average outbound travel distance decreased from 36,77 m to 23,05 m.

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Finally, to everyone who crossed my path along this journey and made this experience complete and full of great moments that I will carry with me forever.

Life is beautiful and meant to be lived.

Isabel Freitas

"Tenho em mim todos os sonhos do mundo."

Fernando Pessoa

Contents

Acronyms and Symbols

GTS	Garland Transport Solutions
WMS	Warehouse Management System
DES	Discrete-Event Simulation
SDG	Sustainable Development Goals
KPI	Key Performance Indicator
ILS	Intelligent Logistics System
VBA	Visual Basic for Applications
LTL	Less-Than-Truckload
FTL	Full Truck Load
JIT	Just-In-Time
CDO	Cross-Docking Operator
SML	Supplier Managed Load
JML	Joint Managed Load
CML	Cross-Dock Managed Load
IoT	Internet of Things
RFID	Radio Frequency Identification
AGV	Automated Guided Vehicle
PDT	Portable Data Terminal
IP	Integer Programming
GRASP	Greedy Randomized Adaptive Search Procedure
TS	Tabu Search
MIP	Mixed Integer Programming
SRT	Shortest Remaining Processing Time
SA	Simulated Annealing
VNS	Variable Neighbourhood Search
EMA	Electromagnetism-like Algorithms
GA	Genetic Algorithm
DRS	Dependency Ranking Search
DF	Door Fitness
MPT	Minimizing Processing Time
MCT	Minimizing Cycle Time
FMCG	Fast-Moving Consumer Goods
VAM	Vogel's Approximation Method
FCFS	First-Come, First-Served
GAMS	General Algebraic Modeling System
CPLEX	C Programming Language EXtended
MILP	Mixed Integer Linear Programming
SCOR	Supply Chain Operations Reference

KA	Key Account
CS	Customer Service
CRM	Customer Request Management
TMS	Transport Management System
RACI	Responsibility Assignment Matrix
POD	Proof of Delivery
CAD	Computer-Aided Design
FIFO	First-In, First-Out
RTLS	Real-Time Locating System

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Chapter 1

Introduction

1.1 Background and Context

Logistics is a fundamental component of daily life, the primary backbone of national and international supply chains. Amid globalization, the efficiency and sustainability of the sector increasingly depend on Intelligent Logistics Systems (ILS) and digital technologies such as Big Data analytics and automation, which collect and process massive volumes of data in real time to optimize the movement of goods, reduce operational costs, and enable a rapid response to market changes (Hryhorak et al., 2025).

Within this ecosystem, freight forwarders assume a crucial role, operating as the *travel agents* of the cargo industry. However, relying solely on low pricing is no longer sufficient to sustain a competitive advantage in this highly competitive industry. The sector must overcome critical operational bottlenecks in warehousing, such as loading/unloading delays and inventory inaccuracies, while urgently embracing digital transformation and Logistics 4.0 (Rajesh et al., 2023).

This dissertation is developed in the context of a cross-docking warehouse operated by the freight forwarder Garland Transport Solutions (GTS). In 2024, GTS implemented a Warehouse Management System (WMS) across its warehouse network, including the facilities in Maia, Abóboda, and Vitória (Spain), to modernize its operations and improve visibility over warehouse activities. Although the system records a large volume of operational data daily, this information is not yet structured or explored from an analytical perspective, limiting its use in supporting decision-making.

To bridge this gap, this project focuses specifically on the Maia facility and aims to develop a decision-support model by analyzing critical operational variables extracted from the WMS. By transforming raw data into actionable knowledge, the project aims to identify inefficiencies in warehouse flows and evaluate alternative scenarios, including layout adjustments and changes in flow organization, supporting the proposal of improvements that contribute to more efficient resource use and enhanced operational performance.

1.2 Garland Transport Solutions

One of Portugal's oldest business groups, the Garland Group was established in 1776 and includes GTS. With operations in logistics, transportation, navigation, customs, and corporate services, the Group has established a significant presence in the logistics and transportation industry over the years. GTS acts as a freight forwarding business under this arrangement, handling and organizing the distribution of goods throughout global markets, offering integrated logistics solutions across air, sea, and road through a network of logistics partners and carriers (Garland, nd).

This project was developed within the Continuous Improvement department, responsible for examining operational procedures and finding ways to improve productivity and overall performance, where the WMS implemented in 2024 enabled thorough documentation of inbound operations, internal movements, and outbound flows.

1.3 Problem Definition

The data produced by the WMS has not yet been thoroughly examined, so many operational decisions at GTS are still made using empirical knowledge and experience rather than data-driven insights. This reflects a deeper issue: the absence of an organized method for analyzing internal warehouse flows, which is the primary problem this dissertation addresses. There is no systematic way to assess how dock doors are assigned and utilized, how cargo is distributed across storage locations, or how these decisions relate to operator and equipment workload, so it is not possible to evaluate the effectiveness of current flows, identify bottlenecks, or compare the performance of alternative layout and assignment policies before implementing them.

This lack of visibility brings operational risks, including ineffective resource use, longer handling times, and poor layout choices, which can directly affect service standards and operating expenses in a cross-docking setting where efficiency depends on reducing movements and delays. The issue is therefore not a lack of data, but the lack of analytical tools to convert this data into useful insights about warehouse flows and operational efficiency.

1.4 Project Objectives

This work is guided by two research questions:

- To what extent does a proximity-based dock-door assignment policy, alone and combined with a zone-based storage layout redesign, reduce internal travel distance and improve operator productivity in a single-sided cross-docking facility?
- Can granular, real-world WMS data be transformed into a credible discrete-event simulation model and an operational decision-support tool for daily dock-door assignment?

To address these questions, the project pursues three main objectives:

- Develop and validate a DES model of the GTS Maia cross-docking operation, calibrated on historical WMS data;
- Evaluate and compare alternative dock-door assignment and storage-layout configurations against the current baseline, quantifying their effect on key operational metrics including internal travel distance, operator productivity and material handling efficiency;
- Translate the best-performing configuration into an operational decision-support prototype for daily dock-door assignment.

1.5 Methodology

The methodology adopted for the project is structured in six main phases, designed to address the research questions and objectives outlined in Section 1.4, developing a data-driven analytical approach to support decision-making and optimize internal flows at GTS.

Phase 1: Assessment and Operational Diagnosis. GTS's organizational structure, logistics business, and warehouse ecosystem were understood through onboarding and internal training, complemented by an initial literature review on cross-docking operations and warehouse process optimization to identify global best practices. Current warehouse operations were characterized through an initial context mapping, establishing how goods physically move within the facility.

Phase 2: Data Engineering and Spatial Analysis. Internal warehouse flows and the underlying operational data recorded in the WMS were structured, with historical data extracted, cleaned, and processed to build a reliable analytical framework. A detailed physical layout assessment analyzed travel distances between gates and storage locations, creating a spatial distance matrix to map physical constraints.

Phase 3: Base Scenario Modeling & Evaluation. Relevant KPIs were defined to establish a baseline for current warehouse efficiency. Current operational rules, capacity constraints, and cross-docking handling limits were mapped and formalized. A DES model of current operations was developed and validated in *AnyLogic*, reflecting real-world conditions to isolate baseline performance.

Phase 4: Alternative Scenarios Modeling & Evaluation. Simulation outputs were analyzed to identify inefficiencies, bottlenecks, and unnecessary movements, leading to targeted improvements in flows, storage strategies, and layout. Scenario 1 and Scenario 2 were designed, developed, and simulated in *AnyLogic* under different layout configurations and flow adjustments, with their impact on movement efficiency and performance assessed against the base conditions.

Phase 5: Operational Decision-Support Development. Flow optimization insights and simulated scenarios were translated into a practical decision-support framework for cross-docking operations: a functional, automated prototype was designed and developed in *Microsoft Excel* using *Visual Basic for Applications (VBA)* to optimize incoming truck-to-gate matching, embedding operational constraints and mathematical logic to automatically allocate the most efficient docks and minimize total internal travel times.

Phase 6: Final Synthesis & Conclusion. The developed models and decision-support tools underwent a final validation phase with the continuous improvement and logistics teams, followed by a thorough review compiling operational feedback, validation findings, and research conclusions.

The project timeline is organized across these six phases, as illustrated in the *Gantt* chart in Figure 1.1, with each phase mapped to a core deliverable and schedule in Table 1.1.

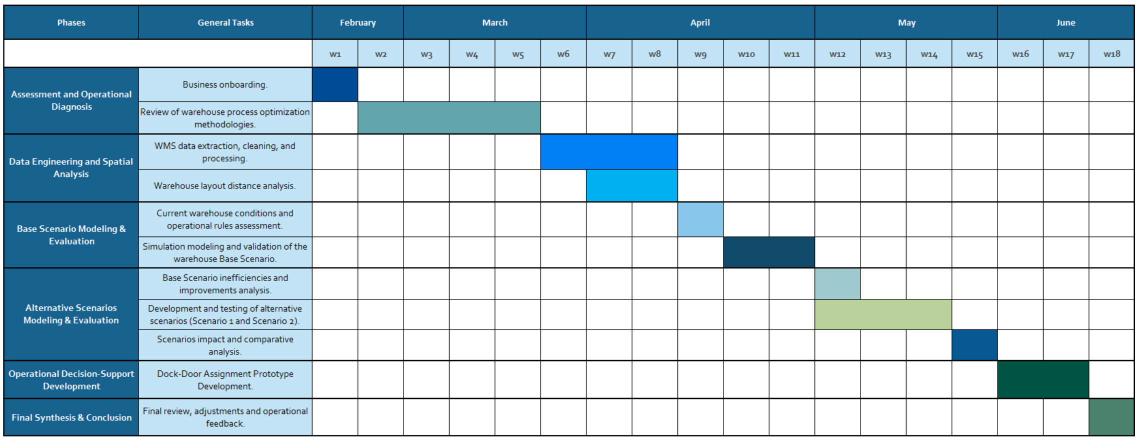


Figure 1.1: Project timeline organized in six main phases

Table 1.1: Project phases, deliverables, and timeline

Phase	Deliverable	Timeline
Assessment and Operational Diagnosis	Presentation and documentation of the selected warehouse optimization methodologies, literature review conclusions, and initial operational context mapping.	March (week 1–5)
Data Engineering and Spatial Analysis	A clean, normalized database extracted from the WMS and a physical distance matrix of the warehouse layout, ready to feed the simulation.	April (week 6–8)
Base Scenario Modeling & Evaluation	A validated *AnyLogic* simulation model reflecting the exact current warehouse conditions, capacity constraints, and operational bottlenecks.	April (week 9–11)
Alternative Scenarios Modeling & Evaluation	Performance evaluation and impact analysis comparing Alternative Scenario 1 and Scenario 2 against the Base Scenario to identify the best operational improvements.	May (week 12–15)
Analytical Development	A functional decision-support prototype developed in *Microsoft Excel* to automatically allocate and select the most efficient dock doors for incoming trucks.	June (week 16–17)
Final Synthesis & Conclusion	Final validation phase, adjustments, review, and operational feedback collection.	June (week 18)

1.6 Thesis Structure

This dissertation is organized into six chapters. Chapter 1 introduces the context, problem, research questions, objectives, and methodology of the project. Chapter 2 reviews the cross-docking literature on dock-door assignment, product allocation, layout design, and simulation, covering the relevant decision levels, technological enablers, performance measurement frameworks, simulation methods, and positioning this work's contribution within the identified research gap.

Chapter 3 characterizes the GTS Maia warehouse, its operational context, transport structure, process flows, resource allocation, and information systems, identifying the data inconsistencies and operational exceptions that shape the assumptions and data preparation procedures of subsequent chapters. Chapter 4 describes the extraction, cleaning, and integration of WMS data into structured simulation inputs, the development and validation of a DES model representing current warehouse operations, and the definition of the KPIs used to evaluate performance across scenarios.

Chapter 5 applies the simulation model to the baseline scenario and to two alternative configurations: a dynamic proximity-based dock-door assignment policy and a redesigned zone-based storage layout. The results of each configuration are presented and compared across key metrics, including internal travel distance, operator productivity, and material handling efficiency. The chapter closes with the presentation of the VBA-based operational prototype developed to translate the best-performing configuration into a decision-support tool for daily dock-door assignment.

Finally, Chapter 6 synthesizes the main conclusions of the project, reflects on its contributions to the cross-docking literature and to operational practice at GTS, discusses the limitations of the study, and identifies directions for future research and development.

Chapter 2

Theoretical Framing

2.1 Operational Challenges of Freight Forwarders

Freight forwarders coordinate the transport of goods between shippers and final destinations, often across borders, while operating in a highly competitive, low margin environment. These challenges stem from operational, technological, economic and regulatory sources, including exchange rate, bunker cost and freight rate fluctuations, infrastructure limitations, and financial risks such as delayed payments. In this context, digitalization is a necessary response for freight forwarders such as GTS to remain competitive (Rajesh et al., 2023).

2.2 Cross-Docking

2.2.1 Definition and Advantages

Cross-docking reduces storage time, typically to under 24 hours, by reorganizing shipments on arrival and consolidating less-than-truckload (LTL) deliveries into full truckloads (FTL), reducing truck movements and improving transport capacity use (Boysen and Fliedner, 2010; Akkerman et al., 2022). Trucks are unloaded, goods sorted and, if needed, briefly staged before outbound transfer (Vogt, 2010), as shown in Figure 2.1.

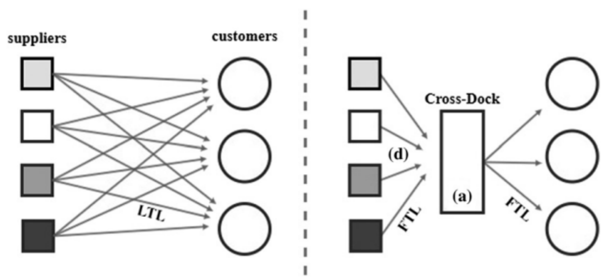


Figure 2.1: Schematic representation of a classical supply chain and a cross-docking supply chain, illustrating the cross-docking decision levels (a) cross-dock location selection and (d) vehicle routing decision (Akkerman et al., 2022)

The approach is widely adopted by operators such as Walmart and UPS (Chen et al., 2009; Forger, 1995; Akkerman et al., 2022), although its benefits depend on strong coordination (Ardakani and Fei, 2020; Akkerman et al., 2022), particularly for freight forwarders such as GTS, where flexible client service increases demand variability. Most advantages stem from reduced storage and handling, lowering holding costs and labour needs (Van Belle et al., 2012; Ertek, 2011) while supporting Lean and Just-in-Time (JIT) practices (Van Belle et al., 2012; Ertek, 2011). Figure 2.2 illustrates the structure of an I-shaped terminal (Akkerman et al., 2022).

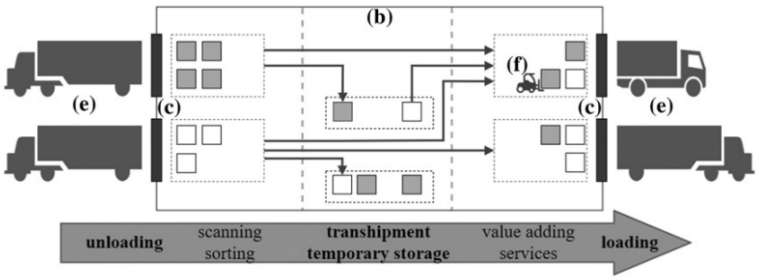


Figure 2.2: Schematic representation of an I-shaped cross-dock, illustrating the decision levels (b) design and terminal layout, (c) door policy and assignment, (e) truck scheduling, and (f) internal resource scheduling (Akkerman et al., 2022)

2.2.2 Cross-Docking vs Traditional Warehouses

Traditional distribution centres rely on receiving, storage, order picking and shipping, with storage and picking being the most expensive due to inventory holding and labour (Van Belle et al., 2012). Cross-docking instead moves goods directly between trucks with limited staging, reducing inventory and handling costs but increasing dependence on timing and coordination (Van Belle et al., 2012), as summarized in Table 2.1.

Table 2.1: Traditional mixed warehouse versus cross-docking warehouse

Traditional Mixed Warehouse	**Cross Docking Warehouse**
Items are put away to storage or order picking areas and reside in the warehouse for at least more than a day;	Items typically flow in and out through the warehouse in a single day without being put away to storage or order picking areas;
Items enter the inventory records in the warehouse system;	Items need not enter the inventory records in the warehouse;
Relabelling and packaging activity may be carried out in the warehouse.	May function without any relabelling or repackaging.

The choice between the two depends on product type, demand pattern and cost structure, with cross-docking favoured under stable, low-risk demand and traditional warehousing preferred when stock-outs are costly (Apte and Viswanathan, 2010; Benrqya et al., 2020; Van Belle et al., 2012). Many operations, including the GTS warehouse, combine both approaches into a more flexible system (Apte and Viswanathan, 2010; Benrqya et al., 2020; Van Belle et al., 2012).

2.2.3 When and How to Use Cross-Docking

Suitability depends on product type, demand pattern, cost structure and coordination quality (Van Belle et al., 2012). Without good coordination, the benefits of cross-docking remain limited regardless of context (Vogt and Pienaar, 2011).

Unit stock-out costs	*Product demand rate*: Stable and constant	*Product demand rate*: Unstable or fluctuating
High	Cross-docking can be implemented with proper systems and planning tools	Traditional warehousing preferred
Low	Cross-docking preferred	Cross-docking can be implemented with proper systems and planning tools

Figure 2.3: Suitability of cross-docking (Apte and Viswanathan, 2010; Van Belle et al., 2012)

As shown in Figure 2.3, cross-docking performs best under stable demand and low stock-out cost, while traditional warehousing suits uncertain demand and costly stock-outs (Van Belle et al., 2012). GTS and similar LTL freight forwarders operate in dynamic contexts shaped by external factors and customer requirements, departing from these ideal conditions and requiring more flexible, adaptive approaches (Van Belle et al., 2012). Longer supplier-customer distances, predictable or short-life-cycle products, and reliable, well-timed suppliers further favour cross-docking, since the absence of buffer stock makes the system sensitive to disruption (Van Belle et al., 2012; Vogt and Pienaar, 2011).

2.2.4 Typology of Cross-Docking Systems

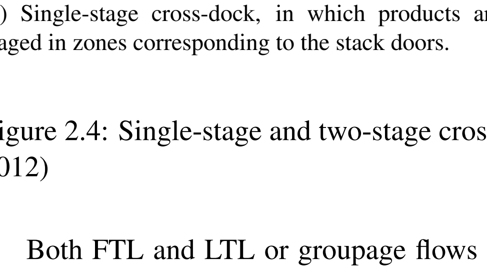
Choosing the right type of cross-dock matters because different configurations require different levels of planning, handling effort and system support (Vogt, 2010; Ahangamage et al., 2020). Classifications differ depending on focus: allocation timing (Napolitano, 2000; Ertek, 2011), operational execution (Vogt, 2010), or the role of the cross-dock within the supply chain (Vogt, 2004; Ahangamage et al., 2020).

Allocation-Based Classification. Three allocation strategies are commonly identified (Napolitano, 2000; Ertek, 2011): pre-allocated supplier consolidation, where suppliers build pallets for specific customers (Type 1); pre-allocated cross-docking operator (CDO) consolidation, with destinations known at the consolidation facility (Type 2); and post-allocated CDO consolidation, where destinations are determined on site (Type 3).

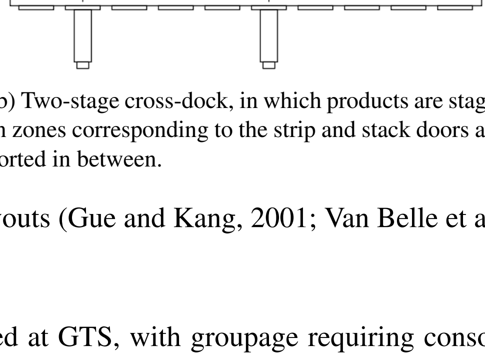
Operational Processing Classification. Vogt (2010) classify cross-dock operations by identification location, sort location and supplier diversity into three types of decreasing efficiency: Supplier Managed Load (SML), where suppliers pre-identify and sort products before arrival, enabling the fastest door turnover; Joint Managed Load (JML), with moderate on-site identification; and Cross-Dock Managed Load (CML), requiring the most staging and manipulation. SML is ideal when upstream pre-identification is possible, though supplier constraints often make JML or CML necessary in practice (Vogt, 2010).

Purpose-Based Classification. Cross-docking is also classified by the role it plays in the supply chain (Vogt, 2004; Ahangamage et al., 2020): manufacturing cross-docking, supporting JIT production; distributor cross-docking, combining sources for downstream delivery, sometimes via merge-in-transit; transportation cross-docking, focused on consolidation and deconsolidation efficiency; retail cross-docking, producing store-ready deliveries; and opportunistic cross-docking, transferring goods directly whenever timing and demand allow.

Stage-Based Classification (Number of Touches). Systems also vary by the number of handling steps involved (Apte and Viswanathan, 2010; Cross-Docking Trends Report, 2008; Gue and Kang, 2001; Specter, 2004). In one-touch or pure cross-docking, products move directly between trucks with no staging. Single-touch or single-stage cross-docking involves brief staging before outbound loading, while multiple-touch or two-stage cross-docking adds a reorganization step between inbound and outbound zones, as shown side by side in Figure 2.4. More touches increase flexibility but also labour, space needs and, in some cases, slower throughput.



(a) Single-stage cross-dock, in which products are staged in zones corresponding to the stack doors.



(b) Two-stage cross-dock, in which products are staged in zones corresponding to the strip and stack doors and sorted in between.

Figure 2.4: Single-stage and two-stage cross-dock layouts (Gue and Kang, 2001; Van Belle et al., 2012)

Both FTL and LTL or groupage flows are handled at GTS, with groupage requiring consolidation of smaller shipments by route and destination. Inbound and outbound flows are planned in advance, and many incoming shipments already have a defined outbound flow soon after arrival. By allocation, this corresponds to a pre-allocated CDO system; by operational processing, to a CML, since most identification and consolidation occur on site; by purpose, it aligns with transportation cross-docking; and by stage, it represents a two-stage system, since goods are temporarily staged and rearranged before shipping. Overall, the GTS operation combines elements from several typologies rather than fitting a single classification.

2.3 Technological Enablers in Cross-Docking

2.3.1 Industry 4.0

Industry 4.0, marked by greater machine connectivity, information transparency and more autonomous decision-making (Kagermann and Wahlster, 2011; Akkerman et al., 2022; Lu, 2017), is supported in cross-docking by cyber-physical systems, the Internet of Things (IoT), Radio Frequency Identification (RFID), Automated Guided Vehicles (AGVs) and machine-to-machine communication (Nazarov and Klarin, 2020; Ivanov et al., 2020; Akkerman et al., 2022). Adoption remains limited, with only around 28% of studies considering such technologies, mostly automated conveyors and Physical Internet hubs (Akkerman et al., 2022). Even so, these systems tend to reduce truck processing times and product dwell time compared to manual setups (Chargui et al., 2018, 2019; Akkerman et al., 2022). Greater automation also increases interdependence between elements, making indicators such as makespan, door utilization, congestion and workload balance important to monitor (Akkerman et al., 2022).

At GTS, labels are printed and scanned by operators using Portable Data Terminals (PDTs) to track goods in real time, and AGVs assist internal movement, working alongside the WMS. These tools, however, prioritize execution rather than the planning and optimization needed in a dynamic environment such as the one under study.

2.3.2 Warehouse Management Systems (WMS)

A WMS supports receiving, cross-docking, internal movement and outbound shipping by enabling real-time monitoring of product location, operator performance and resource use, improving both daily decisions and longer-term planning (Khaled Nabil, 2024). Khaled Nabil (2024) show, in a case study of Algeria's shoe distribution industry, that barcodes and integrated dashboards improve traceability, shorten handling times and help prevent errors such as assigning goods to the wrong dock. More broadly, a WMS can lower cycle times, standardize procedures through automated workflows, and support the allocation of docks, forklifts and labour (Khaled Nabil, 2024).

The GTS warehouse's WMS tracks goods through each PDT label scan, capturing inbound and outbound dock, arrival and exit time and storage location. Despite this extensive data, operational decision-making is not yet fully supported by it, revealing a gap between data collection and effective use.

2.4 Decision Levels in Cross-Docking Planning

Cross-dock characteristics are commonly described through structured frameworks combining decision context and operational environment. Elements originally introduced by Boysen and Fliedner's truck scheduling classification (Boysen and Fliedner, 2010; Ladier and Alpan, 2016) were later reused by Van Belle et al. to organize cross-dock characteristics into physical, operational and flow-related dimensions (Van Belle et al., 2012; Ladier and Alpan, 2016). This study instead follows the more common hierarchical division into strategic, tactical and operational decision levels (Ladier and Alpan, 2016), consistent with prior planning-horizon-based literature (Agustina et al., 2010).

2.4.1 Operational Level

Operational decisions concern short-term coordination of inbound and outbound flows, delay minimization and resource utilization, grouped by Agustina et al. (2010) into truck scheduling, dock-door assignment, transshipment, vehicle routing and product allocation problems. Ladier and Alpan (2016) further distinguish truck-to-door assignment, sequencing and scheduling, and truck sequencing and scheduling. Given the scope of this study, the analysis focuses specifically on truck scheduling, dock-door assignment, truck-to-door assignment and product allocation, as the most relevant decisions for the system under study.

Truck Scheduling. Truck scheduling determines the sequence and timing of inbound and outbound trucks, typically minimizing makespan, total flow time or delay penalties, with poor decisions causing congestion and inefficiency (Agustina et al., 2010). Proposed approaches include a JIT Integer Programming (IP) model (Li et al., 2004; Agustina et al., 2010), later improved with a Reactive Greedy Randomized Adaptive Search Procedure (GRASP) combined with Tabu Search (TS) (Álvarez Pérez et al., 2009; Agustina et al., 2010). Flow-shop formulations solved with Branch and Bound (Chen and Lee, 2009; Agustina et al., 2010) or Mixed Integer Programming (MIP) with heuristic rules (Chen and Song, 2009; Agustina et al., 2010) have also been proposed, alongside further methods such as dynamic programming (Larbi et al., 2009; Agustina et al., 2010), shortest path approaches (Larbi et al., 2007; Agustina et al., 2010), and Shortest Remaining Processing Time (SRT) dispatching rules (Wei et al., 2009; Agustina et al., 2010). A wide range of metaheuristics, including Simulated Annealing (SA), Tabu Search, Variable Neighbourhood Search (VNS) and Electromagnetism-like Algorithms (EMA) (Agustina et al., 2010), as well as simulation-based Genetic Algorithm (GA) approaches (McWilliams et al., 2005; Agustina et al., 2010), have also been applied.

Shakeri et al. (2012) address truck scheduling under limited, non-preemptive resources with a two-phase heuristic: a Dependency Ranking Search (DRS) builds a feasible, deadlock-free truck sequence, and a Door Fitness (DF) heuristic then assigns each truck to a dock door based on availability and proximity, outperforming exact solvers in speed and scalability. Ladier and Alpan (2016) note that truck scheduling primarily captures the temporal dimension of cross-docking operations.

Dock-door Assignment. Dock-door assignment allocates inbound and outbound trucks to specific doors to minimize travel distance, handling cost or workload imbalance, representing the spatial dimension of cross-docking (Ladier and Alpan, 2016). Early Bilinear Programming models solved with Branch and Bound (Tsui and Chang, 1990, 1992; Agustina et al., 2010) were followed by IP models incorporating time windows and dock capacity, solved using TS and GA

(Lim et al., 2006; Agustina et al., 2010), along with MIP solved via SA (Bozer and Carlo, 2008; Agustina et al., 2010), multi-objective workload-balancing models using GA (Ko et al., 2008; Agustina et al., 2010), and three-phase heuristics (Oh et al., 2006; Agustina et al., 2010).

Bartholdi and Gue (2000) (Ladier and Alpan, 2016) minimize labour costs in LTL terminals through distance-based dock assignment, while Bermudez and Cole (2001) (Ladier and Alpan, 2016) apply a GA to breakbulk terminal assignment. Ladier and Alpan (2016) frame the joint optimization of assignment and scheduling as truck-to-door scheduling. Within this stream, Acar et al. (2012) (Ladier and Alpan, 2016) propose robust dock assignment models under uncertainty, and Bjelić et al. (2013) (Ladier and Alpan, 2016) apply GA for time-robust scheduling.

Neamatian Monemi and Gelareh (2023) extend truck-to-door scheduling by incorporating operational resource constraints, such as personnel, equipment and vehicles, formulating an exact arc-time-indexed integer linear programming model solved through Dantzig-Wolfe decomposition and branch-and-price. Wang (2010) propose dynamic, RFID-based trailer scheduling algorithms (Minimizing Processing Time (MPT) and Minimizing Cycle Time (MCT)) that prioritize inbound trailers able to fully load an outbound trailer, reducing pallet cycle times by up to 64% and increasing throughput in simulation.

Product Allocation. Product allocation governs how goods from inbound trucks are assigned to outbound destinations, sometimes through temporary storage buffers (Yu and Egbelu, 2008; Agustina et al., 2010). Yu and Egbelu (2008) (Agustina et al., 2010) address this at a dynamic operational level, deciding whether a product should transfer directly between trucks or be temporarily buffered, using heuristics that jointly optimize docking sequence and product assignment while penalizing buffer use, with the objective of minimizing makespan.

Li et al. (2008, 2009) (Agustina et al., 2010) instead determine which products and quantities should be allocated to cross-docking versus traditional storage in a fast-moving consumer goods (FMCG) context, based on product suitability attributes such as volume, value, popularity, demand variation and life cycle. Using a Linear Programming model solved with Vogel's Approximation Method (VAM) and the UV Method, the resulting macro-level capacity plan directs highly suitable items, such as fast-moving perishables, to cross-docking while reserving warehouse space for less suitable products.

2.4.2 Tactical Level

Tactical decisions concern the mid-term design of the terminal's physical layout, including building dimensions, shape, and the configuration of internal areas (Agustina et al., 2010; Van Belle et al., 2012). Layout design is closely linked to dock-door assignment, since door location dictates material flow and internal travel distances (Agustina et al., 2010).

Gue (1999) combine Linear Programming with simulation, showing that look-ahead scheduling combined with dock assignment yields greater savings than First-Come, First-Served (FCFS) policies. Bartholdi and Gue (2000) propose a layout model minimizing travel time, handling and congestion costs via SA. On building shape, III and Gue (2004) link facility size and door count to the optimal shape, progressing from I to T to X as size increases. Hauser and Chung (2006) show, in a manufacturing context, that a GA optimized V-shaped layout outperforms I and T shapes in minimizing labour and lead time. Yanchang and Min (2009) find that rectangular layouts with conveyors, solved through IP combined with a GA, minimize indoor travel distance most effectively.

On space sizing, Heragu et al. (2005) jointly determine the sizes of storage, forward and cross-docking areas alongside product allocation via Linear Programming, minimizing material handling cost. Vis and Roodbergen (2008) model temporary storage location as a minimum cost flow problem, proposing a row-based storage assignment algorithm. Horta et al. (2016) apply a min-max IP model, solved with General Algebraic Modeling System (GAMS) and C Programming Language EXtended (CPLEX), to store-location allocation in a Portuguese retail JIT case, validated against best-case and projected scenarios. Sandal (2005) combine Arena-based discrete-event simulation with an external tree-search heuristic for the knapsack loading problem, determining optimal trailer loading sequences under random or zoned staging strategies, validated through sensitivity analysis varying revenue and labour costs by $\pm 40\%$.

2.4.3 Strategic Level

Strategic decisions address long-term network design, including the number and location of cross-docking facilities and vehicle allocation within the supply chain (Agustina et al., 2010). Early models contrast a load-driven Mixed-Integer Linear Programming (MILP) model minimizing delays (Ratliff et al., 2001) with a schedule-driven IP model minimizing transportation costs for the United States Postal Service (Donaldson et al., 1998), both solved through Branch and Bound and relaxation techniques.

Facility location research includes a MILP model solved with a spanning-tree GA (Syarif et al., 2002), a two-phase MIP model solved with SA (Jayaraman and Ross, 2003), later improved through hybrid metaheuristics (Ross and Jayaraman, 2008). Joint facility-vehicle allocation models solved with TS (C.S and Song, 2003) were later improved with an exact Branch-and-Price algorithm (Sung and Yang, 2008). Further contributions include a Linear Programming model for cost-efficient network design (Gümüş and Bookbinder, 2004), extended with time windows, capacities and inventory costs solved via TS and SA (Chen et al., 2006), a multi-objective model solved with Hybrid Taguchi-Particle Swarm Optimization (Bachlaus et al., 2008), and a production-distribution model comparing cross-docking against traditional distribution centres (Kreng and Chen, 2008).

2.4.4 Decisions Considered in this Study

Based on this review, the study focuses on dock-door assignment and product allocation as the main decisions under analysis. Using data available from the WMS, which includes information on inbound dock doors, storage locations, and outbound dock doors, it is possible to analyze the internal movements of goods within the GTS warehouse. As highlighted in the literature, spatial design problems are closely linked to dock-door assignment decisions, since the location of dock doors directly influences material flow and travel distances (Agustina et al., 2010), so this study examines how these decisions shape internal flows and directly impact the storage layout, particularly regarding the distribution of goods across storage zones and travel distances within the system.

2.5 Simulation

Simulation evaluates system performance by computationally representing how a real system behaves over time (Law and Kelton, 1991; Pereira, 2016), where a system is a set of interacting entities working toward a common end (Valadares Tavares et al., 1997; Pereira, 2016; Schmidt and Taylor, 1970; Law and Kelton, 1991). Banks et al. (2004) define a system through entities, attributes, state, activities and events, distinguishing discrete systems, whose state changes only at specific event points, from continuous ones.

DES represents systems as sequences of events, making it well suited to cross-docking, where activities occur at specific moments (Pereira, 2016), and requires fewer mathematical assumptions than analytical models (Law and Kelton, 1991; Fernandes, 2018). Monte Carlo sampling is commonly used to represent input variability such as processing or arrival times (Law and Kelton, 1991). Common tools include *AnyLogic*, supporting discrete-event, agent-based and system dynamics models for complex supply chains (Nunes, 2018); *SIMUL8*, focused on visual discrete-event modelling (Pereira, 2016); and *Arena*, widely used for detailed cross-dock and staging analysis (Sandal, 2005).

Simulation allows decision-makers to compare layouts and dock-door assignment strategies without risking real operations (Van Belle et al., 2012; Pereira, 2016), although results require multiple runs to account for randomness (Law and Kelton, 1991; Pereira, 2016). Building an accurate model can also be time-consuming, requiring careful data integration and clearly defined goals (Law and Kelton, 1991), and realistic visual outputs may create overconfidence in the results (Law and Kelton, 1991).

In this study, simulation is used to analyze the current GTS operating scenario and evaluate alternative layout configurations, assessing how product allocation and dock-door assignment affect internal flows and travel distances. Compared to analytical techniques such as MILP and heuristic methods, simulation offers greater flexibility for dynamic, variable systems (Agustina et al., 2010), while DES specifically supports the integrated analysis of layout-related decisions in real-world contexts.

2.6 Performance Measurement in Cross-Docking

The growing complexity and network-like structure of supply chains increases the need to track information that supports an overall evaluation of supply chain functioning (Leończuk, 2016). Performance is commonly defined as the ability to deliver the right product to the right location at the right time at the lowest logistics cost (Zhang and Okoroafo, 2015; Leończuk, 2016), and is typically assessed along three criteria: efficacy (results versus pursued objectives), efficiency (resources and effort relative to cost), and effectiveness (satisfaction with the results obtained) (Estampe, 2014; Leończuk, 2016).

The literature classifies these measures from different perspectives. By decision-making level, indicators are grouped into strategic, tactical and operational dimensions (Gunasekaran et al., 2004; Leończuk, 2016). By type, they range from traditional cost-based measures, such as production cost and productivity, to non-cost measures of time, quality and flexibility (De Toni and Tonchia, 2001; Leończuk, 2016). Structured reference models, notably Supply Chain Operations Reference (SCOR), are also widely adopted, organizing performance around reliability, responsiveness, flexibility, cost and asset management efficiency (Ganga and Carpinetti, 2011; Leończuk, 2016).

In cross-docking specifically, these generic supply chain metrics translate into targeted physical and operational KPIs aligned with each decision level. Strategic KPIs evaluate long-term network efficiency through total transportation costs and overarching delays (Donaldson et al., 1998; Ratliff et al., 2001). Tactical KPIs assess spatial design efficiency through lead time reduction (Hauser and Chung, 2006) and total material handling costs (Heragu et al., 2005). Operational KPIs focus on short-term execution, captured through makespan and system throughput (Yu and Egbelu, 2008), internal travel distances and labor costs (Bartholdi and Gue, 2000), and workload imbalance across dock doors (Ko et al., 2008).

2.7 Research Gap and Study Contribution

The cross-docking literature provides extensive analytical, optimization-based and simulation evidence on truck scheduling, dock-door assignment, product allocation and layout planning. However, most studies address these decisions in isolation, under deterministic parameters or stylized configurations, with little focus on their interaction in dynamic, highly variable real-world settings such as freight forwarding. Performance metrics such as material handling efficiency and travel distance are also typically assessed through analytical models or estimated flows rather than actual operational data, despite the increasing availability of detailed WMS tracking data.

Most studies further assume standard layouts with inbound and outbound dock doors on opposite sides of the facility, enabling linear, structured flows. Alternative configurations, such as warehouses with doors on a single side where inbound and outbound operations share the same physical space, receive comparatively little attention, even though product allocation, door assignment and layout decisions become more complex in such settings.

This study addresses these gaps by examining an actual cross-docking operation at GTS, using WMS data to evaluate internal flows and travel distances. Particular attention is given to the relationship between dock-door assignment and product allocation decisions, and their effects on the storage layout and overall operational efficiency, within a dynamic environment with a single-sided dock configuration.

Chapter 3

Case Study

This chapter presents the case study developed in collaboration with GTS, focusing on its cross-docking warehouse in Maia, characterizing the operational context, process flows, system structure, and key operational elements that support daily logistics activities and provide the foundation for the analysis developed in subsequent chapters.

3.1 Operational Context and Flow Structure

The GTS warehouse operates in a highly interconnected freight forwarding environment involving multiple stakeholders: the Quoting and Key Account (KA) teams, Customer Service (CS) for customers and agents, the National and International Planning teams, and Warehouse operations, each with a specific function in coordinating and executing transport operations.

All operations are triggered by a customer request, formalized as a booking that defines the origin and destination of the cargo. Depending on the consignment, especially for international transport, the booking can be divided into several legs or shipments (Figure 3.1): the pick-up leg (customer to Maia hub), the freight leg (Maia hub to international agent or hub), and last-mile delivery (agent's hub to final destination).

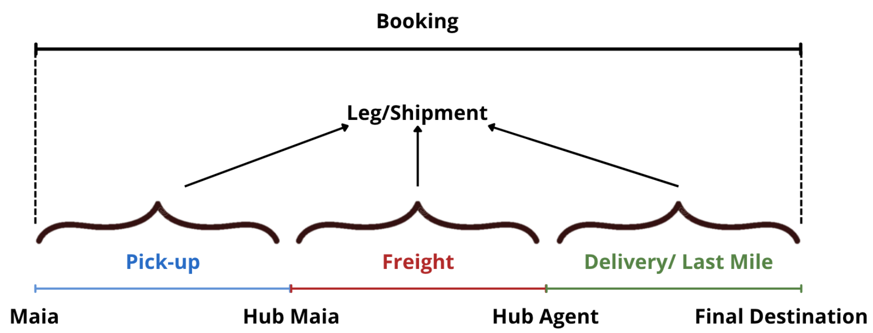


Figure 3.1: Structure of a booking and its decomposition into shipment legs

This decomposition is followed by grouping shipments into loads by planning teams, which define transport execution and directly impact warehouse operations. The warehouse acts as a central node where multiple flows converge under time-constrained conditions.

Several information systems support these operations across different teams (Figure 3.2): Quoting and KA teams use a Customer Request Management (CRM) for requests and quotations, CS for clients uses K2, while CS for agents uses the Planning Manager, where bookings are divided into legs or shipments. Planning teams use a Transport Management System (TMS) to consolidate shipments into loads by grouping cargo and assigning vehicles, while warehouse execution is controlled via a WMS, where cargo movements and handling activities are registered.

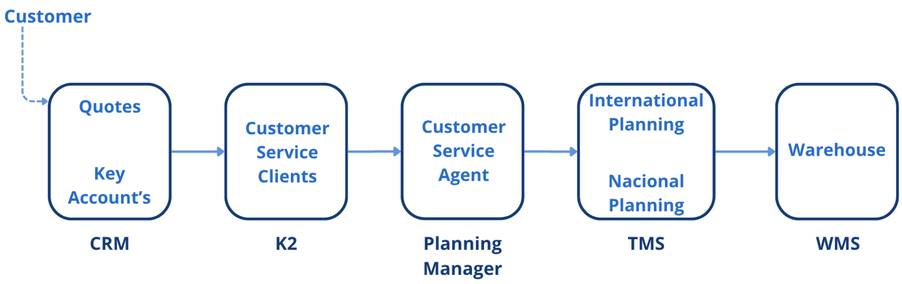


Figure 3.2: Information systems used across the operational flow

This multiplicity of systems across process stages reinforces information fragmentation and increases the need for integration and coordination between teams.

GTS handles four main operational flows: import, delivery, pick-up, and export, which are documented through the cross-functional process flow diagrams presented in Appendix A (Figures A.1 to A.4).

The import flow (Figure A.1) describes how cargo arriving from international partners is scheduled, received, and registered in the warehouse systems before being processed and distributed. The delivery flow (Figure A.2) represents the outbound movement of cargo from the warehouse to final customers. The pick-up flow (Figure A.3) illustrates the collection of cargo from customers and its integration into the warehouse network, while the export flow (Figure A.4) shows the preparation and dispatch of cargo to international destinations.

To complement the process characterization, Responsibility Assignment Matrices (RACI) for the import and export operations are provided in Appendix A (Figures A.5 and A.6). These matrices map the responsibilities of the different organizational units involved throughout each process, from customer interaction and planning activities to warehouse execution and billing.

The diagrams and matrices highlight the central role of the warehouse in executing inbound, storage, handling, and outbound activities, while also illustrating the coordination required between planning teams, customer service units, key account management, and external carriers to ensure the effective movement of cargo across the network.

3.2 Transport Structure and Operational Complexity

The variety of transport types and vehicle configurations significantly impacts warehouse operations, in addition to the structural complexity described previously, and is essential in planning, consolidation, and cargo handling.

Cargo is classified into three transport types based on taxable weight, a measure of the space occupied during transport that determines pricing, taken as the highest of gross weight, volumetric weight, and loading meters:

- **Full Truck Load**, typically over 20000 kg taxable weight, where a single load occupies the whole vehicle;
- **Part Load**, shipments between 2500 kg and 20000 kg taxable weight;
- **Groupage**, shipments under 2500 kg taxable weight, generally consolidated with others in the same vehicle.

These categories also directly impact operational planning: International Planning primarily handles FTL and LTL, while groupage is overseen by Customer Service agents and national planning, each with different planning logics, priorities, and consolidation rules. FTL is typically easiest to manage as a single dedicated load. LTL and groupage require increasing consolidation effort, with groupage representing the highest operational complexity.

Vehicle type diversity adds further complexity: ***Carros-dia*** are used in national planning for daily pick-ups and deliveries, often along predefined routes serving specific geographic zones. **Linehaul** trucks move cargo between the Garland hub and international agent hubs. **Shuttle** vehicles operate daily between the Maia and Abóboda hubs, redistributing cargo between the two main facilities. All transportation is outsourced to external carriers, introducing variability in arrival patterns, capacity, and handling requirements.

3.3 Resource Allocation and Operational Documents

Day-to-day operations rely on a combination of people, equipment, planning tools, and identification systems working in an integrated way.

The warehouse operates six fixed shifts across the week: on Mondays the early shift (1h to 9h) has one operator, increasing to three from Tuesday to Friday. Additional daytime shifts cover 8h to 17h (2 operators), 9h to 18h (7 operators), and 14h to 22h (5 operators), complemented by a night shift from Sunday to Monday (21h to 5h) with 2 operators, aligning workforce availability with peak activity. Two back-office employees support administrative and coordination tasks, alternating between 9h to 17h and 14h to 21h shifts.

Material handling uses seven forklifts and five pallet trucks, shared across all dock areas and processes, so their allocation directly impacts efficiency (illustrative images in Appendix C, Figures B.1 and B.2).

Operational planning is managed through a daily *Excel* spreadsheet (Appendix B, Figure B.3), manually updated to coordinate truck arrivals and warehouse activities, including the Load number, origin/ service line, import/export classification, truck plate, expected and actual arrival times, assigned operator, dock door allocation, operation start and end times, and recorded incidents.

Trucks are classified into six operational typologies (A, B, C, D, E, P) defined by the warehouse manager based on field experience, each reflecting expected handling time and required workforce: type A approximately 3 hours with 2 operators, type B 2 hours with 2 operators, type C 2 hours with 1 operator, type D 1 hour with 1 operator, type E 30 minutes with 1 operator, and type P around 4 hours with 4 operators. This classification structures daily planning but remains heavily dependent on manual input and experience, so resource allocation may not always fully adapt to real-time variability, given fluctuating consolidation needs and shared dock infrastructure.

Several operational documents support execution and coordination across inbound and outbound flows, ensuring cargo verification and alignment between planning and warehouse operations. For pick-ups, a transport guide (Appendix B, Figure B.4) accompanies cargo from customer to warehouse. For inbound, a discharge manifest (Figure B.6) records unloading and received cargo. For outbound, a cargo manifest (Figure B.5) details assigned cargo and deliveries per vehicle, alongside a transport guide with origin, destination, and carrier information (Figure B.7). Both manifests are signed by the responsible operator and include start/end timestamps. Cargo manifests also record shipment count, responsible planner, and planning date. For last-mile deliveries, drivers collect a Proof of Delivery (POD) (Figure B.8) on completion, including shipment details, destination, date and time, and receiver signature, ensuring end-to-end traceability.

3.4 WMS and Cargo Tracking

GTS operates its warehouse through a WMS, recording and tracking cargo movements across operational stages, with real-time visibility accessed via PDTs on the warehouse floor and desktop interfaces for back-office and coordination teams. Eighteen PDTs are currently in operation (examples in Appendix C, Figure C.1).

Each cargo unit is identified through a label generated during warehouse operations (Figure C.2), printed either by the back-office team, mainly for import flows, or at dock-level printers (Figure C.3). Seven label printers are distributed across worktables (Figure C.4) between dock doors 5 and 6, 9 and 10, 13 and 14, 16 and 17, 19 and 20, 23A and 24, and 26 and 26A, reducing walking distances during handling.

Operators use PDTs to scan labels at key stages (receiving, storage, and shipping), updating the WMS in real time. For inbound operations, cargo is registered at arrival and linked to the inbound dock door before being assigned to a storage location. For outbound operations, the dock door is similarly recorded at the point of departure, enabling full traceability of dock usage, storage locations, and timestamps throughout the cargo lifecycle.

Each storage location is associated with a unique QR code (Figure C.5), also available on worktables for quick scanning during handling (Figure C.6). This setup improves efficiency but introduces some inaccuracies, since operators may scan storage locations at the worktable rather than at the final physical placement, leading to small deviations between recorded movements and actual handling times.

3.4.1 Storage Location Allocation

The warehouse does not operate under a formal storage allocation policy. There are no system rules in the WMS that enforce where cargo should be placed, and location assignment is left to the discretion of the operators based on availability and operational experience. Over time, informal associations have emerged between certain storage areas and destination types or consolidating agents (e.g., OSL, Unireco, and PalletWays), freight consolidation agents that regularly route cargo through the Maia facility. These associations, as identified by the warehouse manager, are summarised in Table 3.1.

Table 3.1: Informal storage area associations by destination type, as identified by the warehouse manager

Storage Location(s)	**Informal Association**
MAI-A-1-1	No predefined destination
MAI-B-1-1, *MAI-C-1-1*	Spain
MAI-E-1-1	France
MAI-F-1-1, *MAI-G-1-1*	Maia–Abóboda Shuttle
MAI-H-1-1	Poland
MAI-I-1-1	Benelux
MAI-J-1-1, *MAI-K-1-1*, *MAI-L-1-1*	Germany
MAI-BUFFER6	Unireco, OSL
MAI-EI-1-1, *MAI-EI-1-2*, *MAI-EH-1-1*, *MAI-EH-1-2*, *MAI-EG-1-1*, *MAI-EG-1-2*, *MAI-EF-1-1*, *MAI-EF-1-2*	Customs / Import
MAI-EE-1-1, *MAI-EE-1-2*, *MAI-ED-1-1*, *MAI-ED-1-2*, *MAI-EC-1-1*, *MAI-EC-1-2*, *MAI-EB-1-1*, *MAI-EB-1-2*	Customs / Export
MAI-W-1-1, *MAI-X-1-1*	Italy, Sweden
MAI-PW I1	Non-manifested PalletWays cargo
MAI-PW I2	PalletWays Import
MAI-PW E1, *MAI-PW E2*	PalletWays Export
MAI-PENDURADOS	Hanging garments

As noted by the operational management team, these associations serve as an informal guide rather than a strictly followed rule. Operators try to respect them when possible, but capacity constraints or operational urgency frequently result in loads of different destinations sharing the same storage area. *MAI-BUFFER7*, although not assigned to any specific destination, is regularly used as an overflow storage area when primary locations reach capacity. *MAI-BUFFER1*, *MAI-BUFFER2*, *MAI-BUFFER3*, *MAI-BUFFER4*, and *Maia-ARR* serve a different purpose: they are used as temporary holding areas for non-manifested cargo or incomplete loads that cannot yet be assigned to a permanent storage location. The degree to which each location follows its informal association therefore varies considerably from day to day. This lack of spatial structure in storage allocation is one of the root causes of unnecessary internal travel, and is directly addressed by the zone-based redesign proposed in Scenario 2 (Section 5.1.3).

3.5 Operational Exceptions and Data Inconsistencies

Although the WMS supports registration and traceability, several operational exceptions and manual interventions still occur in practice, typically associated with missing information, delays, or discrepancies between physical operations and system records. The exceptions documented in this section were identified and described with the support of the GTS Maia operational management team.

Non-Manifested Cargo and Temporary Labelling. Non-manifested cargo sometimes arrives without a corresponding booking or load registered in the system. Temporary BKS labels (Appendix C, Figure C.7) are created to allow reception and handling, later replaced once booking information is available while keeping the same label ID.

Load Availability Exceptions in the WMS. When a load is not available in the WMS during unloading, operators must request the warehouse office to manually open it before the operation can continue.

Manual Load-Closure Corrections. Operators occasionally forget to close loads after completing an operation, requiring back-office finalization through the desktop WMS, which may artificially increase recorded durations and introduce additional administrative intervention.

Pallet-Level Scanning and Timestamp Granularity. In some unloading operations, multiple pallets are scanned under a single label with the same timestamp, so recorded data does not accurately reflect individual pallet handling time, introducing noise into duration-related analyses. In the most extreme case, an entire load is scanned this way, with the first and last pallet movements recorded at the same timestamp, so the difference between them is zero and the truck operation is recorded with a duration of 0 hours, addressed in Section 3.6.1.

Storage Location Registration Timing. Storage locations are often registered when operators scan the worktable barcode rather than when the pallet is physically placed, so recorded timestamps do not capture travel time between worktable and storage location, potentially underestimating handling and internal movement times.

Dock Door Selection Bias (*MAI_01*). Operators frequently select *MAI_01*, the first option in the WMS interface, regardless of the dock actually used, creating a bias in recorded dock door information that required correction during data preparation (Section 4.2.7).

The 2025 Load-Closure Validation Gap and Artificial Stock. In 2025, loads could be closed even when some associated bookings had not been registered as exited, so cargo remained recorded in storage longer than its actual physical presence, generating artificial stock. This validation rule was only implemented in 2026, and the resulting data distortion required a dedicated outlier purging and dwell-time calibration procedure, described in Section 4.3.8.

Summary and Implications. These situations show that, despite digital support systems, warehouse operations still depend on manual procedures and are subject to operational errors, both of which may introduce data inaccuracies and discrepancies between physical execution and system records, potentially affecting traceability and the reliability of operational analyses based on WMS data.

Taken together, organizational complexity (Section 3.1), variability from transport types and vehicle configurations (Section 3.2), reliance on manual planning and resource allocation (Section 3.3), and the data quality issues identified above (Section 3.5) justify the assumptions adopted in the remainder of this chapter, as well as the data preparation procedures and simulation model presented next, which provide the basis for analyzing internal flows and evaluating alternative layout configurations in subsequent chapters.

3.6 Assumptions

The following assumptions were defined to support the data preparation and simulation modelling processes. All assumptions were reviewed and validated with the GTS Maia operational management team.

3.6.1 Truck Operation Duration

For each truck operation, duration was calculated as the time elapsed between the first and last pallet movement recorded for that load, capped at 4 hours, the estimated handling time for Type P, the most time-consuming category.

When a truck operation showed 0 hours duration, due to all pallets being scanned simultaneously under a single label, duration was instead estimated from an average handling time. A sample of 30 individual pallet handling time records was collected through direct observation on the warehouse floor (Table 3.2), yielding an average of approximately 1,5 minutes per pallet, adopted as the reference value for zero-duration cases.

Table 3.2: Sample of individual pallet handling times (n = 30), used to estimate the average handling time per pallet

#	Time (min:sec)	#	Time (min:sec)	#	Time (min:sec)
1	1:41	**11**	0:50	**21**	1:24
2	1:06	**12**	1:35	**22**	1:03
3	1:50	**13**	1:12	**23**	1:54
4	1:12	**14**	1:39	**24**	0:51
5	2:17	**15**	0:57	**25**	1:30
6	2:00	**16**	1:48	**26**	1:15
7	1:32	**17**	1:18	**27**	1:45
8	1:00	**18**	1:33	**28**	1:06
9	1:48	**19**	0:42	**29**	1:36
10	2:29	**20**	2:06	**30**	1:56

3.6.2 Dock Door Usage Constraints

Dock door *MAI_01* is never used for truck operations, as confirmed by warehouse management, due to its physical configuration, with a ramp that prevents trucks from docking properly against it. *MAI_02* and *MAI_03* also have a ramp configuration and are used exclusively for customers using their own means of transport other than trucks. *MAI_29* and *MAI_30* likewise have a ramp configuration and are used exclusively for customer operations, particularly hanging garments (*Pendurados*).

3.6.3 Cargo Unit Standardization

The GTS warehouse handles multiple cargo typologies in the WMS, including pallets, half pallets, packages, boxes, bundles, rolls, bags, skids, units, volumes, and hanging garments, among others. Non-standard classifications (*CAMIÃO*, *CONTENTOR*, *20'D - Dry*, *40'D - Dry*, *40'H - High Cube*) were identified and removed, as detailed in the data preparation section.

To simplify the simulation model, all remaining cargo movements were converted into a common unit and represented as pallets. Whenever recorded quantity exceeded 50 units, the value was divided by 50, given the large number of cargo typologies and the absence of reliable conversion factors for many of them.

3.6.4 Material Handling Equipment

The model assumes seven forklifts and five pallet trucks, with no specific allocation rules, equipment assigned solely on availability. All pallet movements are assumed to use forklifts or pallet trucks, with no manual handling considered.

3.6.5 Label Printing and Application Time

The time to print and apply cargo labels was estimated from a sample of 30 records collected through direct observation on the warehouse floor (Table 3.3), including a small number of temporary BKS labels for non-manifested cargo (Section 3.5), which resulted in longer processing times. The average obtained, approximately 10 seconds per pallet, was adopted as the reference value for the *printerDelay* and *printerDelayExit* blocks of the simulation model.

Table 3.3: Sample of label printing times (n = 30), used to estimate the average label printing time per pallet

#	Time (m:s)	#	Time (m:s)	#	Time (m:s)
1	0:40	**11**	0:06	**21**	0:07
2	0:05	**12**	0:07	**22**	0:06
3	0:06	**13**	0:05	**23**	0:08
4	0:07	**14**	0:06	**24**	0:05
5	0:05	**15**	0:45	**25**	0:06
6	0:08	**16**	0:07	**26**	0:09
7	0:06	**17**	0:04	**27**	0:06
8	0:05	**18**	0:08	**28**	0:07
9	0:09	**19**	0:06	**29**	0:05
10	0:06	**20**	0:50	**30**	0:07

3.6.6 Workforce Allocation per Truck Type

The number of operators assigned to each truck operation followed the classification established by the warehouse manager, based on the operation duration calculated as described in Section 3.6.1 (*hoursOperation*), applied equally to inbound and outbound operations (Table 3.4). For durations between 2 and 3 hours, the original classification could correspond to either type B or type C. Since the available data did not allow these to be distinguished, type B was adopted as the more conservative workforce requirement.

Table 3.4: Workforce allocation rule per truck type, based on operation duration

Truck Type	Operation Duration	Operators Needed
P	≥ 4 h	4
A	3 h – 4 h	2
B	2 h – 3 h	2
D	1 h – 2 h	1
E	$<$ 1 h	1

Chapter 4

Simulation Model

Following the characterization of warehouse operations in the previous chapter, this chapter analyzes WMS data and develops a simulation model representing the current warehouse configuration. Operational data on cargo movements, storage locations, dock doors, and timestamps were extracted, cleaned, and integrated to calculate KPIs and distance-related metrics. A DES model was then developed to identify inefficiencies and serve as the basis for evaluating alternative scenarios in subsequent chapters. The model is designed as a decision-support tool for the relative comparison of operational configurations rather than as an absolute predictor of performance, and results should be interpreted accordingly.

4.1 Data Sources and Extraction

The analysis is based on data extracted from the GTS Warehouse Management System (WMS), comprising four datasets: *Movements*, *Completed Documents*, *Bookings*, and *Loads*. Illustrations of the WMS tables are in Appendix D.

Movements captures cargo handling activity (inbound, outbound, storage), including *Planned Load*, *Booking Number*, *Action*, *Type*, *Origin Location*, *Destination Location*, *Volume Type*, *Quantity*, *Volume ID*, and *Modification Date*. *Completed Documents* records executed operations and dock usage (*Load*, *Booking*, *Type*, *Dock Door*, *Modification Date*). *Bookings* provides geographical attributes (*Origin Postal Code*, *Destination Postal Code*, *Origin Country*, *Destination Country*). *Loads* includes operational transport information (*Origin Place*, *Destination Place*, *Transporter*, *Service*, *Equipment*), enabling classification of transport activities and cross-docking flows.

All datasets were exported to *Excel* for preparation and integration, only Maia warehouse records were retained.

4.2 Data Preparation and Cleaning

Given the data inaccuracies and operational exceptions identified in Section 3.5, several preparation and cleaning procedures were applied to the raw WMS records to improve consistency and reliability prior to analysis.

4.2.1 Missing Load Values Treatment

Of the 316532 movement records, 15583 had no *Load ID* assigned. Since the *Load ID* serves only to group pallet movements into truck operations and does not influence any of the distance, productivity, or utilization metrics computed in this study, the recovery procedure prioritized completeness over strict precision.

Four sequential matching steps were applied to unresolved records, propagating *Load IDs* first within *Movements* by *Booking Number* and *Movement Type*, then by *Volume ID* and *Movement Type*, and finally through cross-referencing with *Completed Documents*, which was enriched with *Volume ID* from *Movements* to enable the match, using *Volume ID* alone in the third step and *Booking Number* with *Movement Type* in the fourth. Cases where directional ambiguity could not be resolved were left unassigned. In total, 14315 records were recovered (91,9%), leaving 1268 unresolved.

4.2.2 Data Integration

With *Load ID* values recovered, *Movements* was integrated with *Completed Documents* to associate each cargo movement record with its corresponding dock door. The matching was performed in two sequential steps: first on *Booking Number* and *Movement Type*, which resolved the majority of cases; for remaining records, a second match was performed on *Load ID*. Together, these two steps assigned dock-door information to approximately 97,6% of movement records (309080 out of 316532).

Bookings was subsequently linked via *Booking Number*, adding *Origin* and *Destination Postal Code* and *Country* information. *Loads* was integrated via *Load ID*, adding *Origin Place*, *Destination Place*, *Transporter*, *Service*, and *Equipment*.

4.2.3 Removal of Non-Relevant Operational Records

Non-operational entries were removed, including non-warehouse locations (*MAI-EXTERIOR*, *Maia-ALF*) and non-standard cargo types unrelated to pallet-based flows (*CAMIÃO*, *CONTENTOR*, *20'D - Dry*, *40'D - Dry*, *40'H - High Cube*), which correspond to containerized or non-standard transport units.

4.2.4 Name Standardization

Naming inconsistencies across locations and dock identifiers were corrected (e.g., *Mai-A-1-1* to *MAI-A-1-1*, *Mai-BUFFER7* to *MAI-BUFFER7*), and dock identifiers standardized from numeric references to the formal MAI_XX format.

4.2.5 Derived Datasets for Simulation

Two structured datasets, *StorageEntry* and *StorageExit*, were created from the cleaned movement data to represent inbound and outbound flows respectively, sharing the same structure except for direction-specific fields. Common variables include:

- ***Load***: identifier of the load operation;
- ***Storage Location***: warehouse location associated with the movement;
- ***Dock Door***: inbound or outbound dock door used in the operation;
- ***Date***: timestamp of the movement;
- ***Quantity***: number of pallets moved;
- ***Origin Place*** (inbound) / ***Destination Place*** (outbound): geographical location associated with the transport flow;
- ***Transporter***: carrier responsible for the operation;
- ***Service***: type of transport service;
- ***Equipment***: vehicle or equipment used;
- ***Country*** (Origin/Destination): country associated with the transport flow;
- ***Postal Code*** (Origin/Destination): postal code associated with the transport flow.

StorageEntry uses origin-related attributes and *StorageExit* destination-related attributes, with direction differentiated by dock doors and timestamps, ensuring structural symmetry for direct integration into the simulation model.

4.2.6 Correction of Operational Dock Assignment Rules

Several inconsistencies in dock assignment were identified, mainly due to operators defaulting to MAI_01 instead of the actual dock, as described in Section 3.5. Four operational rules provided by warehouse management were implemented to correct this, applied to both *StorageEntry* and *StorageExit* except HUB-specific rules, which apply only to inbound. For each record, the assigned dock was validated against the corresponding rule. When invalid, it was replaced by a valid dock for that category. Table 4.1 summarizes the rules.

When rules overlapped, a priority hierarchy enforced deterministic correction, summarized in Table 4.2.

In total, 113380 movement records were corrected according to operational specifications defined by warehouse management. For the *Carro-Dia* flow, operational procedures define a sequential dock pattern from *MAI_14* to *MAI_04*, but since the historical dataset cannot reconstruct the exact occupation sequence, dock assignments were distributed at random across valid docks.

Table 4.1: Operational dock assignment rules applied during data preparation

Priority	Condition	Assigned Dock(s)	Rows Affected
1	Service contains “SHUTTLE”	MAI_15 or MAI_16	*StorageEntry*: 7345 *StorageExit*: 9549
2	Service = “CARRO-DIA”	MAI_04 to MAI_14	*StorageEntry*: 33804 *StorageExit*: 61486
3	Origin Place = “HUB GARLAND MAIA” and Storage Location = “MAI-PENDURADOS”	MAI_29 or MAI_30	*StorageEntry*: 4
4	Origin Place = “HUB GARLAND MAIA” (excluding SHUTTLE and CARRO-DIA)	MAI_02 or MAI_03	*StorageEntry*: 1919

Table 4.2: Conflict resolution hierarchy applied during dock assignment correction

Scenario	Conflicting Rules	Cases	Resolution
HUB GARLAND MAIA + SHUTTLE	Rule 1 vs Rule 4	187	SHUTTLE applied
HUB GARLAND MAIA + CARRO-DIA	Rule 2 vs Rule 4	540	CARRO-DIA applied

4.2.7 MAI_01 Dock Bias Correction

After applying the operational rules, a significant number of records remained assigned to *MAI_01* (11206 inbound, 9791 outbound). Since *MAI_01* is not used operationally, these were redistributed based on the historical distribution of dock assignments per storage location, retaining only alternatives with more than 10% historical usage share as valid candidates. Redistribution was performed at the load level: all rows belonging to the same load were assigned the same dock, consistent with the operational reality that a single truck operates through one door. For each load, the dominant storage location, defined as the location with the highest share of pallet quantity within that load, determined the set of valid alternative docks, from which one was selected with probability proportional to its historical usage share. The procedure was applied independently to inbound and outbound flows. Table 4.3 summarizes the redistribution impact.

Table 4.3: Impact of MAI_01 redistribution procedure

Flow	Before	Redistributed	After	Method
Inbound	11206	9959 (88,9%)	1347	Historical >10% usage, load-level
Outbound	9791	8767 (89,5%)	1024	Historical >10% usage, load-level

Records were only kept at *MAI_01* when no statistically relevant alternative existed. Full redistribution logic is in Appendix E.

4.2.8 Removal of Duplicate Volume IDs

Each *StorageEntry*/*StorageExit* record is identified by a unique *Volume ID*, but duplicates were detected: 4134 removed from *StorageEntry* and 3594 from *StorageExit*, retaining only the first occurrence. *StorageEntry* decreased from 146489 to 142355 rows and *StorageExit* from 143768 to 140174, with total pallet quantities adjusted from 231079 to 224330 (inbound) and 226749 to 222446 (outbound), as summarized in Table 4.4.

Table 4.4: Summary of volume ID duplicate removal

Dataset	**Rows Before**	**Rows Removed**	**Rows After**	**Qty After**
StorageEntry	146489	4134	142355	224330
StorageExit	143768	3594	140174	222446

4.2.9 EntryLoad and ExitLoad Dataset Creation

After cleaning and corrections, two aggregated datasets, *EntryLoad* and *ExitLoad*, were created from *StorageEntry* and *StorageExit* using the key (*Load ID* + *Dock Door*). Both include load identifier, dock, first timestamp, total quantity, duration (capped at 4 hours), day of week, and equipment. This resulted in 15527 records in *EntryLoad* and 14917 in *ExitLoad*.

Cross-docking adjustments matched inbound and outbound operations by vehicle identifier: when the same vehicle performed both within 20 hours, the outbound dock was aligned with the inbound dock if still available. Of 3077 vehicle pairs identified, 2720 had their outbound dock updated. The remaining 357 retained independent assignments, as the dock had been reallocated during the interval.

4.2.10 Load Duration Calculation

Duration was calculated from the time difference between the first and last pallet movement per (*Load ID*, *Dock Door*) combination, capped at four hours and with zero-duration cases estimated from average pallet handling time, as described in Section 3.6.1.

4.3 Simulation Model Development

A discrete-event simulation model was developed in *AnyLogic* to represent current warehouse operations at GTS, reproducing inbound and outbound flows, including truck arrivals, dock usage, storage movements, and shipping activities. By integrating WMS data with the physical layout, the model enables analysis of internal flows, storage allocation, dock utilization, and resource interactions, replicating existing system behavior to identify inefficiencies related to product allocation and dock assignment.

The model is intended as a decision-support tool for the relative comparison of operational configurations, rather than as an absolute predictor of operational performance. Accordingly, results should be interpreted as the directional and proportional impact of each configuration relative to the baseline, not as point forecasts of realized values.

This section presents the simulation approach, scope, inputs, operational logic, layout representation, assumptions, and performance metrics.

4.3.1 Simulation Approach

Given the dynamic and stochastic nature of cross-docking operations, where interdependent decisions (truck scheduling, dock assignment, product allocation, internal movements) and variability in arrivals and handling times significantly affect performance, a DES approach was adopted. DES is widely used in logistics for systems where the state changes at discrete points in time triggered by events, enabling analysis of resource interactions and system behaviour without the restrictive assumptions of analytical models, and supports evaluating alternative scenarios without disrupting real operations. *AnyLogic* was selected for its ability to combine discrete-event logic with spatial and operational modelling.

4.3.2 Model Scope and Objectives

The model represents the current GTS Maia configuration, reproducing receiving, temporary storage, internal movements, and shipping, with particular emphasis on the relationship between dock assignment and storage allocation, since this directly impacts internal travel distances and efficiency. Internal travel distance is a key performance driver: material handling is widely recognized as a major source of cost and inefficiency, and dock-door assignment and layout decisions significantly influence travel distances, congestion, and labour utilization (Bartholdi and Gue, 2000; Vis and Roodbergen, 2008; Ladier and Alpan, 2016), as well as overall flow efficiency (Gue, 1999; Bartholdi and Gue, 2000). The model aims to:

- Represent inbound and outbound flows based on historical WMS data;
- Analyze dock utilization and storage allocation patterns;
- Evaluate internal travel distances between dock doors and storage locations;
- Identify inefficiencies in product allocation and dock assignment;
- Support the evaluation of alternative scenarios and future configurations.

4.3.3 Model Inputs

The model integrates *StorageEntry*, *StorageExit*, *EntryLoad*, and *ExitLoad*, together with the physical layout and resource information. *StorageEntry*/*StorageExit* represent pallet-level movements and update stock levels, storage assignment, and travel distances. *EntryLoad*/*ExitLoad* generate truck entities, schedule operations, assign docks, estimate durations, and define operator requirements.

The physical layout includes dock positions, storage zones, circulation paths, and operational areas. A distance matrix was developed combining Computer-Aided Design (CAD) documentation with on-site laser measurements. Figure F.1 (Appendix F) presents the measured warehouse dimensions and reference points used to construct it, with the complete matrix presented in Tables F.1 and F.2 of the same appendix. Resource inputs include operator availability per shift, schedules, and equipment capacity.

4.3.4 Model Logic and Entities

The model architecture was structured around five agent types: *Truck*, *Pallet*, *Operator*, *Forklift*, and *Pallet Truck*, each with operational variables required to represent warehouse activities, resource allocation, and cargo handling.

Truck Agent. The *Truck* agent represents inbound and outbound transport operations. Table 4.5 presents its main variables and parameters.

Table 4.5: Main variables and parameters associated with the Truck agent implemented in the simulation model

Variable / Parameter	Description	Type
`truckType`	Operational classification of the truck	String
`assignedDock`	Dock door assigned to the truck	String
`hoursOperation`	Estimated loading/unloading duration	Double
`workersNeeded`	Number of operators required	Int
`loadID`	Identifier of the associated load	String
`numPaletes`	Number of pallets associated with the truck	Int
`waitingTime`	Truck waiting time before operation	Double
`truckOperation`	Inbound (Imp) or outbound (Exp) operation	String

Pallet Agent. The *Pallet* agent represents cargo units moving between dock doors and storage locations, simulating inbound storage, outbound retrieval, and internal flow dynamics. Its main variables and parameters are presented in Table 4.6.

Table 4.6: Main variables and parameters associated with the Pallet agent implemented in the simulation model

Variable / Parameter	Description	Type
`entryDock`	Inbound dock door associated with the pallet	String
`storageLocation`	Storage location assigned to the pallet within the warehouse	String
`exitDock`	Outbound dock door associated with the pallet during shipping operations	String
`distance`	Total travel distance associated with pallet movements	Double
`startTime`	Timestamp associated with the beginning of the pallet movement	Date
`endTime`	Timestamp associated with the completion of the pallet movement	Date
`loadID`	Identifier of the load associated with the pallet	String

The agent uses *getNodeFromLocation()* to map storage locations for distance calculations, processing inbound storage and outbound retrieval from *StorageEntry* and *StorageExit* respectively.

Material Handling Equipment Agents. The *Forklift* and *Pallet Truck* agents represent the material handling equipment operating within the warehouse, with their parameters summarised in Table 4.7.

Table 4.7: Parameters associated with the Forklift and PalletTruck agents implemented in the simulation model

Parameter	Description	Type
`speed`	Movement speed of the forklift	Double
`isAvailable`	Availability status of the forklift resource	Boolean

Forklift speed follows Triangular(1,0; 3,33; 2,5) m/s (max 12 km/h). Pallet truck speed follows Triangular(0,5; 1,94; 1,4) m/s (max 7 km/h), reflecting manufacturer limits and observed variability. Availability is managed via dedicated pools (*forkliftPool*, *palletTruckPool*), of seven forklifts and five pallet trucks, allocated dynamically by demand.

Operator Agent. The *Operator* agent represents warehouse workers, with its parameters presented in Table 4.8.

Six schedule objects were implemented to replicate workforce allocation (Table 4.9).

Dedicated resource pools (*operatorPool1h9h*, *operatorPool1h9h1*, *operatorPool8h17h*, *operatorPool9h18h*, *operatorPool14h22h*) were assigned to each schedule. Operator movement is coupled with the seized equipment, so travel speeds reflect the forklift or pallet truck used.

Table 4.8: Main parameters associated with the Operator agent implemented in the simulation model

Parameter	Description	Type
`shift`	Operational shift assigned to the warehouse operator	String
`shiftStart`	Start time of the assigned operational shift	Double
`shiftEnd`	End time of the assigned operational shift	Double

Table 4.9: Operator shift schedules and workforce allocation used to represent warehouse labor availability in the simulation model

Schedule	Working Days	Working Hours	Number of Operators
1h–9h (Shift A)	Monday	01:00–09:00	1
1h–9h (Shift B)	Tuesday to Friday	01:00–09:00	3
8h–17h	Monday to Friday	08:00–17:00	2
9h–18h	Monday to Friday	09:00–18:00	7
14h–22h	Monday to Friday	14:00–22:00	5
21h–5h	Sunday and Monday	21:00–05:00	2

4.3.5 Main Model Logic

The *Main* agent coordinates truck scheduling, data retrieval, inventory updates, resource allocation, distance calculations, and performance monitoring.

4.3.5.1 Functions

Table 4.10 summarizes the auxiliary functions implemented.

Table 4.10: Functions implemented in the Main agent

Function	Purpose
`createPallet()`	Creates pallet agents and inserts them into the inbound pallet flow.
`scheduleEntryTrucks()`	Initiates the generation of inbound trucks based on historical arrival data.
`scheduleExitTrucks()`	Initiates the generation of outbound trucks based on historical departure data.
`getDockNode()`	Returns the dock access node used as the destination point for truck movements.
`getDockInteriorNode()`	Returns the internal dock node used as the starting or ending point for pallet movements inside the warehouse.
`cameraRotation()`	Controls the camera rotation used in the 3D simulation visualization.

4.3.5.2 Variables

The *Main* agent manages simulation execution through three variable categories: operational control, performance statistics, and indexing and reference structures (Tables 4.11, 4.12, and 4.13).

Operational Control Variables. These manage progression of inbound and outbound activities, tracking current loads, dock assignments, and dataset records.

Table 4.11: Operational control variables

`Variable`	**Description**
`truckEntryRowIndex`	Current row being processed in the EntryLoad dataset.
`truckExitRowIndex`	Current row being processed in the ExitLoad dataset.
`currentEntryRowIndex`	Current row being processed in the StorageEntry dataset.
`currentExitRowIndex`	Current row being processed in the StorageExit dataset.
`currentEntryDock`	Dock currently associated with an inbound operation.
`currentExitDock`	Dock currently associated with an outbound operation.
`currentLoadID`	Identifier of the load currently being processed.
`currentExitLoadID`	Identifier of the outbound load currently being processed.

Performance Statistics Variables. These accumulate indicators on throughput, distances, utilization, queues, dock activity, and occupancy.

Table 4.12: Performance statistics variables

`Variable`	**Description**
`palletCount`	Total number of inbound pallets processed.
`exitPalletCount`	Total number of outbound pallets processed.
`totalDistanceEntry`	Total distance travelled by inbound pallets.
`totalDistanceExit`	Total distance travelled by outbound pallets.
`totalHoursOperatorEntry`	Total operator working hours associated with inbound operations.
`totalHoursOperatorExit`	Total operator working hours associated with outbound operations.
`monthEntries`	Monthly distribution of inbound pallet movements.
`monthExits`	Monthly distribution of outbound pallet movements.
`dayOfWeekEntries`	Distribution of inbound pallet movements by day of the week.
`dayOfWeekExits`	Distribution of outbound pallet movements by day of the week.

(continued from previous page)

`Variable`	**Description**
`monthVolume`	Monthly volume processed within the warehouse.
`dayOfWeekVolume`	Volume processed by day of the week.
`monthCount`	Counter used for monthly statistics collection.
`dayOfWeekCount`	Counter used for day-of-week statistics collection.
`simulationDays`	Total number of simulated days.
`dockEntryCount`	Number of inbound truck operations per dock.
`dockExitCount`	Number of outbound truck operations per dock.
`dockEntryPalletCount`	Number of inbound pallets processed per dock.
`dockExitPalletCount`	Number of outbound pallets processed per dock.
`palletList`	Collection containing pallet agents created during the simulation.
`dailyStock`	Estimated daily pallet stock level per storage location, calculated by matching inbound and outbound movements within a maximum dwell time per location.
`actualStock`	Real-time inventory counter tracking the current pallet quantity at each storage location, incremented on inbound movements and decremented on outbound movements throughout the simulation run.
`locationEntryCount`	Number of inbound pallet movements recorded per storage location.
`locationExitCount`	Number of outbound pallet movements recorded per storage location.
`locationMaxOccupancy`	Mean daily occupancy reached by each storage location during the simulation.

Indexing and Reference Structures. These support efficient retrieval of loads, storage locations, dock doors, distance records, and dwell-time thresholds.

Table 4.13: Indexing and reference variables

Variable	**Description**
`storageIndex`	Indexing structure that associates each load–dock combination with the corresponding StorageEntry records.
`storageExitIndex`	Indexing structure that associates each load–dock combination with the corresponding StorageExit records.
`distanceIndex`	Indexing structure used to retrieve travel distances between storage locations and dock doors.
`meanWindows`	Reference structure providing dwell-time thresholds per storage location, as defined in Appendix G.

4.3.5.3 Events

Five event objects were implemented (Table 4.14).

Table 4.14: Events implemented in the Main agent

Event	**Purpose**
`nextEntryTruckEvent`	Triggers the creation of inbound truck entities according to the historical arrival timestamps contained in the EntryLoad dataset.
`nextExitTruckEvent`	Triggers the creation of outbound truck entities according to the historical departure timestamps contained in the ExitLoad dataset, while managing overlapping departures assigned to the same dock and timestamp.
`dailyEvent`	Collects daily operational statistics, including warehouse stock levels, occupancy indicators and volume metrics.
`weeklyEvent`	Records weekly warehouse stock levels for subsequent performance analysis.
`monthlyEvent`	Records monthly warehouse stock levels for long-term operational analysis.

These events ensure accurate scheduling and continuous collection of performance indicators. The *Main* agent also centralizes the six operator schedules, their resource pools, and the equipment pools described in Section 4.3.4.

4.3.6 Operational Process Flows

The model's logic is organized into four interconnected process flows (Figure 4.1), integrating the agents, resource pools, and functions described above to replicate the real warehouse's operational sequence.

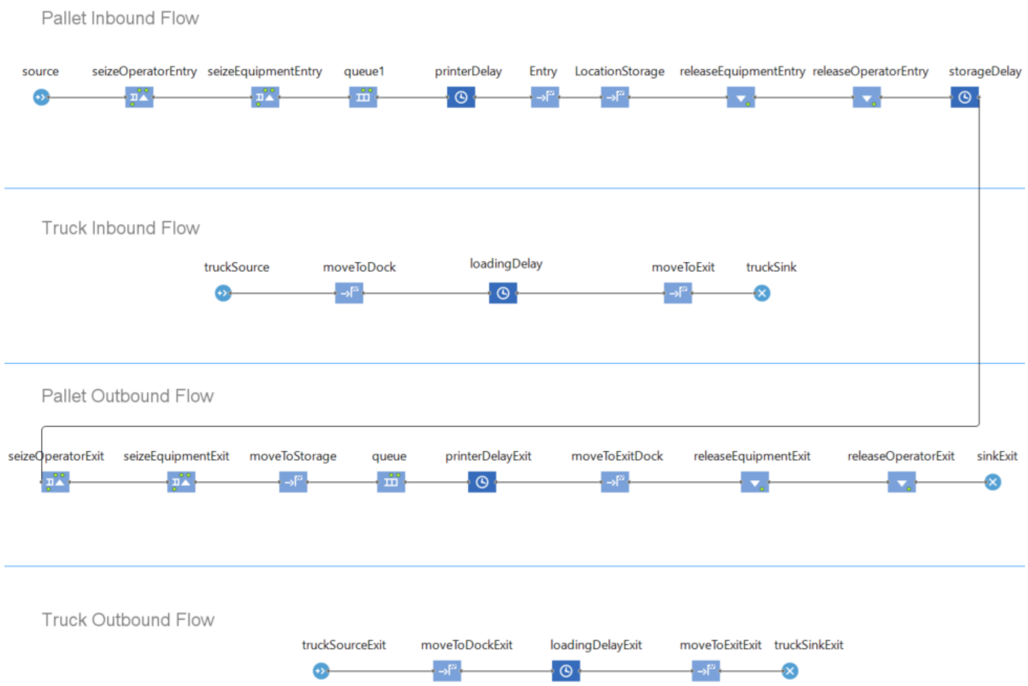


Figure 4.1: *AnyLogic* process flow diagram of pallet and truck inbound and outbound operations

Pallet Inbound Flow. *Pallet* agents are created via the *source* block, triggered by the *Truck Inbound Flow* (4.3.6), and initialized with *storageLocation*, *entryDock*, and *loadID* from *StorageEntry*. Movement speed follows the seized equipment. The agent seizes an operator and equipment from their pools per the shift schedules, waits in FIFO *queue1* before a 10 second *printerDelay* labeling simulation, is routed to the inbound dock and then to its storage location via *getNodeFromLocation()*, releases resources on arrival, and enters *storageDelay* until triggered for retrieval by the *Truck Outbound Flow* (4.3.6).

Truck Inbound Flow. Triggered by *nextEntryTruckEvent* based on *EntryLoad*, trucks are injected at the *enterTrucks* node. Each truck is assigned *assignedDock*, *loadID*, *numPaletes*, and *workersNeeded*, updating global counters. Trucks move to their assigned dock, where unloading duration is the maximum of the historical operation time or a per-pallet estimate (1,5 minutes, capped at 4 hours). *StorageEntry* records update operational statistics and inventory.

Pallet Outbound Flow. Once triggered, the agent leaves *storageDelay*, seizes an operator and equipment, moves to its *storageLocation* for pickup, enters a FIFO queue with a 10 second *printerDelayExit* for outbound label scanning, and is routed to the assigned outbound dock, releasing resources and exiting at *sinkExit*.

Truck Outbound Flow. Generation follows the inbound logic: *nextExitTruckEvent* creates trucks from *ExitLoad* records, each initialized with dock assignment and operator requirements before moving to its loading position. Loading duration uses historical times or per-pallet estimates. On arrival, the truck updates inventory statistics and computes outbound metrics directly from the full *StorageExit* dataset, covering all pallet movements regardless of whether a corresponding *Pallet* agent was generated. In parallel, *palletList* is searched for any matching sampled agents, which are released from *storageDelay* into the Pallet Outbound Flow to complete the visual cargo cycle within the simulation. Together, the four flows form a complete cargo cycle, linked by shared resource pools and indexing structures.

4.3.7 Warehouse Layout Representation

The GTS Maia layout was modeled in *AnyLogic* to reflect its single-sided dock configuration, where inbound and outbound operations share the same perimeter, incorporating 32 dock doors and 43 internal storage and buffer locations. Storage racks, staging areas, and corridors were mapped to preserve realistic spatial relationships, with a node network supporting agent routing and visualization. Although operational distance calculations use a pre-calculated distance matrix, the node network underlies agent movement and animation, ensuring travel times, equipment interactions, and cargo flows remain consistent with observed operations.

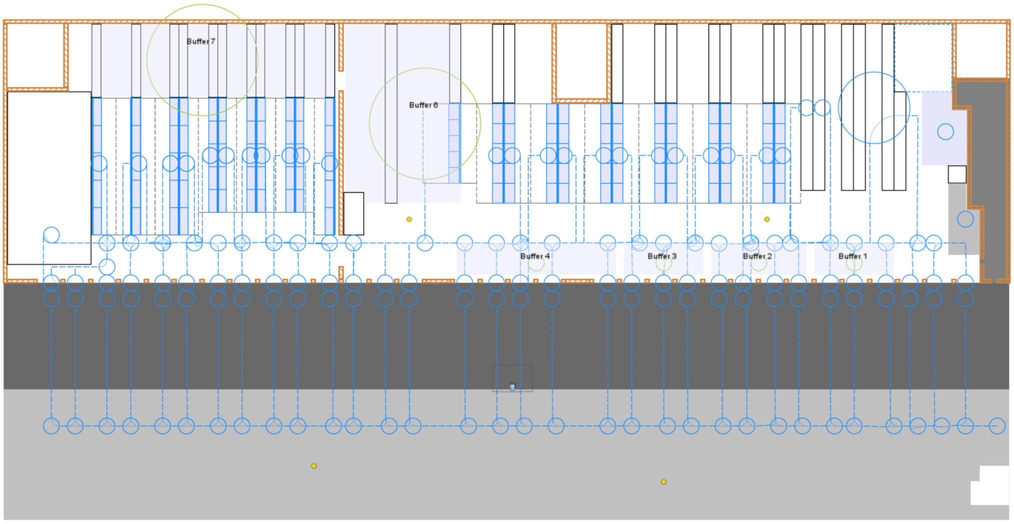


Figure 4.2: GTS Maia warehouse layout and node network implemented in the simulation model

4.3.8 Assumptions and Simplifications

Implementing the model required additional assumptions beyond those of Section 3.6, related to how operational logic was translated into *AnyLogic*, categorized below.

Agent Population and Computational Scaling. AnyLogic imposes a limit of 50000 active agents per simulation run. Since the dataset comprises several hundred thousand pallet movements, generating a *Pallet* agent for every physical pallet would exceed this limit. To manage this constraint, *Pallet* agents are created at a 0,1% sampling rate: for each physical pallet processed in *loadingDelay* (inbound) and *loadingDelayExit* (outbound), a *Pallet* agent is generated with a probability of 0,001. Aggregate performance metrics are nonetheless computed independently from the full pallet volume recorded in *StorageEntry* and *StorageExit*, ensuring that throughput, travel distance, and productivity indicators reflect the complete dataset rather than the sampled subset.

Pallet Matching Logic and Dwell Time Calibration The *storageDelay* block proxies physical dwell time, releasing agents only on matching a booking number with an outbound movement via *storageExitIndex*. As detailed in Section 3.5, the 2025 WMS dataset contained distortions from a lack of load-closure validation, creating “ghost stock” and inflated durations. An external *Excel* pipeline was developed to purge outliers and calibrate subzone-specific dwell time windows.

Step 1: Pair Matching and Individual Dwell Time Calculation. Entry and exit lines were grouped by *Booking Number* and *Storage Location*. The earliest entry timestamp ($T_{\text{entry},i} = \min(T_{\text{entry}})$) and exit timestamp ($T_{\text{exit},i} = \min(T_{\text{exit}})$) were retained, giving the individual raw dwell time in days:

$$D_i = T_{\text{exit},i} - T_{\text{entry},i} \tag{4.1}$$

This generated 78719 candidate pairs, 61 with negative durations, a residual WMS export inconsistency, were excluded, leaving 78658 valid pairs for calibration.

Step 2: Subzone Threshold Calculation and Outlier Flagging. For each subzone, a single, non-iterative baseline average ($\mu_{\text{raw, subzone}}$) was computed as the unweighted mean of D_i:

$$\mu_{\text{raw, subzone}} = \frac{1}{N}\sum_{i=1}^{N} D_i \tag{4.2}$$

where N is the matched pairs in the subzone. Any pair with $D_i > \mu_{\text{raw, subzone}}$ was flagged as an outlier. The threshold was computed once, against the full population, and not recalculated after flagging, so $A_{\text{subzone}} = \mu_{\text{raw, subzone}}$ served as both the outlier threshold and the final calibrated window.

Of the 78658 pairs, 24721 (approximately 31%) exceeded their location-specific threshold and were flagged as outliers, leaving 53937 pairs within the calibrated window, such as 1,35 days for

MAI-E-1-1 and 0,86 days for *MAI-BUFFER6*. These thresholds govern *storageDelay* release in *AnyLogic*, with the full ledger in Appendix G.

Queue Disciplines and Operational Prioritization. The model's internal buffers (*queue1*, *queue*) follow strict FIFO, dictated by the absence of historical data indicating any alternative prioritization in real-world label printing and forklift dispatch.

Material Handling Equipment and Distance Routing Mechanisms. Pallet movement speed reflects the seized equipment's specifications. While the *AnyLogic* node network supports logical routing and 3D visualization, all performance metrics rely on a deterministic distance matrix, keeping travel calculations geometrically consistent with the physical layout independent of graphical routing.

Buffer Location Distance Exclusion. Internal buffer locations (*MAI-BUFFER1*, *MAI-BUFFER2*, *MAI-BUFFER3*, *MAI-BUFFER4*, and *MAI_ARR*) are excluded from travel distance calculations. These locations serve as temporary holding areas for exceptional cargo that could not be immediately assigned to a permanent storage location, representing unplanned movements that fall outside the scope of the dock-door assignment and storage allocation logic being evaluated. Including these distances would introduce noise into the performance metrics, as they reflect operational exceptions rather than the expected flow patterns that the simulation is designed to model. Although *MAI-BUFFER6* and *MAI-BUFFER7* share the buffer naming convention, they currently function as active storage areas and are therefore included in distance calculations.

4.3.9 KPIs

The model records a comprehensive set of KPIs, summarized in the console upon each run (Table 4.15), organized into four categories: aggregate throughput and travel (total pallets, distances, operator-hours), productivity (pallets per operator-hour), temporal distribution (inbound volume by day of week and month), and ranking indicators (storage locations and dock doors by stock and traffic).

Table 4.15: Model KPIs, corresponding model variables, and calculation method

Metric	**Variables Used**	**Calculation**
Total entry distance	`totalDistanceEntry`	Direct value
Total exit distance	`totalDistanceExit`	Direct value
Total distance	`totalDistanceEntry`, `totalDistanceExit`	Sum of inbound and outbound total distances
Inbound pallets	`palletCount`	Direct value
Outbound pallets	`exitPalletCount`	Direct value

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Metric	Variables Used	Calculation
Inbound operator hours	totalHoursOperator-Entry	For each truck, accumulates the larger of the recorded operation duration and a per-pallet estimate (1,5 min/pallet), capped at 4 h
Outbound operator hours	totalHoursOperator-Exit	For each truck, accumulates the larger of the recorded operation duration and a per-pallet estimate (1,5 min/pallet), capped at 4 h
Inbound productivity	palletCount, totalHoursOperator-Entry	palletCount divided by totalHoursOperatorEntry (pallets per operator-hour)
Outbound productivity	exitPalletCount, totalHoursOperator-Exit	exitPalletCount divided by totalHoursOperatorExit (pallets per operator-hour)
Average time per inbound pallet	totalHoursOperator-Entry, palletCount	Minutes of operator time divided by palletCount
Average time per outbound pallet	totalHoursOperator-Exit, exitPalletCount	Minutes of operator time divided by exitPalletCount
Inbound pallets per machine per day	palletCount, simulationDays	palletCount divided by equipment count and simulationDays
Outbound pallets per machine per day	exitPalletCount, simulationDays	exitPalletCount divided by equipment count and simulationDays
Daily entry rate	palletCount, simulationDays	palletCount divided by simulationDays
Daily exit rate	exitPalletCount, simulationDays	exitPalletCount divided by simulationDays
Average entry distance	totalDistanceEntry, palletCount	totalDistanceEntry divided by palletCount
Average exit distance	totalDistanceExit, exitPalletCount	totalDistanceExit divided by exitPalletCount
Entries per day of week	dayOfWeekEntries	Direct values, one per weekday
Entries per month	monthEntries	Direct values, one per month
Ranking of locations by average daily stock	dailyStock	Average daily stock level per storage location, ranked in descending order
Ranking of entry docks (trucks)	dockEntryCount	Number of inbound truck operations per dock, ranked in descending order

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Metric	Variables Used	Calculation
Ranking of exit docks (trucks)	`dockExitCount`	Number of outbound truck operations per dock, ranked in descending order
Ranking of entry docks (pallets)	`dockEntryPalletCount`	Number of inbound pallets per dock, ranked in descending order
Ranking of exit docks (pallets)	`dockExitPalletCount`	Number of outbound pallets per dock, ranked in descending order

4.3.10 Model Limitations

Despite reproducing the GTS Maia warehouse's structure and dynamics in detail, the model presents limitations worth considering when interpreting results.

The 0,1% Pallet agent sampling described in Section 4.3.8 means that *loadingDelayExit* cannot guarantee that the agent released from *storageDelay* corresponds exactly to the booking-level pair identified during preparation, instead releasing any sampled agent available at the matching *storageLocation*. Aggregate indicators are unaffected, but visualized movement acts as a representative proxy rather than one-to-one tracking.

Operator and equipment allocation is dynamic, based on real-time availability rather than reproduced historical patterns, so movement speeds depend solely on the equipment seized without accounting for individual operator variation.

The redistribution of *MAI_01* movements (Appendix E) was performed to correct a systematic data quality issue, but since the actual dock used in each operation was not recorded, the corrected assignments are an approximation of real operational behaviour rather than an exact reconstruction.

4.4 Model Verification and Validation

Following the three-step approach of Naylor et al. (1967), validation was primarily addressed through the first two of the three perspectives discussed (Naylor et al., 1967; Banks et al., 2004).

Face validity was established through review of the input data and assumptions with the warehouse manager and continuous improvement team at GTS, an informal validation technique relying on human reasoning and subjectivity but highly effective with subject matter experts (Balci, 1997), conducted iteratively during data preparation, consistent with treating validation as continuous throughout the simulation life cycle rather than an isolated final step (Balci, 1997). This process led to concrete dataset corrections, including the *MAI_01* dock bias (Section 4.2.7, Appendix E) and the standardization of cargo units, with quantities exceeding 50 units divided by 50 (Section 3.6.3), both defined in agreement with the operational team, ensuring the data fed into the model reflected the operational reality recognized by those responsible for it.

The *conceptual assumptions* underlying the model were similarly reviewed and agreed with the warehouse manager, who confirmed they constituted reasonable approximations of the operational rules followed in practice (Section 3.6).

A formal input-output comparison against independent historical records was not performed, since the historical dataset used to validate the input data was the same dataset feeding the simulation. The iterative review and correction process described above, conducted jointly with personnel directly responsible for the modeled operations, nonetheless provided a substantive basis for establishing the model's credibility, recognizing that subjectivity is an inherent and necessary part of credibility assessment in any reasonably complex simulation study (Balci, 1997).

The primary contribution of the model lies in the relative comparison of alternative configurations rather than in the prediction of absolute performance values. Differences between scenarios should therefore be interpreted directionally, as indicators of the magnitude and direction of improvement each configuration provides over the baseline, rather than as precise forecasts of realized operational outcomes.

Chapter 5

Scenario Analysis and Results

This chapter applies the simulation model developed in the previous chapter to evaluate the current state of the GTS Maia warehouse and to test two alternative configurations aimed at reducing internal travel distances and improving resource utilization. The baseline scenario first establishes a reference for current operational performance. Scenario 1 explores a dynamic, proximity-based dock-door assignment policy on the existing storage layout. Scenario 2 reconfigures the storage layout into zones defined by destination-country volumes, combined with the same proximity-based dock assignment logic. Each scenario is described and its results presented, the three are then compared against one another, and the chapter closes with the development of an operational dock-door assignment prototype translating the best-performing configuration into a tool for daily use. Results are presented as directional and proportional indicators relative to the baseline, consistent with the validation scope described in Section 4.4.

5.1 Experimental Design

The experimental analysis used three scenarios: a baseline, corresponding to the current configuration, and two alternatives. All three were built on the same simulation model base (Chapter 4), with the same assumptions and simplifications (Sections 3.6 and 4.3.8), and the same historical demand, truck arrival patterns, workforce schedules, and equipment resources, so that differences in performance reflect the operational configuration tested rather than the input data. Performance was evaluated using the common KPIs defined in Section 4.3.9: pallet throughput, travel distances, operator productivity, processing times, warehouse daily occupancy, and dock and storage rankings.

Scenario 1 retains the current storage layout but replaces the historical dock-door assignment with a dynamic, proximity-based policy: dock doors are ranked by travel distance to each storage location, and pallets are assigned to the nearest available dock, cascading to the next nearest when the closest is occupied. For cross-docking trucks, the outbound dock is selected based on proximity to the cargo to be loaded, rather than the historical assignment.

Scenario 2 redesigns the storage layout into zones defined by destination-country volume, route, and agent, applying the same proximity-based dock assignment logic as Scenario 1, including the cross-docking-aware outbound selection.

5.1.1 Baseline Scenario (Current State)

5.1.1.1 Scenario Description

The baseline scenario corresponds to the simulation model of Chapter 4, representing the current configuration without modifications: 32 dock doors and 43 storage, staging, and buffer locations (Section 4.3.7), the historical dock-door assignment patterns recorded in the corrected *StorageEntry* and *StorageExit* datasets, including the dock assignment corrections (Section 4.2.6) and MAI_01 redistribution (Section 4.2.6 and 4.2.7), and truck arrivals and departures following *EntryLoad* and *ExitLoad* (Section 4.2.5). Workforce follows the six schedules of Table 4.9, with material handling performed by seven forklifts and five pallet trucks.

The baseline introduces no changes to the model's operational logic and provides the reference values against which Scenarios 1 and 2 are compared. Figures J.1, J.2, and J.3 in Appendix J illustrate the simulation model running under baseline conditions, showing the 2D and 3D warehouse layout views and the model logic structure.

5.1.1.2 Baseline Scenario Results

This section presents the baseline results, organized by the four KPI categories of Section 4.3.9: aggregate throughput and travel, productivity, temporal distribution, and ranking indicators.

Aggregate, Travel and Productivity Indicators. Table 5.1 summarizes the aggregate throughput, travel distance, operator workload, and productivity indicators obtained for the baseline scenario.

The model processed slightly more inbound pallets (224331) than outbound (222446), with a combined travel distance of approximately 16907 km. Outbound productivity (20,7 pallets/operator-hour) was marginally higher than inbound (19,7), reflecting the lower processing time per outbound pallet (2,9 min versus 3,0 min). Each material handling unit processed around 51 pallets per day.

Temporal Distribution. Table 5.2 presents average daily pallet volume by day of week and Table 5.3 the monthly totals. Since this distribution depends solely on historical demand, not on dock assignment or storage layout, it is equal across all three scenarios and presented only once, here.

Inbound activity is strongly concentrated on Fridays (1463 pallets/day on average), more than double any other weekday. Outbound peaks on Fridays too (942), but Saturday shows an inversion, 776 outbound against only 192 inbound, suggesting much of the weekly intake is dispatched over

Table 5.1: Aggregate, travel and productivity indicators (baseline scenario)

Metric	**Value**
Total entry distance	8727,23 km
Total exit distance	8179,61 km
Total distance	16906,84 km
Inbound pallets	224331
Outbound pallets	222446
Inbound operator hours	11380,8 h
Outbound operator hours	10746,0 h
Inbound productivity	19,7 pallets/operator-hour
Outbound productivity	20,7 pallets/operator-hour
Average time per inbound pallet	3,0 min
Average time per outbound pallet	2,9 min
Inbound pallets per machine per day	51,4
Outbound pallets per machine per day	51,0
Daily entry rate	617 pallets/day
Daily exit rate	612 pallets/day
Average entry distance	38,90 m
Average exit distance	36,77 m

Table 5.2: Average daily pallet volume by day of week (applies to all scenarios)

Day of Week	**Inbound (avg/day)**	**Outbound (avg/day)**
Monday	599	824
Tuesday	666	709
Wednesday	571	566
Thursday	700	587
Friday	1463	942
Saturday	192	776
Sunday	133	81

the weekend. Sunday is the quietest day for both flows (133 inbound, 81 outbound), consistent with reduced weekend staffing.

The monthly distribution is comparatively stable across most of the year, as shown in Table 5.3, with inbound volumes ranging from 17263 (January) to 21141 (October) and outbound from 15335 (January) to 20999 (February). August is the clear outlier in both directions, recording the lowest volumes of the year at 13581 inbound and 14388 outbound pallets, reflecting the typical seasonal slowdown in freight forwarding operations during the summer period. December also shows a moderate reduction relative to adjacent months, with 15728 inbound and 16058 outbound pallets.

Ranking Indicators. Figures J.4 and J.5 (Appendix J.1) present pallet entry volumes and average daily occupancy by storage location, and entry/exit volumes by dock door, respectively.

Table 5.3: Monthly pallet volume, inbound and outbound (applies to all scenarios)

Month	**Inbound (pallets)**	**Outbound (pallets)**
January	17263	15335
February	19870	20999
March	20477	20786
April	19485	18976
May	19813	20107
June	18488	18332
July	19558	18509
August	13581	14388
September	19934	19427
October	21141	20432
November	18993	20097
December	15728	16058
Total	**224331**	**222446**

The four locations with the highest average daily stock, *MAI-BUFFER6* (57,7 pallets), *MAI-PW I1* (52,7), *MAI-K-1-1* (50,9), and *MAI-A-1-1* (44,9), also register the highest entry volumes (22198 to 29634 pallets), confirming a direct link between throughput and occupancy. At the other extreme, several locations, including *MAI-BUFFER1*, *MAI-BUFFER3*, *MAI-PW I2*, and *MAI-EF-1-2*, average below one pallet per day, reflecting their role as temporary or exception-handling areas with very low regular utilization.

Dock *MAI_06* is consistently among the busiest for both directions, and *MAI_14* is the busiest for outbound specifically (25586 pallets). Despite the redistribution in Section 4.2.7, *MAI_01* still registers 2252 inbound and 1567 outbound pallets, corresponding to the 1347 and 1024 records (Table 4.3) that remained assigned to it.

5.1.2 Scenario 1: Dynamic Dock Assignment

5.1.2.1 Scenario Description

Scenario 1 retains the physical layout (Section 4.3.7), demand, truck arrivals, workforce schedules (Table 4.9), and material handling resources unchanged from the baseline. The only modification is the dock-door assignment logic, replaced by a dynamic, proximity based policy described below, supported by new functions and variables in the Main agent (Tables 5.4 and 5.5).

Identification of cross-docking truck pairs. A relevant share of inbound trucks subsequently perform an outbound operation with the same vehicle. Scenario 1 identifies the cross-docking pairs dynamically: the Equipment field of each *EntryLoad*/*ExitLoad* record is matched against the Portuguese license-plate pattern and indexed by plate, and each outbound record is matched to the same vehicle's closest preceding inbound load, up to 20 hours apart, recorded as a pair (*bidirec* and *bidirec_reverse*, Table 5.5).

Table 5.4: New functions implemented in the Main agent for Scenario 1

Function	Description
`getDockIdx(dock)`	Converts a dock identifier into its index (0 to 31) within the `dockFree`, `dockRanking`, and `dockDist` arrays, mapping MAI_22A/MAI_26A to the same index as MAI_22/MAI_26.
`freeDock(dock)`	Marks a dock door as available in `dockFree` once the corresponding truck operation has been completed and the truck has left the dock.
`assignDock(loadID)`	Determines the inbound dock assignment for a load, applying the eligibility rules (MAI_01/02/03/29/30), the cross-docking logic, and the quantity-weighted proximity criterion.
`assignDockExit(loadID)`	Determines the outbound dock assignment for a load, applying the same-dock rule for cross-docking pairs and the quantity-weighted proximity criterion otherwise.

Table 5.5: New variables implemented in the Main agent for Scenario 1

Variable	Type	Description
`bidirec`	Map	Maps an inbound Load ID to the Load ID of the outbound operation performed by the same vehicle within 20 hours, if any.
`bidirec_reverse`	Map	Inverse mapping of `bidirec`, from an outbound Load ID to the corresponding inbound Load ID.
`assignedEntry Docks`	Map	Maps an inbound Load ID to its assigned dock (from `assignDock()`), retrieved by `assignDockExit()` for cross-docking pairs.
`dockFree`	boolean[32]	Current availability of each dock door, updated by `assignDock()`, `assignDockExit()`, and `freeDock()`.
`locationNames`	String[43]	Names of the 43 storage locations, loaded from the DockRanking table.
`ALL_DOCKS`	String[32]	Reference list of the 32 dock door identifiers, used to build eligible dock sets in `assignDock()/assignDockExit()`.
`lastOriginalDock`, `lastOriginalDock Exit`	String	Historical dock (from *EntryLoad*/*ExitLoad*) associated with the inbound and outbound load currently being processed, respectively.
`lastScoreOriginal`, `lastScoreNew`	double	Quantity-weighted distance to the historical dock and to the newly assigned dock, respectively, for the inbound operation.
`lastScoreOriginal Exit`, `lastScoreNewExit`	double	Equivalent of `lastScoreOriginal`/`lastScoreNew` for the outbound operation.

Proximity-based dock assignment. The warehouse distance matrix (Appendix F) is loaded as a flat lookup table, *distanceIndex* (Table 4.13), keyed by storage location and dock door, queried by *assignDock()* and *assignDockExit()* (Table 5.4).

Inbound. Dock eligibility follows the baseline rules: *MAI_01* never eligible, *MAI_02*/*MAI_03* only for *HUB GARLAND MAIA* origin, *MAI_29*/*MAI_30* only for *HUB GARLAND MAIA* loads to *MAI-PENDURADOS*. For cross-docking loads, where the same truck performs an inbound operation followed immediately by an outbound operation, the dock assignment is based on the storage locations and quantities of the paired outbound load (*StorageExit*) rather than the inbound load. This ensures that the dock assigned on arrival already minimizes the travel distance for the subsequent loading operation, anticipating the truck's full cargo cycle rather than optimizing each direction independently.Among available, eligible docks (*dockFree*), the model selects the one minimizing the quantity-weighted average distance via *distanceIndex*, marks it unavailable, and records it for the paired outbound leg (*assignedEntryDocks*).

Outbound. For loads that form the outbound side of a cross-docking pair, the dock assigned during the paired inbound operation is reused, reflecting the operational practice of keeping the truck at the same dock for both operations. If no valid paired dock exists, the same selection logic as inbound applies: eligible docks exclude *MAI_01*, *MAI_02*, *MAI_03*, *MAI_29*, and *MAI_30*, and the closest available dock to the load's storage locations is selected. *freeDock()* releases the dock once the truck departs.

It is important to note that Scenario 1 applies the proximity-based dock assignment policy on top of the existing, unstructured storage allocation. No changes are made to where cargo is stored within the warehouse: loads continue to be placed according to the informal associations described in Section 3.4.1, following the historical patterns recorded in *StorageEntry* and *StorageExit*. The dock assigned to each truck is therefore optimized relative to the historical storage locations of the cargo, rather than to any predefined spatial structure. This means that while dock assignment improves, the absence of a structured storage allocation policy remains unchanged.

Operation duration adjustment. Duration is adjusted to reflect the change in travel distance between the newly assigned dock and the historical dock, by accumulating two quantity-weighted distances across all of the load's storage locations:

$$D_{\text{historical}} = \sum_i d(\text{location}_i, \text{historical\_dock}) \times qty_i \tag{5.1}$$

$$D_{\text{new}} = \sum_i d(\text{location}_i, \text{assigned\_dock}) \times qty_i \tag{5.2}$$

where the summation is over all storage locations i. The ratio between these totals scales the load's duration:

$$\text{ratio} = \frac{D_{\text{new}}}{D_{\text{historical}}} \tag{5.3}$$

The base duration, taken from *EntryLoad*/*ExitLoad* when available or estimated at 1,5 minutes per pallet otherwise, is scaled by this ratio:

$$\text{hoursOperation} = \text{duration\_base} \times \text{ratio} \tag{5.4}$$

hoursOperation determines truck type and workforce requirement as in the baseline, and accumulates into *totalHoursOperatorEntry*/*totalHoursOperatorExit* (Section 4.3.9), letting the distance change propagate into operator workload, unlike the baseline, where duration depends only on the historical record. For loads with no recorded historical duration, the per-pallet estimate of 1,5 minutes was adjusted to reflect the distance reduction of the new layout before being scaled by the ratio, consistent with the assumption that travel time scales proportionally with distance at constant equipment speed ($t = d/v$). The adjusted estimates were 1,01 minutes per pallet for inbound operations ($1{,}5 \times 0{,}671$) and 1,06 minutes per pallet for outbound operations ($1{,}5 \times 0{,}707$), where 0,671 and 0,707 correspond to the inbound and outbound distance reduction ratios relative to the baseline, respectively.

5.1.2.2 Scenario Results

This section presents the results of Scenario 1, organized according to the same four KPI categories used for the baseline.

Aggregate, travel and productivity indicators. Table 5.6 summarizes the aggregate throughput, travel distance, operator workload, and productivity indicators obtained for Scenario 1.

Table 5.6: Aggregate, travel and productivity indicators (Scenario 1)

Metric	**Value**
Total entry distance	5852,40 km
Total exit distance	5782,05 km
Total distance	11634,45 km
Inbound pallets	224331
Outbound pallets	222446
Inbound operator hours	6989,8 h
Outbound operator hours	7237,7 h
Inbound productivity	32,1 pallets/operator-hour
Outbound productivity	30,7 pallets/operator-hour
Average time per inbound pallet	1,9 min
Average time per outbound pallet	2,0 min
Inbound pallets per machine per day	51,4
Outbound pallets per machine per day	51,0
Daily entry rate	617 pallets/day
Daily exit rate	612 pallets/day
Average entry distance	26,09 m
Average exit distance	25,99 m

Scenario 1 processed the same pallet volumes as the baseline (224331 inbound, 222446 outbound), since throughput depends only on demand. The proximity-based policy reduced total travel distance from 16906,84 km to 11634,45 km (approximately 31%; entry from 8727,23 to 5852,40 km, exit from 8179,61 to 5782,05 km), propagating into operator hours through the duration adjustment: inbound fell from 11380,8 h to 6989,8 h (38,6%), outbound from 10746,0 h to 7237,7 h (32,6%). Productivity rose to 32,1 (inbound) and 30,7 (outbound) pallets/operator-hour (from 19,7 and 20,7 in the baseline), and average distance per pallet fell to 26,09 m inbound and 25,99 m outbound.

Temporal distribution. Temporal demand distribution depends solely on historical data and is equal across all scenarios. The distributions of Section 5.1.1.2 apply equally here.

Ranking indicators. Since the storage layout and demand are unchanged, the occupancy ranking is identical to the baseline: Figure J.6 (Appendix J.2) confirms *MAI-BUFFER6*, *MAI-PW I1*, *MAI-K-1-1*, and *MAI-A-1-1* remain the four highest average daily stock locations.

The dock ranking, by contrast, changes substantially, since dock assignment is the element altered. Figure J.7 (Appendix J.2) shows *MAI_19* becoming the busiest entry dock by pallet volume (23916), and *MAI_11* the busiest exit dock (23361), both different from the baseline (*MAI_07* entry, *MAI_14* exit). The reduction in traffic at *MAI_02* and *MAI_03* reflects the correct enforcement of their operational restriction to *HUB GARLAND MAIA* inbound flows: loads historically misassigned to these docks in the baseline, due to residual data quality issues, are correctly redirected to proximity-optimal alternatives in Scenario 1.

5.1.3 Scenario 2: Layout Redesign and Dynamic Dock Assignment

5.1.3.1 Scenario Description

Scenario 2 explores a more substantial intervention than Scenario 1: rather than only changing dock assignment, it redesigns the storage layout itself into zones defined by cargo destination, reducing operator travel distance and complementing the proximity-based dock assignment of Scenario 1.

To support the zone definition, two additional fields were incorporated into the *StorageEntry* and *StorageExit* datasets: *Line*, identifying the distribution line associated with each booking, and *Direction*, classifying the operational flow as Iberian, Export, Import, or Foreign. These fields were sourced from the company's internal database, which associates each booking with its corresponding line and operational direction, and joined to the movement records via *Booking Number*.

Defining the zones required analyzing the data along three dimensions: cargo volume per destination country, the operational direction of each booking, and the consolidating agent routing cargo through a single distribution point. This analysis, summarised in Tables J.1, J.2, and J.3 in Appendix J, was translated into rules for grouping destinations into seven zones and a physical area allocation for each.

Volume by Destination Country. The first dimension considered was inbound pallet volume by destination country, summarized in Table J.1 (Appendix J.3). Portugal alone accounts for nearly half of all inbound pallets (109736; 48,92%), reflecting the warehouse's role as a national distribution hub. France (26833; 11,96%), Germany (22825; 10,17%), and Spain (12994; 5,79%) follow as the next largest individual destinations, with Sweden and the United Kingdom each accounting for around 5%. The remaining 52 countries combined represent only 2,02% of total volume (4537 pallets), confirming that grouping zones by individual country would create too many undersized, operationally unviable zones, and motivating the consolidation of low-volume destinations into broader groupings.

Operational Direction. The second dimension considered was operational direction, summarized in Table J.2 (Appendix J.3), classifying each booking as Export, cargo originating in Maia and destined for a foreign country (101538 pallets, 45,26%). Iberian, distribution within Portugal and flows to/from Spain (71063; 31,68%). Import, cargo originating abroad with final destination in Portugal (51660; 23,03%); or Foreign, residual volume not classified above (70; 0,03%).

Consolidating Agents. The third dimension considered was the consolidating agent responsible for routing cargo to multiple final destinations through a single distribution point, derived from the *Line* field and summarized in Table J.3 (Appendix J.3). Palletways Iberia is the largest single agent (23092 pallets, 10,29%), followed by Unireco Logistica (15555; 6,93%) and Online Systemlogistik / OSL (11835; 5,28%). OSL handles volume destined for several countries (Germany, Austria, Poland, Czech Republic, France, Spain, Romania), but all of it leaves through the same Munich consolidation point. The Mainfreight network (Netherlands, Belgium, Poland), Nuova Transports (Italy and Southern Europe), and Rhenus Logistics (UK and Italy) follow the same pattern. A substantial share of volume, 104443 pallets (46,56%), has no agent identified in the data, while the remaining 122 smaller agents together account for 9491 pallets (4,23%).

Rules for Zone Allocation.

- **Minimum volume threshold**: destinations below 2 to 3% of total volume do not justify an individual zone.
- **Operational direction over WMS country**: the Direction field determines whether cargo is import, iberian or an export flow, regardless of the origin country recorded in the WMS.
- **Consolidating agents treated as a single unit**: agents such as OSL, Mainfreight, and Nuova Transports serve multiple destination countries but route all cargo through a single consolidation point. Their volume is therefore assigned to the zone of their primary destination rather than split across individual country zones.

Applying these rules resulted in seven zones, validated against the simulation dataset. Z1 (Portugal and Shuttle) combines Import cargo and the Maia-Aboboda shuttle, the largest zone by volume (48,92%). Z2 (France) is the export flow to France, the second largest destination.

Z3 (Germany and OSL) merges general German cargo with the OSL flow, avoiding two adjacent zones feeding the same traffic. Z4 (Nordics and Italy) groups two distinct but operationally similar low frequency, long haul flows. Z5 (Spain) is kept separate from Z1 despite proximity, using distinct docks and carriers (PalletWays, Unireco, TVS Spain). Z6 (Central Europe, Benelux and other EU countries) consolidates small destinations served by the Mainfreight network. Z7 (Non EU / Customs) groups all non EU destinations (post Brexit UK, USA, Switzerland), subject to customs procedures with longer dwell times.

Physical Dimensioning of the Zones. As in the baseline, the maximum dwell time windows follow the calibration procedure described in Section 4.3.8. Since Scenario 2 reorganizes the warehouse into subzones rather than individual storage locations, the calibration was recomputed at the subzone level, with the full results presented in Appendix H.

Zone area was determined by average daily simultaneous stock, not annual movement volume. The seven zones were subdivided into a total of 18 logical subzones, generally corresponding to a major agent or destination grouping (e.g., Z3 comprises DEU_GERAL, OSL, and SCHMALZ).

Daily simultaneous stock was computed at the subzone level following the same procedure as the baseline calibration (Section 4.3.8), with records paired by *Booking Number* and *Subzone*, retaining only pairs within the calibrated dwell time window, and accumulating each pair's pallet quantity into the subzone's daily stock for every day spanned between entry and exit across a 365-day calendar starting 2 January 2025:

$$\text{Stock}(Z,t) = \sum_{i \in \text{valid pairs of } Z} Q_i \times \mathbf{1}\left[T_{\text{entry},i} \leq t \leq T_{\text{exit},i}\right], \quad t \in \{1,2,\ldots,365\} \tag{5.5}$$

This yielded, per subzone, 365 daily stock values, from which the Mean, Median, P90, P95, and Maximum statistics of Table 5.7 were derived. The Mean was adopted for area allocation, since dimensioning by peak values would systematically overallocate space given the irregular occupancy of several subzones.

The total usable storage area, net of the 3 meter circulation corridors between zones, is 1143,75 m^2. Table 5.8 presents the resulting area per zone, reflecting both average daily stock and the physical constraints of the existing block geometry.

Each of the 18 logical subzones was further divided into physical subzones to reflect the floor-level pallet allocation within each zone, resulting in 34 physical subzones, each with a fixed reference point used to compute the distance matrix (Figure J.8, Appendix J). Implementing this redesign in *AnyLogic* required adapting variables previously indexed by the warehouse's 43 physical locations (e.g., *meanWindows*, *stockDiario*) to operate instead on the 18 logical or 34 physical subzones, plus the supporting structures listed in Tables 5.9, 5.10, and 5.11.

Table 5.7: Daily stock statistics by subzone

Subzone	Mean (pal)	P95 (pal)	Maximum (pal)	Dwell Window (days)	% of Total
Z1_NATIONAL	243,3	534	622	1,35	39,8%
Z1_SHUTTLE	20,7	56	80	0,70	3,4%
Z2_GERAL	74,9	397	813	0,64	12,3%
Z2_SAFRAM	0,4	0	23	1,34	0,1%
Z3_DEU_GERAL	43,0	221	535	0,88	7,0%
Z3_OSL	21,7	57	72	1,92	3,6%
Z3_SCHMALZ	1,8	10	33	1,33	0,3%
Z4_ITA	11,7	48	245	1,90	1,9%
Z4_SWE_NOR	43,0	224	671	0,83	7,0%
Z5_GERAL	9,2	37	127	1,28	1,5%
Z5_PALLETWAYS	16,2	38	76	0,60	2,7%
Z5_UNIRECO	2,3	10	63	1,56	0,4%
Z6_BENELUX	17,8	70	142	1,30	2,9%
Z6_EUROPA_CENTRAL	10,5	62	114	1,05	1,7%
Z6_OUTROS_UE	14,7	71	290	2,75	2,4%
Z7_AMERICAS_CHE	23,8	78	182	2,61	3,9%
Z7_GBR	49,4	150	316	4,40	8,1%
Z7_RESTO_MUNDO	6,4	24	109	3,72	1,0%

Table 5.8: Final area allocation per zone

Zone	Area (m^2)	% of Total
Z1 (Portugal + Shuttle)	330,75	28,9%
Z7 (Non EU / Customs)	182,25	15,9%
Z2 (France)	175,50	15,3%
Z3 (Germany + OSL)	137,25	12,0%
Z4 (Nordics + Italy)	110,25	9,6%
Z6 (Central Europe + Benelux)	110,25	9,6%
Z5 (Spain)	97,50	8,5%

Table 5.9: Function added in Scenario 2

Function	Description
`getBestDockForLoad(loadID, isExit)`	Computes the dock that minimizes the quantity weighted distance across the physical subzones associated with a load, restricted to a fixed set of eligible doors and to doors not currently occupied. Full mechanics described in Section 5.1.3.1.

Table 5.10: Variables added in Scenario 2

Variable	**Description**
`bidirec`	Reused unchanged from Scenario 1 (Table 5.5); consulted by `getBestDockForLoad()` to anticipate the outbound subzones of a cross docking pair when assigning the inbound dock.
`bidirec_reverse`	Inverse mapping of `bidirec`, from an outbound `Load ID` to the corresponding inbound `Load ID`; consulted by `getBestDockForLoad()` to force the outbound operation of a cross docking pair onto the same dock used for the inbound operation.
`assignedEntryDocks`	Maps an inbound `Load ID` to the dock assigned to it by `getBestDockForLoad()`, retrieved for the corresponding outbound operation of a cross docking pair via `bidirec_reverse`.
`storageIndex`, `storageExitIndex`	Rebuilt for this scenario, now keyed only by `LoadID` (in the baseline and Scenario 1 they were keyed by `loadID` + dock).
`distanceIndex`	Rebuilt from the redesigned layout distance sheet (physical subzone + dock), then expanded with the legacy distance matrix, so historical and new distances coexist in the same lookup table.
`subzonaFaixas`	Maps each logical subzone to its array of physical lanes.
`subzonaCounter`	Round robin counter, per logical subzone, used to assign each entry line to one of its physical lanes.
`entryLoadSubzonas`, `entryLoadSubzonaQty`, `entryLoadSubzonaFisica`	Per load: the list of physical subzones touched by its entry lines, the quantity per (load, physical subzone), and the physical subzone of the first entry line encountered for that load.
`exitLoadSubzonas`, `exitLoadSubzonaQty`, `exitLoadSubzonaFisica`	Exit side equivalents of the three variables above.
`zoneEntryCount`, `zoneExitCount`	Total pallet quantity entered or exited per logical subzone, accumulated during startup.
`countedEntryLoads`, `countedExitLoads`	Prevent operator hours from being counted more than once for loads with multiple subzone records.
`meanWindows`	Dwell time thresholds per logical subzone, as defined in Appendix H.
`occupiedDocks`	Set tracking dock doors currently in use, consulted by `getBestDockForLoad()` when selecting an available dock.

Table 5.11: Additions to the Pallet agent in Scenario 2

Element	Description
`subzonaFisica`	Attribute set from `entryLoadSubzonaFisica` when the load exits the source block, storing the pallet's assigned physical subzone.
`getNodeFromSubzona()`	Function that maps the pallet's `subzonaFisica` string to the corresponding GIS node in Main (e.g., "Z1_NACIONAL3" to the Z1_NACIONAL3 node), used to route the pallet to its physical storage destination. Falls back to Z1_NACIONAL1 if no match is found.

Distance Matrix and Physical Reference Points. While 18 logical subzones sufficed for area allocation (Section 5.1.3.1), distance calculations need finer granularity, comparable to the 43 named locations of the current layout (Appendix F). Each logical subzone was therefore subdivided into physical lanes, yielding 34 physical subzones (e.g., NACIONAL, the largest, into seven lanes), each with its own fixed reference point.

A new distance matrix, covering these 34 physical subzones and the 32 dock doors (1088 values), was developed following the same methodology as the current layout: each reference point set back 8 meters from the dock doors, with distances measured along the redesigned circulation paths. Figure J.8 (Appendix J) illustrates the redesigned layout and reference points.

Proximity-Based Dock Assignment As in Scenario 1, dock assignment is computed at runtime by *getBestDockForLoad(loadID, isExit)*, which retrieves the physical subzones associated with the load's cargo and computes the distance-weighted score for each eligible dock. For inbound cross-docking loads, the function substitutes the inbound subzones with those of the paired outbound load, so that the dock assigned on arrival already minimizes travel distance for the subsequent loading operation rather than optimizing the inbound leg in isolation.

Eligible docks follow the same operational constraints as Scenario 1: *MAI_01* is never used; *MAI_02*, *MAI_03*, *MAI_29*, and *MAI_30* are restricted to inbound loads originating from *HUB GARLAND MAIA*; and all remaining docks (*MAI_04* to *MAI_28*, including *MAI_22A* and *MAI_26A*) are unconditionally available. Among the eligible docks not currently occupied, the one with the lowest quantity-weighted average distance to the load's physical subzones is selected.

Operation Duration Adjustment. Duration is scaled by a distance ratio comparing the newly assigned dock with the dock historically recorded for the load, letting the redesigned layout propagate into operator workload.

Since *EntryLoad*/*ExitLoad* contain one record per load-subzone combination, only the first record for a given load performs the calculation and accumulates into *totalHoursOperatorEntry* (*totalHoursOperatorExit*), preventing double counting across multiple subzone records of the same physical operation.

For that load, two quantity-weighted distances are computed. The historical distance iterates over all *StorageEntry*/*StorageExit* rows retrieved via *storageIndex*/*storageExitIndex*, using each row's own historical storage location and dock:

$$D_{\text{historical}} = \sum_i d(\text{location}_i, \text{historical\_dock}_i) \times qty_i \tag{5.6}$$

The new distance iterates over all physical subzones of the load, retrieved from *entryLoadSubzonas*/*exitLoadSubzonas*, using the quantity per subzone from *entryLoadSubzonaQty*/*exitLoadSubzonaQty* and the newly assigned dock:

$$D_{\text{new}} = \sum_j d(\text{subzone}_j, \text{assigned\_dock}) \times qty_j \tag{5.7}$$

where j iterates over all physical subzones of the load. The historical distance uses the baseline distance matrix (Appendix F) and the new distance uses the redesigned layout matrix (Appendix I). The ratio between the two,

$$\text{ratio} = \frac{D_{\text{new}}}{D_{\text{historical}}} \tag{5.8}$$

This ratio is applied to the base duration in all cases: when a historical duration is available, it is scaled directly by the ratio; when no historical duration exists, the per-pallet estimate of 1,5 minutes is first adjusted to reflect the distance reduction of the new layout, consistent with the assumption that travel time scales proportionally with distance at constant equipment speed ($t = d/v$), and then scaled by the ratio. The adjusted per-pallet estimates were 1,10 minutes for inbound operations ($1{,}5 \times 0{,}733$) and 0,94 minutes for outbound operations ($1{,}5 \times 0{,}628$), where 0,733 and 0,628 correspond to the inbound and outbound distance reduction ratios relative to the baseline, respectively. The final duration determines truck type and workforce requirements as in the baseline and accumulates into *totalHoursOperatorEntry*/*totalHoursOperatorExit* (Section 4.3.9).

Physical Lane Assignment. Since each logical subzone comprises multiple physical lanes (e.g., *Z1_NACIONAL* is subdivided into seven lanes), each inbound load must be assigned to a specific lane to obtain a fixed reference point for distance calculation. This assignment follows a round-robin sequence per logical subzone: each new load is allocated to the next lane in order, cycling back to the first once all lanes have been used. The resulting physical lane is stored in *entryLoadSubzonaFisica* and used consistently across the distance matrix lookups throughout the simulation, ensuring that each load has a single, coherent physical location for all distance calculations. The mapping between each logical subzone and its physical lanes is presented in Table 5.12.

Table 5.12: Mapping between logical subzones and physical lanes used for distance calculation in Scenario 2

Logical Subzone	Lanes	Physical Lanes
Z1_NACIONAL	7	*Z1_NACIONAL1* to *Z1_NACIONAL7*
Z1_SHUTTLE	2	*Z1_SHUTTLE1*, *Z1_SHUTTLE2*
Z2_GERAL	5	*Z2_GERAL1* to *Z2_GERAL5*
Z2_SAFRAM	1	*Z2_SAFRAM*
Z3_DEU_GERAL	2	*Z3_DEU_GERAL1*, *Z3_DEU_GERAL2*
Z3_OSL	1	*Z3_OSL*
Z3_SCHMALZ	1	*Z3_SCHMALZ*
Z4_SWE_NOR	2	*Z4_SWE_NOR1*, *Z4_SWE_NOR2*
Z4_ITA	1	*Z4_ITA*
Z5_PALLETWAYS	1	*Z5_PALLETWAYS*
Z5_UNIRECO	1	*Z5_UNIRECO*
Z5_GERAL	1	*Z5_GERAL*
Z6_BENELUX	1	*Z6_BENELUX*
Z6_EUROPA_CENTRAL	1	*Z6_EUROPA_CENTRAL*
Z6_OUTROS_UE	1	*Z6_OUTROS_UE*
Z7_GBR	2	*Z7_GBR1*, *Z7_GBR2*
Z7_AMERICAS_CHE	2	*Z7_AMERICAS_CHE1*, *Z7_AMERICAS_CHE2*
Z7_RESTO_MUNDO	2	*Z7_RESTO_MUNDO1*, *Z7_RESTO_MUNDO2*
Total	**34**	

5.1.3.2 Scenario Results

This section presents the results obtained from Scenario 2, organized according to the same four KPI categories used for the baseline and Scenario 1.

Aggregate, travel and productivity indicators. Table 5.13 summarizes the aggregate throughput, travel distance, operator workload, and productivity indicators obtained for Scenario 2.

Scenario 2 achieved a total travel distance of 11518,89 km, a reduction of approximately 31,8% relative to the baseline (inbound from 8727,23 to 6390,74 km, outbound from 8179,61 to 5128,14 km), and marginally below Scenario 1 (11634,45 km). The most pronounced gains were in outbound operations, where the zone-based layout produced a 37,3% reduction against the baseline, compared to 26,8% inbound.

Operator workload showed a more differentiated picture. Inbound hours fell from 11380,8 h to 7732,3 h (-32,1%), still above the 6989,8 h of Scenario 1, while outbound hours fell from 10746,0 h to 5854,2 h (-45,5%), well below Scenario 1's 7237,7 h. Consequently, inbound productivity reached 29,0 pallets/operator-hour, below Scenario 1's 32,1, while outbound productivity reached 38,0 pallets/operator-hour, substantially above both the baseline (20,7) and Scenario 1 (30,7). Average distance per pallet fell to 28,49 m inbound and 23,05 m outbound, the lowest across all scenarios for outbound.

Table 5.13: Aggregate, travel and productivity indicators (Scenario 2)

Metric	**Value**
Total entry distance	6390,74 km
Total exit distance	5128,14 km
Total distance	11518,89 km
Inbound pallets	224331
Outbound pallets	222446
Inbound operator hours	7732,3 h
Outbound operator hours	5854,2 h
Inbound productivity	29,0 pallets/operator-hour
Outbound productivity	38,0 pallets/operator-hour
Average time per inbound pallet	2,1 min
Average time per outbound pallet	1,6 min
Inbound pallets per machine per day	51,4
Outbound pallets per machine per day	51,0
Daily entry rate	617 pallets/day
Daily exit rate	612 pallets/day
Average entry distance	28,49 m
Average exit distance	23,05 m

Temporal distribution. As with Scenario 1, demand distribution depends exclusively on historical data and is equal across all scenarios. The distributions of Section 5.1.1.2 apply equally here.

Ranking indicators. Figures J.9 and J.10 (Appendix J.3) present pallet entry volumes and average daily occupancy by subzone, and entry/exit volumes by dock door.

Z1_NACIONAL dominates occupancy with an average daily stock of 233,86 pallets, well above *Z2_GERAL* (58,52) and *Z7_GBR* (49,89), reflecting the concentration of import and shuttle flows.

On the dock side, *MAI_09* is the busiest inbound dock by truck count (2131), *MAI_08* handles the highest pallet volumes in both inbound (23942) and outbound (18010), and *MAI_07* registers the highest outbound truck count (2117). As in Scenario 1, *MAI_02*, *MAI_03*, *MAI_29*, and *MAI_30* record negligible activity given their restricted eligibility.

5.2 Comparative Analysis and Discussion

This section provides a comparative evaluation of the three scenarios: the baseline configuration, Scenario 1 (dynamic dock assignment), and Scenario 2 (layout redesign combined with dynamic dock assignment).

5.2.1 Summary of Key Results Across Scenarios

Table 5.14 presents a consolidated comparison of the main performance indicators across all scenarios.

Table 5.14: Comparison of key performance indicators across all scenarios

Metric	Baseline	Scenario 1	Scenario 2
Total entry distance (km)	8727,23	5852,40	6390,74
Total exit distance (km)	8179,61	5782,05	5128,14
Total distance (km)	16906,84	11634,45	11518,89
Inbound operator hours (h)	11380,8	6989,8	7732,3
Outbound operator hours (h)	10746,0	7237,7	5854,2
Inbound productivity (pallets/op-hr)	19,7	32,1	29,0
Outbound productivity (pallets/op-hr)	20,7	30,7	38,0
Average entry distance (m)	38,90	26,09	28,49
Average exit distance (m)	36,77	25,99	23,05

Impact on Travel Distance. Both scenarios significantly reduce total travel distance relative to the baseline: approximately 31% for Scenario 1 (11634,45 km) and 31,8% for Scenario 2 (11518,89 km). The difference between the two scenarios is marginal at the total level, but the composition differs: Scenario 1 achieves more balanced reductions across inbound (33,0%) and outbound (29,3%), while Scenario 2 concentrates the gains in outbound flows (37,3% reduction) at the cost of a smaller inbound reduction (26,8%), reflecting the structural logic of the zone-based layout, which is designed to minimize outbound retrieval distances. In both scenarios, cross-docking operations optimize dock assignment based on the outbound storage locations rather than the inbound ones. This prioritization was defined at the request of the operational management team, reflecting the view that outbound operations are more sensitive to dock proximity: on the outbound side, operators must travel to each storage location where the load's cargo is held and transport it to the assigned dock for loading, a process that spans multiple locations and accumulates internal travel distance. Minimizing the distance between those storage locations and the outbound dock therefore reduces total internal travel more effectively than optimizing the inbound leg alone.

Impact on Operator Productivity. Operator productivity improves substantially in both scenarios relative to the baseline. Since both scenarios apply the same cross-docking dock prioritization logic based on outbound storage locations, the differences in productivity between them reflect the structural impact of the zone-based layout rather than the assignment policy itself. Scenario 1 achieves the highest inbound productivity (32,1 pallets/operator-hour), as cargo continues to follow the historical, unstructured allocation, and the proximity-based dock assignment translates directly into shorter inbound paths. Scenario 2 shows slightly lower inbound productivity

(29,0 pallets/operator-hour), a difference of approximately 3 pallets per operator-hour, since cross-docking operations optimize the dock based on the outbound storage locations, which in Scenario 2 are the predefined destination zones. These zones may be farther from the arrival dock than the historical storage locations used in Scenario 1, resulting in longer average inbound paths. Despite this, Scenario 2 achieves a lower total travel distance (11518,89 km versus 11634,45 km), driven by its outbound gains: outbound productivity reaches 38,0 pallets/operator-hour against Scenario 1's 30,7, a direct consequence of co-locating cargo with its destination zone and substantially reducing retrieval distances (5128,14 km versus 5782,05 km).

Operational Trade-offs. Scenario 1 achieves significant efficiency gains through a single operational change with no structural reorganization required, making it a low-cost, immediately deployable improvement. Scenario 2 requires a full redesign of storage allocation and physical zoning, but achieves the lowest total travel distance (11518,89 km), the lowest outbound distance (5128,14 km), and the highest outbound productivity (38,0 pallets/operator-hour) across all scenarios, making it the stronger candidate where overall and outbound efficiency are the primary concern.

Final Discussion. In cross-docking operations, throughput speed is widely recognized as the primary operational priority, with facilities designed to minimize the time cargo spends between inbound receipt and outbound dispatch (Apte and Viswanathan, 2010). At GTS Maia, this is confirmed by the historical data: the majority of matched inbound-outbound pairs exit within one calendar day of arrival, reflecting the transient nature of cargo at the facility. A common operational pattern involves trucks arriving during the day, being allocated to a dock door, and remaining parked overnight to be loaded with outbound cargo the following morning. This is particularly characteristic of the *Carro-Dia* service, which operates daily distribution routes to customers, typically beginning loading operations in the early hours before departing on their first route of the day and returning to the facility for additional loading and unloading cycles throughout the day. In this context, the efficiency of the outbound operation is operationally more critical than the inbound leg, since delays in outbound loading directly impact departure schedules and customer service levels. This is precisely why the operational management team requested that dock assignment for cross-docking pairs be driven by the outbound storage zones rather than the inbound arrival dock, ensuring that when the outbound operation begins, the assigned dock is already as close as possible to where the cargo is stored.

Both scenarios deliver on this logic, with Scenario 2 going further by structurally co-locating cargo with its destination zone. Overall, proximity-based decision rules alone already provide substantial operational benefits, and combining them with a spatially optimized layout yields further gains in travel efficiency. From an implementation perspective, Scenario 1 is a highly practical short-term improvement requiring no structural changes and no strictly enforced storage rules, as cargo placement continues to follow the informal associations described in Section 3.4.1 rather than a formalized allocation policy. Scenario 2 is a longer-term strategic redesign with higher implementation complexity but stronger structural impact on outbound flow efficiency and total distance reduction, precisely because it replaces those informal associations with enforced destination zones.

5.3 Dock-Door Assignment Modeling in a Cross-Docking Warehouse

Following the identification of Scenario 2 as the strongest configuration (Section 5.2), an operational prototype translated its redesigned, zone based dock-door layout into a tool warehouse staff could use in day to day planning. Unlike the simulation model, which evaluates a full simulated year, the prototype operates at the level of a single day, suggesting the dock door for each expected truck.

The prototype is a *Microsoft Excel* workbook driven by a *Visual Basic for Applications (VBA)* module, fed by *Loads*, *Legs*, and *Bookings* records for November and December 2025, extracted from the company's internal database. The source data mirrors the inbound/outbound structure used throughout the simulation model (Section 4.2.5): *Loads*, *Legs*, and *Bookings* describe trucks arriving at Maia, while *Loads1*, *Legs1*, and *Bookings1* describe trucks departing. Given the trucks scheduled for a given day, the bookings they carry, and each booking's destination, the tool computes the dock door minimizing operator travel distance to the cargo's storage zone, reusing the seven zone, eighteen subzone layout and distance matrix developed for Scenario 2 (Sections 5.1.3.1 and 5.1.3.1). Screenshots of the prototype's interface and reference sheets are presented in Appendix K.

Table 5.15 summarizes the main procedures implemented in the prototype's VBA module.

5.3.1 Cross-Docking Pair Identification

As in Scenarios 1 and 2, the prototype identifies cross-docking pairs, the same vehicle performing an inbound operation followed by an outbound operation within a short interval. For each vehicle, loads are sorted chronologically. Each outbound load is matched to the closest preceding, unmatched inbound load of the same vehicle within 20 hours, the same window used in the *EntryLoad/ExitLoad* matching of Section 4.2.9:

$$\text{partner}(L') = \underset{\substack{L \in \text{unmatched inbound loads} \\ 0 < t_{\text{in}}(L') - t_{\text{in}}(L) \leq 20}}{\arg\min} \big(t_{\text{in}}(L') - t_{\text{in}}(L)\big) \tag{5.9}$$

When a match is found, the door assignment for the inbound load uses the storage subzones of its paired outbound load rather than its own:

$$Z_L = \begin{cases} Z_{L'}, & \text{if } L \text{ is the inbound load of a pair with outbound load } L' \\ Z_L, & \text{otherwise} \end{cases} \tag{5.10}$$

This anticipates the truck's next operation, in the same way as *assignDock()* in Scenario 1 and *getBestDockForLoad()* in Scenario 2.

Table 5.15: Main VBA procedures implemented in the dock-door assignment prototype

Procedure	**Description**
ImportarDados / *ProcessarDirecaoOrigem*	Reads the raw *Loads*/*Legs*/*Bookings* sheets for both directions, matches legs to bookings and loads, classifies each load into a storage subzone, and consolidates the result into a single working sheet (Figure K.3) with a direction flag (inbound or outbound).
GetSubzona	Rule based classifier that assigns each booking leg to one of the eighteen logical subzones used in Scenario 2, following the criteria summarized in Figure K.1.
DuracaoDeEstimada	Estimates the unloading or loading duration of a truck from its total cargo volume (LDM), described in Section 5.3.2.
BuildDistDict / *GetDist*	Builds and queries a lookup table of average travel distance between each logical subzone and each dock door, from the redesigned-layout distance sheet (Figure K.2); described in Section 5.3.3.
DetetarRestricaoPorta	Identifies whether a load corresponds to a *Carro-Dia* or *Shuttle* service, so the corresponding dedicated door set can be applied (Section 5.3.3).
EscolherPortaPonderada	Core allocation function: selects, among a candidate set of dock doors, the one minimizing the quantity-weighted distance to the load's storage subzones, subject to availability; described in Section 5.3.3.
GerarPlanoPonderado	Orchestrates the daily plan: identifies cross docking pairs by vehicle license plate, processes all loads for the selected day chronologically, and writes the door assignments to the daily plan sheet (Figure K.5).
AtualizarGrelhaOcupacao / *DetetarConflitosPortas*	Generate a 24-hour occupancy grid per dock door (Figure K.6) and flag genuine scheduling conflicts, excluding cases where the same vehicle occupies a door for consecutive unloading and loading operations.

5.3.2 Estimated Operation Duration

The prototype estimates each truck's unloading or loading duration from its volume in loading metres (LDM), through *DuracaoDeEstimada()*:

$$\text{minutes} = \text{SETUP\_MIN} + LDM \times 2{,}4 \times 1{,}5 \tag{5.11}$$

$$\text{hours} = \frac{1}{2}\left\lfloor 2 \times \frac{\text{minutes}}{60} + 0{,}5 \right\rfloor \tag{5.12}$$

rounding to the nearest half hour, the granularity of the daily plan. SETUP_MIN, 10 minutes, is the fixed time a truck spends parking and exchanging documentation before physical handling begins, added once per truck regardless of cargo volume.

The first multiplicative factor, 2,4 pallets per LDM, follows from the standard definition of the loading meter: 1 LDM is 1 meter of trailer length across the standard 2,4 meter internal width of a European semi-trailer, that is, 2,4 m^2 of floor space (Quicargo, 2025). Approximating a standard pallet footprint at 1 m^2 (a Euro pallet is 0,8 m $\times$ 1,2 m, or 0,96 m^2), consistent with the general formula $LDM = (L \times W)/2{,}4$ used across the road freight industry (Deni Internacional, 2019; Savino Del Bene, 2026), where L and W are the cargo length and width in meters, yields the conversion used here. The second factor, 1,5 minutes per pallet, is the handling time established in Section 3.6.1 (Table 3.2), reused for consistency with the simulation model.

5.3.3 Dock-Door Allocation Logic

Subzone-to-dock distance lookup. For each logical subzone z and dock door p, *BuildDistDict()* averages the recorded distances from every physical subzone belonging to z (Figure K.2), as in Section 5.1.3.1:

$$d(z,p) = \frac{1}{N_{z,p}} \sum_{j=1}^{N_{z,p}} d_{\text{raw}}(z_j, p) \tag{5.13}$$

where z_j ranges over the physical subzones of z and $N_{z,p}$ is the number of records found. The table is queried at runtime by *GetDist()*.

Door scoring and selection. For a load L with subzone quantities $Z_L = \{(z, q_z)\}$, where q_z is the number of pallets assigned to subzone z, each candidate door p is scored as the quantity-weighted sum of distances to every subzone touched by the load:

$$\text{score}(p,L) = \sum_{(z,q_z) \in Z_L} q_z \times d(z,p) \tag{5.14}$$

The assigned door minimizes this score among doors that are both eligible and available:

$$p^*(L) = \underset{p \in P_L \cap P_{\text{available}}(t_{\text{in}}, t_{\text{out}})}{\arg\min} \text{score}(p,L) \tag{5.15}$$

where $P_L \subseteq P$ is the set of eligible dock doors for load L, determined by the service-specific constraints described in Section 5.3.3 and $P_{\text{available}}(t_{\text{in}}, t_{\text{out}})$ is the set of doors with no other load scheduled during $[t_{\text{in}}, t_{\text{out}}]$.

Reserved window for cross-docking pairs. For an inbound load L paired with outbound load L', the door is reserved through the end of the subsequent loading operation, so the vehicle finds its door still available when it returns:

$$t_{\text{out}}(L) = \max\Big(t_{\text{in}}(L) + d(L),\ \ t_{\text{in}}(L') + d(L')\Big) \tag{5.16}$$

where $d(L)$ and $d(L')$ are the estimated durations from Equation 5.12. This extended interval is the t_{out} used in Equation 5.15.

Excluded doors. Four doors, *MAI_02*, *MAI_03*, *MAI_29*, and *MAI_30*, are excluded from the candidate set entirely and unconditionally, regardless of distance score, service type, or availability. This reflects a physical constraint rather than an operational preference: these doors are fitted with ramps suited to cars and vans, used by customers collecting or delivering cargo with this type of vehicle, rather than the dock-level ramps required by freight trucks.

Restricted door sets. The warehouse team requested that *Carro-Dia* and *Shuttle* trucks each be allocated to their own dedicated set of doors, implemented by classifying each load's service and line fields (*DetetarRestricaoPorta*):

$$P_L = \begin{cases} P_{\text{Carro-Dia}} = \{\text{MAI\_06}, \ldots, \text{MAI\_11}\}, & \text{if } L \text{ is a } \textit{Carro-Dia} \text{ service} \\ P_{\text{Shuttle}} = \{\text{MAI\_12}, \text{MAI\_13}\}, & \text{if } L \text{ is a } \textit{Shuttle} \text{ service} \\ P_{\text{all}}, & \text{otherwise} \end{cases} \tag{5.17}$$

where P_{all} already excludes MAI_02, MAI_03, MAI_29, and MAI_30.

Since *Carro-Dia* trucks represent more than half of all loads, their six doors are often insufficient at peak hours. The restriction is therefore a preference, not a hard rule: the algorithm first searches only within P_L for an available door. Only when none of the doors in P_L are free at the required time does it search again across the full set P_{all}, selecting the closest available door overall. This preserves the requirement under normal conditions while avoiding artificial conflicts when dedicated capacity is exceeded.

This fallback is independent of the cargo substitution defined in Equation 5.10: for a *Carro-Dia* cross-docking truck, Z_L is already set to the paired outbound load's subzones before the door search begins and remains so regardless of which door set is used, ensuring that dock assignment is always based on the cargo to be loaded rather than the cargo being unloaded.

5.3.4 Operational Outputs

For a selected day, chosen through a date selection form (Figure K.4), the prototype writes one row per load to a daily plan sheet (Figure K.5), including the assigned dock door, matricula, line, estimated duration, and a cross-docking flag. Loads are processed in a single chronological pass, so availability checks in Equation 5.15 always run against a fully up to date schedule.

Two further outputs support visual verification: a 24-hour occupancy grid (Figure K.6) per dock door, and an automatic conflict detector flagging loads assigned to the same door with overlapping time windows, excluding the case of a single vehicle occupying a door for both legs of a cross-docking pair. In practice, the allocation algorithm accounts for each truck's time window when selecting a door, ensuring that no two loads are assigned to the same dock during overlapping periods. The conflict detector therefore serves as a safeguard for manual adjustments made after the automatic allocation, rather than a correction mechanism for the algorithm itself.

Chapter 6

Conclusion

This chapter synthesizes the main findings and contributions of this dissertation, reflecting on the research objectives, the analytical framework developed, and the results obtained across the three simulated scenarios. It also discusses the practical and theoretical implications of the work, acknowledges the limitations that shaped the analysis, and identifies directions for future research building on the foundation established here.

6.1 Conclusion

This dissertation was guided by two research questions. The central question asked: to what extent does a proximity-based dock-door assignment policy, alone and combined with a zone-based layout redesign, reduce internal travel distance and improve operator productivity in a single-sided cross-docking facility? The subsidiary question asked whether granular, real-world WMS data can be transformed into a credible discrete-event simulation model and an operational decision-support tool for daily dock-door assignment.

The answer to the central question is not simply that travel distance fell by 31% or 32%. The more fundamental finding is that the single largest driver of internal inefficiency at GTS Maia is not the physical layout, but the absence of a systematic spatial criterion in dock-door allocation. Once that criterion was introduced, the warehouse achieved a 31,2% reduction in total travel distance and productivity gains of 62,9% inbound and 48,3% outbound, without any physical reorganization. Adding the zone-based layout of Scenario 2 reduced total distance by a further 1,0% and produced the strongest outbound gains: operator hours fell 45,5% and productivity reached 38,0 pallets per operator-hour, a 83,6% improvement over the baseline. The layout redesign thus addresses the root cause the assignment policy alone cannot: the absence of spatial structure in cargo storage, which acts as a ceiling on the gains achievable through dock assignment alone.

The answer to the subsidiary question is affirmative. Despite systematic data inconsistencies, the WMS dataset provided sufficient signal to support both a calibrated simulation model and an automated daily planning prototype. The model was validated iteratively with warehouse management through face validity assessment, consistent with its purpose as a decision-support tool for the relative comparison of operational configurations rather than an absolute predictor of performance. The results should therefore be read as directional and proportional indicators of the impact of each configuration relative to the baseline, not as point forecasts of realized operational values.

Each project objective was fulfilled: the simulation model was developed and validated through iterative review with warehouse management; the three-scenario analysis quantified the impact of assignment policy and layout redesign on key performance indicators; and the VBA-based prototype translated the best-performing configuration into a daily planning tool that classifies loads into storage subzones, identifies cross-docking pairs, and allocates distance-minimizing dock doors subject to service-specific constraints.

Beyond the simulation and prototype, the findings of this study have already generated tangible operational impact: the analytical framework informed a formal development request submitted to the GTS WMS provider, covering the implementation of a configurable storage location suggestion engine within the warehouse management interface, including destination-based mapping rules, automatic recalculation of suggested locations upon changes to cargo attributes, and logging of suggested versus confirmed locations for continuous improvement. This confirms that the contribution of this work extends beyond the academic scope of the dissertation into the facility's core information systems and daily operational planning.

Methodologically, this work demonstrates how granular WMS data can be transformed into a calibrated simulation model and operational tool in a real freight-forwarding setting. Practically, it addresses a single-sided cross-docking configuration that receives comparatively little attention in existing research, confirming that proximity-based decision rules yield substantial efficiency gains even where inbound and outbound operations compete for the same dock perimeter.

6.2 Future Work

Several directions emerge naturally from the findings and limitations of this study.

Field Validation. Controlled pilot implementation of the proposed assignment logic and storage rules, allowing the recommended configuration to be tested under real operating conditions and confirming whether the simulated gains translate into measurable operational improvements.

WMS Integration and Real-Time Assignment. The prototype currently operates offline, fed by manually exported data. A direct integration of the assignment logic into the GTS WMS would enable real-time dock allocation as loads are confirmed, removing the export-and-import step and allowing the tool to respond dynamically to late arrivals, cancellations, and last-minute changes. This transition would also generate a systematic record of recommended versus actual assignments, enabling continuous improvement of the allocation rules over time.

Stochastic Modelling and Robustness Analysis. The current model relies on historical average values for handling times, truck arrivals, and dwell durations, producing deterministic point estimates for each KPI. Replacing these with stochastic distributions would allow the model to capture day-to-day variability and assess the robustness of each configuration under demand peaks, equipment failures, or partner delays. This extension is particularly relevant for Scenario 2, where the rigid zone structure may amplify the impact of shifts in cargo composition across destination countries.

Multi-Hub Network Extension. The study focused exclusively on the Maia facility. The methodology developed here, including the data engineering pipeline, distance matrix framework, simulation model, and proximity-based assignment logic, is transferable to other GTS facilities, such as the Abóboda and Vitória hubs, as well as any future facilities the company may operate. Applying the same approach across the network would enable a broader assessment of internal flow inefficiencies and support coordinated, network-level optimization of storage allocation and dock assignment.

Digital Twin Architecture. The simulation model constitutes a functional foundation for a digital twin. Connecting it to real-time data streams from IoT sensors or Real-Time Locating System (RTLS) infrastructure would allow the model to reflect the live state of the warehouse at all times, enabling proactive rather than reactive planning. Combined with the WMS integration above, this would support continuous re-optimization of dock assignments as the day unfolds, rather than a single daily plan generated the previous evening.

Sustainability Metrics. The performance framework developed here focuses on travel distance and operator productivity. Extending it to include energy consumption per forklift movement and the associated carbon footprint of internal operations would allow the same optimization model to support sustainability objectives alongside cost and throughput targets, aligning warehouse planning with the broader environmental reporting requirements increasingly relevant to freight forwarding operators.

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Appendix A

Cross-Functional Process Flow Diagrams and RACI Matrices

This appendix presents the cross-functional process flow diagrams developed to characterize the four main operational flows of GTS: import, delivery, pick-up and export (Figures A.1 to A.4). These diagrams illustrate the sequence of activities and the stakeholders involved in each flow, from the initial customer request to the final handling of cargo. In addition, two Responsibility Assignment Matrices (RACI) are presented for the import and export flows (Figures A.5 and A.6), detailing how responsibilities for each activity are distributed across the different organizational units involved in the process.

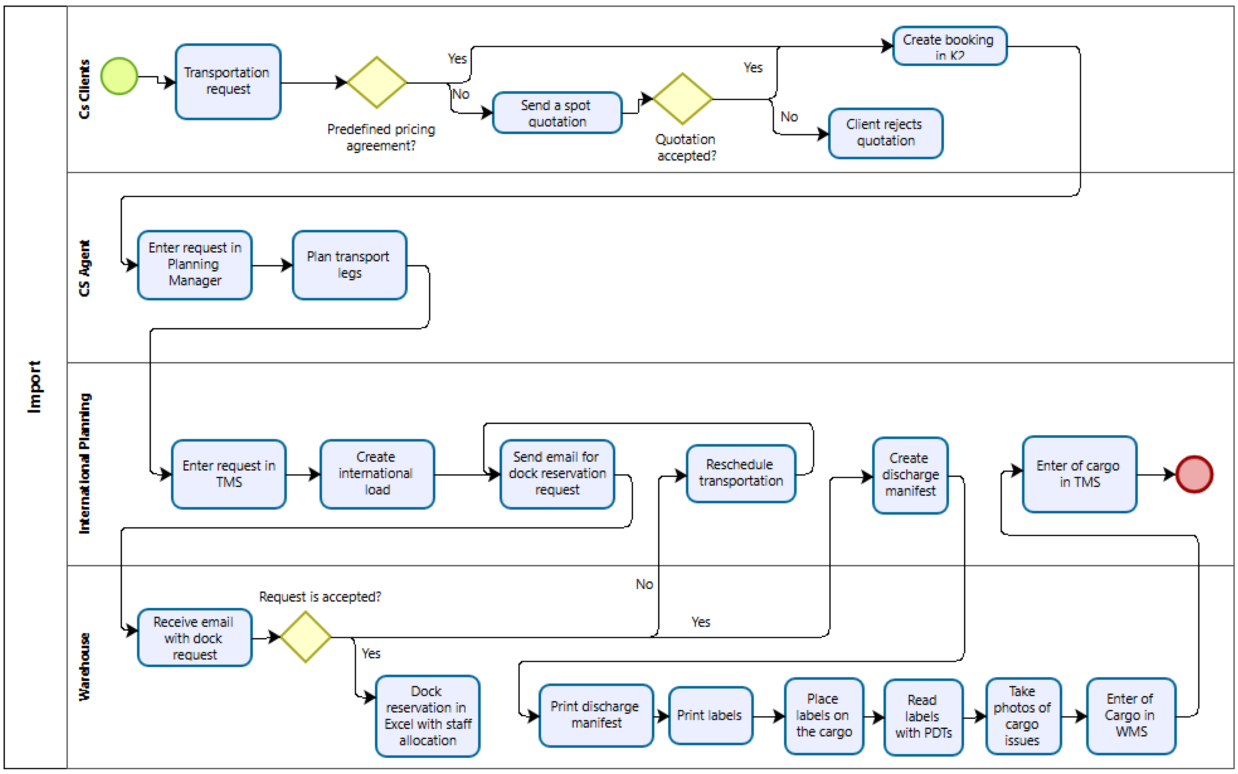


Figure A.1: Cross-functional process flow diagram of the import operation at GTS

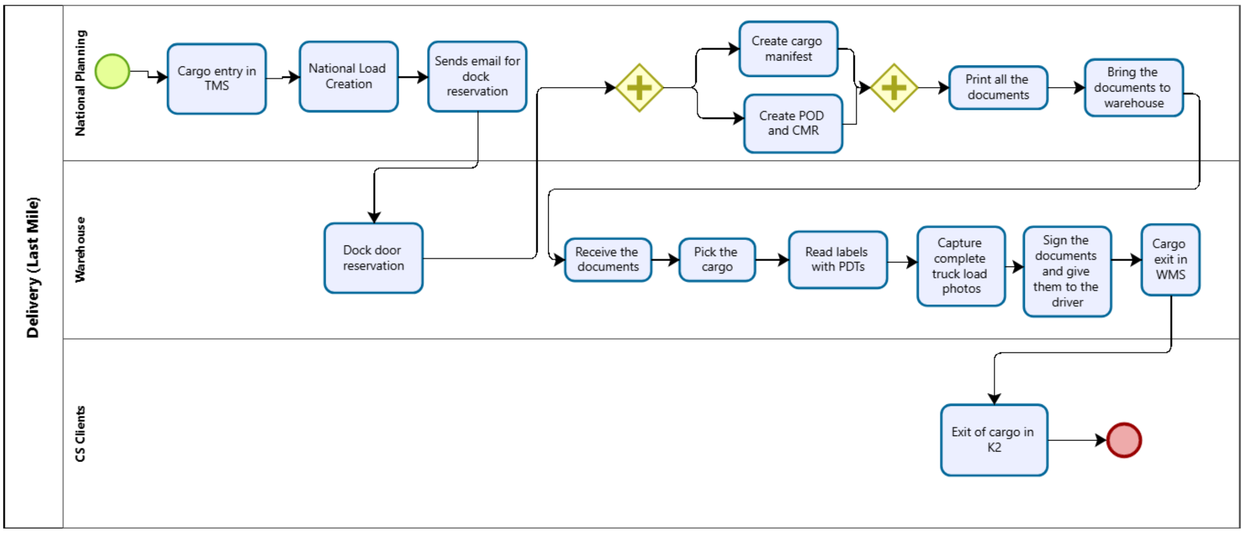


Figure A.2: Cross-functional process flow diagram of the delivery operation at GTS

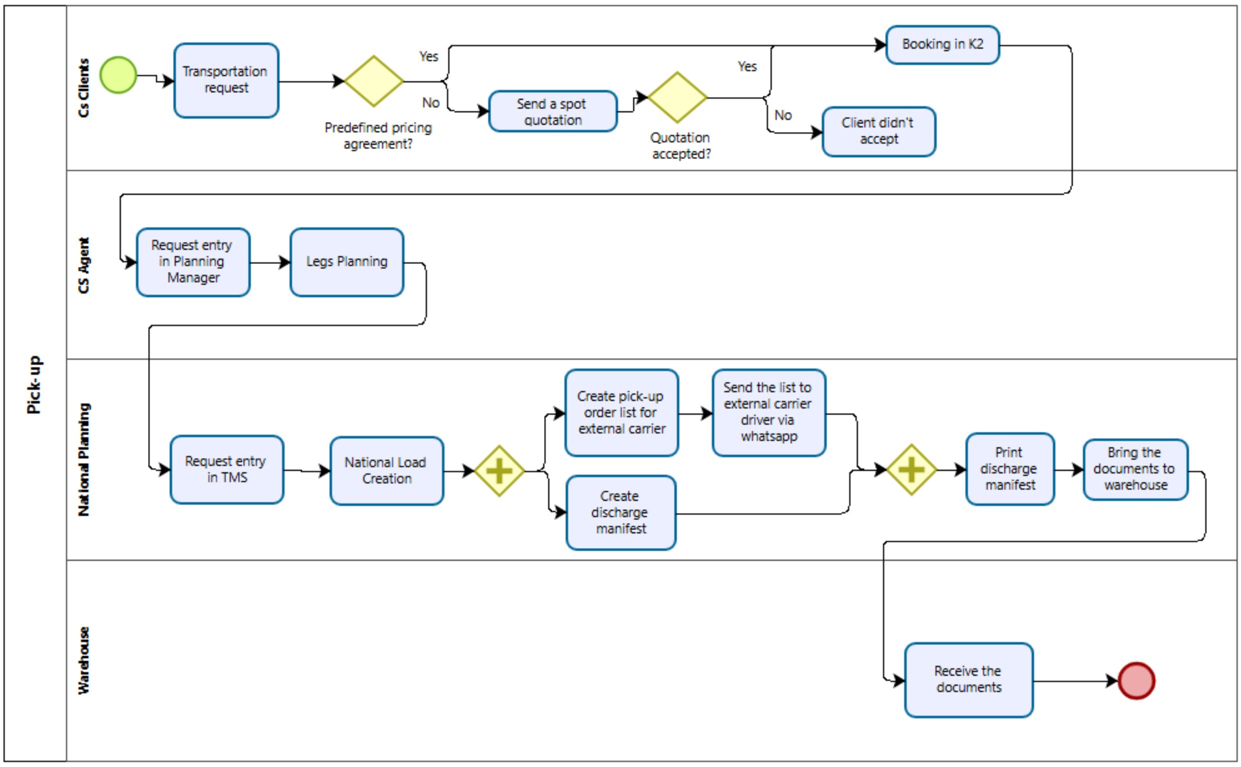


Figure A.3: Cross-functional process flow diagram of the pick-up operation at GTS

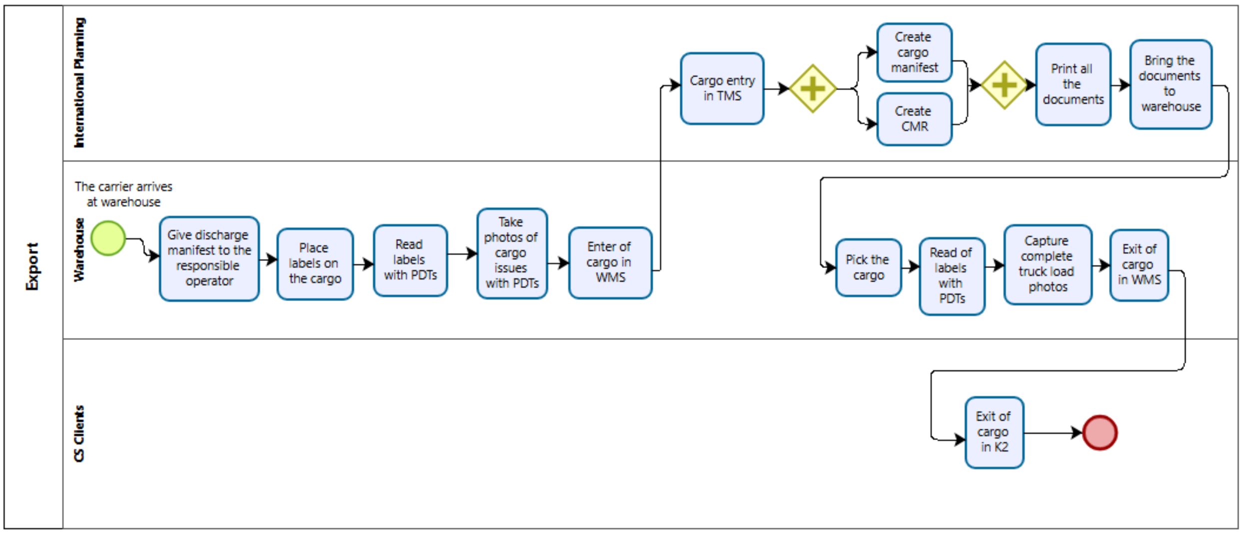


Figure A.4: Cross-functional process flow diagram of the export operation at GTS

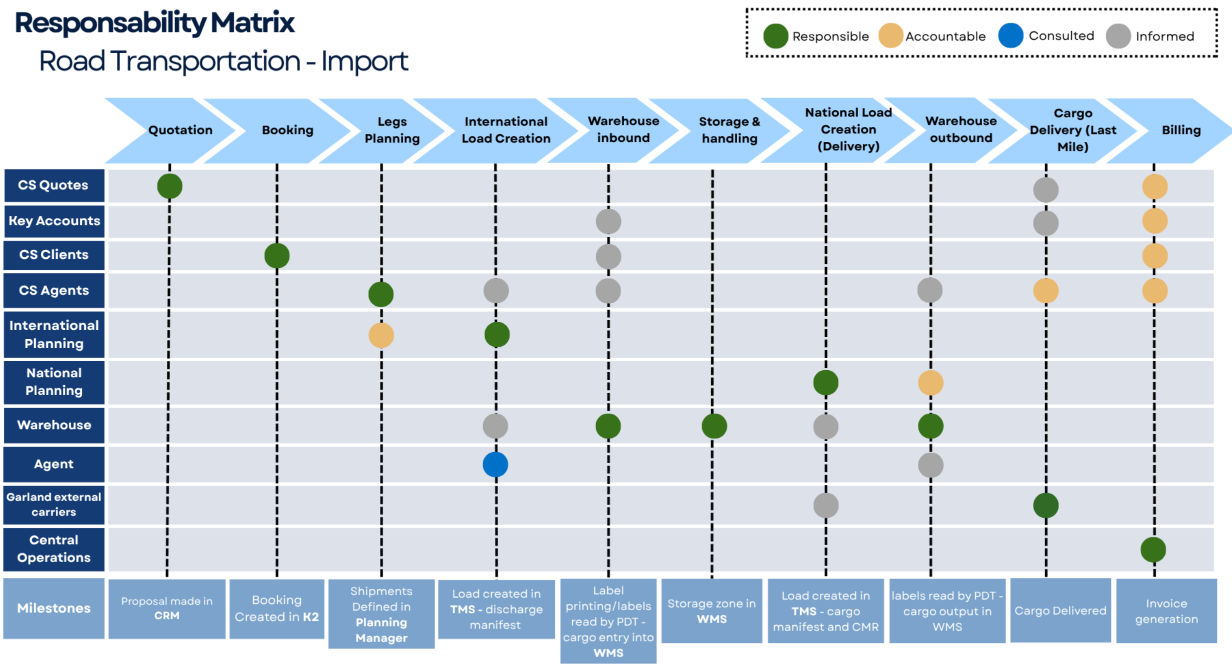


Figure A.5: Responsibility Assignment Matrix (RACI) for the import operation

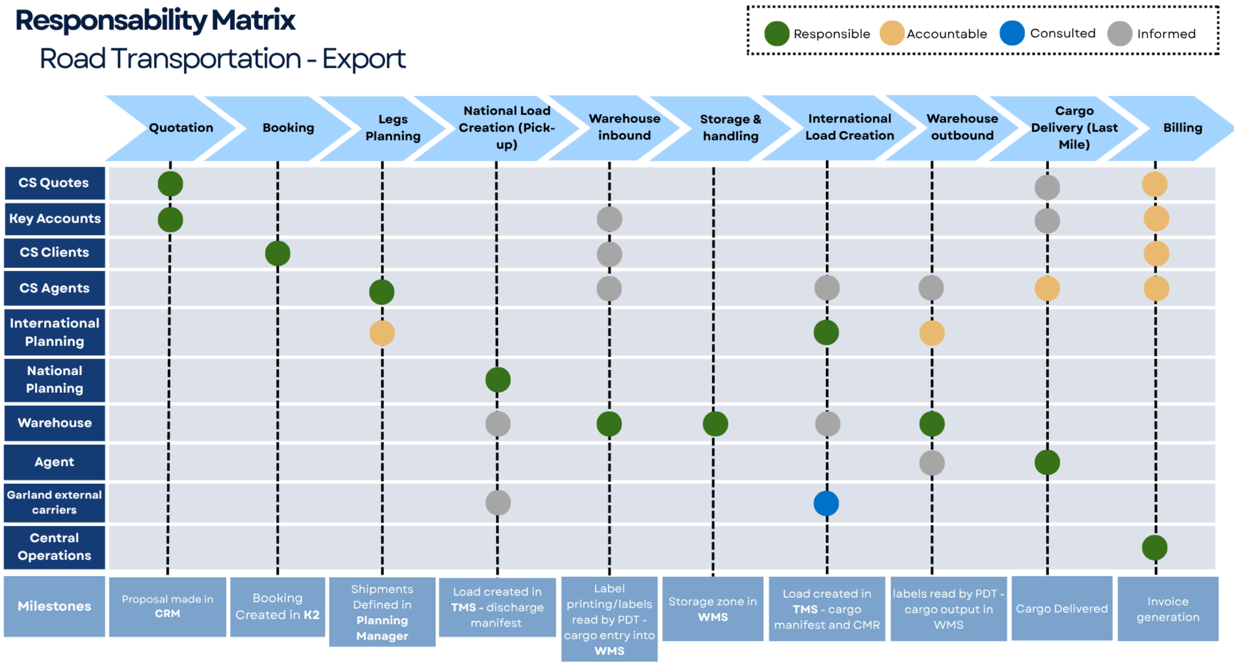


Figure A.6: Responsibility Assignment Matrix (RACI) for the export operation

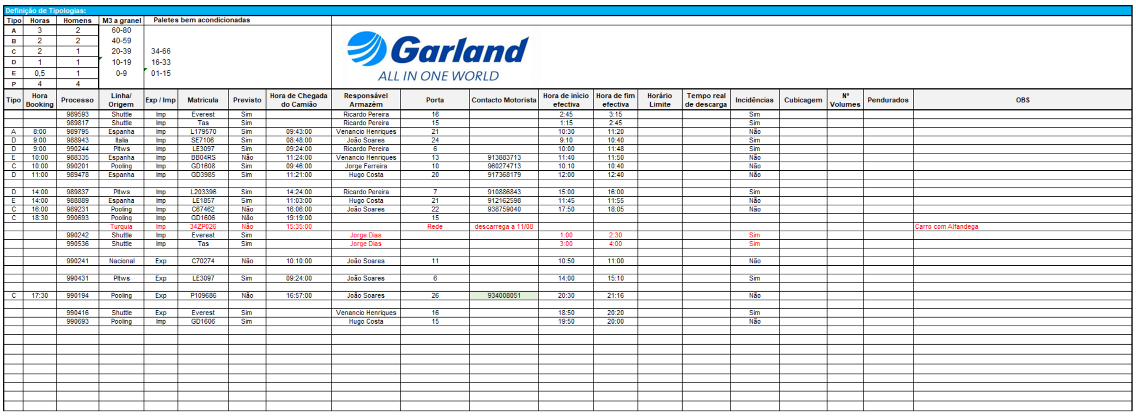
Appendix B

Operational Documentation

This appendix presents the operational documents and planning tools referenced in the description of warehouse activities (Section 3.3), including the daily *Excel* used for operational planning, transport guides, discharge and cargo manifests, and proof of delivery documents used to support inbound, outbound, pick-up and last-mile delivery operations (Figures B.3 to B.7). It also includes illustrative images of material handling equipment, namely forklifts and pallet trucks, used in daily warehouse operations (Figures B.1 and B.2).

Figure B.1: Forklift

Figure B.2: Pallet Truck

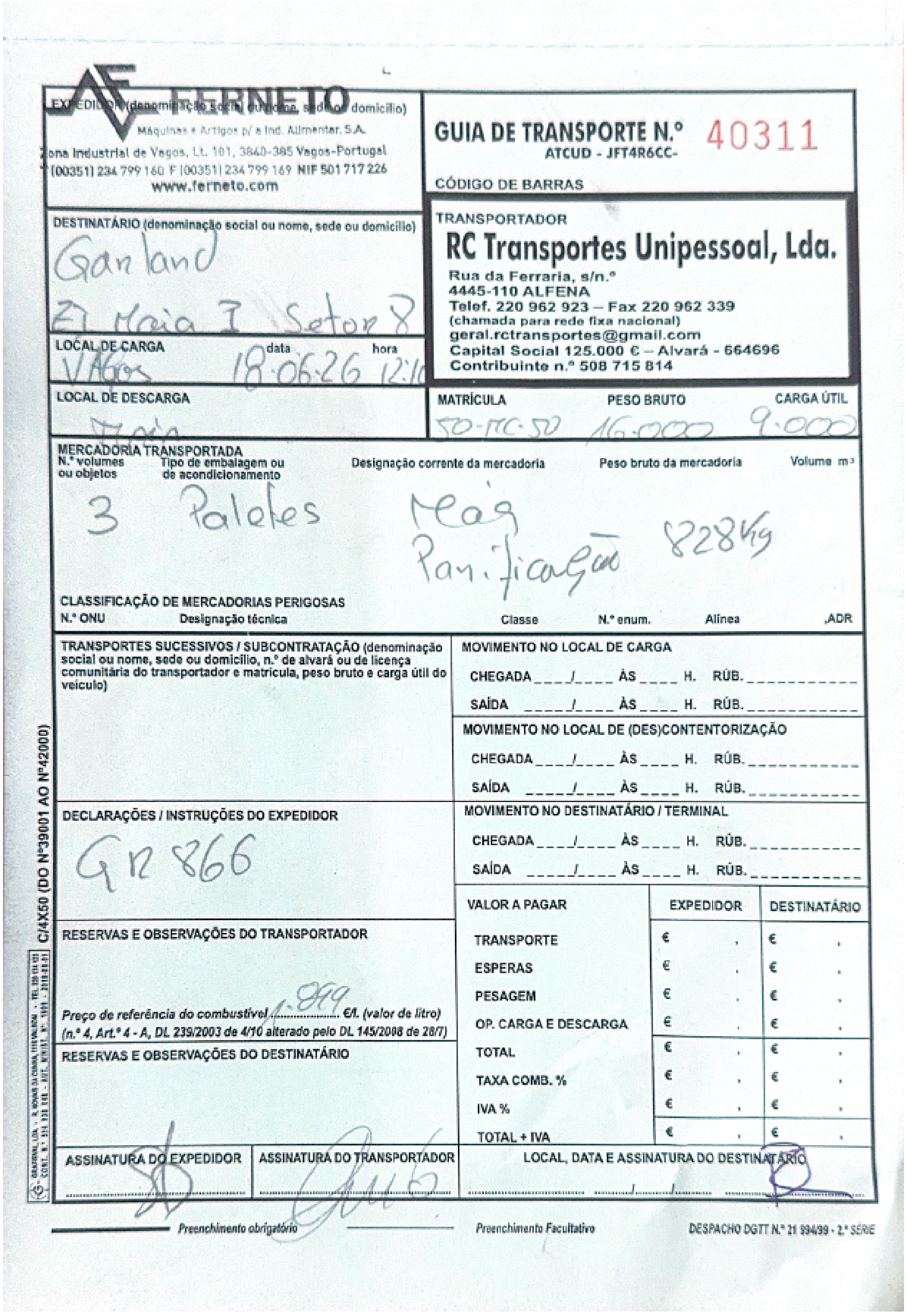


Definição de Tipologias:

Tipo	Horas	Homens	M3 a granel	Paletes bem acondicionadas
A	3	2	60-80	
B	2	2	40-59	
C	2	1	20-39	34-66
D	1	1	10-19	16-33
E	0,5	1	0-9	01-15
P	4	4		

Tipo	Hora Booking	Processo	Linha/ Origem	Exp / Imp	Matricula	Previsto	Hora de Chegada do Camião	Responsável Armazém	Porta	Contacto Motorista	Hora de início efectiva	Hora de fim efectiva	Horário Limite	Tempo real de descarga	Incidências	Cubicagem	Nº Volumes	Pendurados	OBS
		989593	Shuttle	Imp	Everest	Sim		Ricardo Pereira	16		2:45	3:15			Sim				
		989817	Shuttle	Imp	Tas	Sim		Ricardo Pereira	15		1:15	2:45			Sim				
A	8:00	989795	Espanha	Imp	L179570	Sim	09:43:00	Venancio Henriques	21		10:30	11:20			Não				
D	9:00	988943	Italia	Imp	SE7106	Sim	08:48:00	João Soares	24		9:10	10:40			Sim				
D	9:00	990244	Pltws	Imp	LE3097	Sim	09:24:00	Ricardo Pereira	6		10:00	11:48			Sim				
E	10:00	988335	Espanha	Imp	BB04RS	Não	11:24:00	Venancio Henriques	13	913883713	11:40	11:50			Não				
C	10:00	990201	Pooling	Imp	GD1608	Sim	09:46:00	Jorge Ferreira	10	960274713	10:10	10:40			Não				
D	11:00	989478	Espanha	Imp	GD3985	Sim	11:21:00	Hugo Costa	20	917368179	12:00	12:40			Não				
D	14:00	989837	Pltws	Imp	L203396	Sim	14:24:00	Ricardo Pereira	7	910886843	15:00	16:00			Sim				
E	14:00	988889	Espanha	Imp	LE1857	Sim	11:03:00	Hugo Costa	21	912162598	11:45	11:55			Não				
C	16:00	989231	Pooling	Imp	C67462	Não	16:06:00	João Soares	22	938759040	17:50	18:05			Não				
C	18:30	990693	Pooling	Imp	GD1606	Não	19:19:00		15										
			Turquia	Imp	34ZP026	Não	15:35:00		Rede	descarrega a 11/08									Carro com Alfandega
		990242	Shuttle	Imp	Everest	Sim		Jorge Dias			1:00	2:30			Sim				
		990536	Shuttle	Imp	Tas	Sim		Jorge Dias			3:00	4:00			Sim				
		990241	Nacional	Exp	C70274	Não	10:10:00	João Soares	11		10:50	11:00			Não				
		990431	Pltws	Exp	LE3097	Sim	09:24:00	João Soares	6		14:00	15:10			Sim				
C	17:30	990194	Pooling	Exp	P109686	Não	16:57:00	João Soares	26	934008051	20:30	21:16			Não				
		990416	Shuttle	Exp	Everest	Sim		Venancio Henriques	16		18:50	20:20			Sim				
		990693	Pooling	Imp	GD1606	Sim		Hugo Costa	15		19:50	20:00			Não				

Figure B.3: Daily Excel-based operational planning file used for truck scheduling and dock allocation



FERNETO
EXPEDIDOR (denominação social ou nome, sede ou domicílio)
Máquinas e Artigos p/ a Ind. Alimentar, S.A.
Zona Industrial de Vagos, Lt. 101, 3840-385 Vagos-Portugal
T (00351) 234 799 160 F (00351) 234 799 169 NIF 501 717 226
www.ferneto.com

GUIA DE TRANSPORTE N.º 40311
ATCUD - JFT4R6CC-
CÓDIGO DE BARRAS

DESTINATÁRIO (denominação social ou nome, sede ou domicílio)
Ganland
ZI Maia I Setor 8

TRANSPORTADOR
RC Transportes Unipessoal, Lda.
Rua da Ferraria, s/n.º
4445-110 ALFENA
Telef. 220 962 923 – Fax 220 962 339
(chamada para rede fixa nacional)
geral.rctransportes@gmail.com
Capital Social 125.000 € – Alvará - 664696
Contribuinte n.º 508 715 814

LOCAL DE CARGA Vagos data 18.06.26 hora 12:1[illegible]

LOCAL DE DESCARGA Maia

MATRÍCULA 50-RC-50 PESO BRUTO 16.000 CARGA ÚTIL 9.000

MERCADORIA TRANSPORTADA

N.º volumes ou objetos	Tipo de embalagem ou de acondicionamento	Designação corrente da mercadoria	Peso bruto da mercadoria	Volume m³
3	Paletes	Maq Panificação	828Kg	

CLASSIFICAÇÃO DE MERCADORIAS PERIGOSAS
N.º ONU Designação técnica Classe N.º enum. Alínea ,ADR

TRANSPORTES SUCESSIVOS / SUBCONTRATAÇÃO (denominação social ou nome, sede ou domicílio, n.º de alvará ou de licença comunitária do transportador e matrícula, peso bruto e carga útil do veículo)

MOVIMENTO NO LOCAL DE CARGA
CHEGADA ___/___ ÀS ___ H. RÚB. ______
SAÍDA ___/___ ÀS ___ H. RÚB. ______

MOVIMENTO NO LOCAL DE (DES)CONTENTORIZAÇÃO
CHEGADA ___/___ ÀS ___ H. RÚB. ______
SAÍDA ___/___ ÀS ___ H. RÚB. ______

DECLARAÇÕES / INSTRUÇÕES DO EXPEDIDOR
GR 866

MOVIMENTO NO DESTINATÁRIO / TERMINAL
CHEGADA ___/___ ÀS ___ H. RÚB. ______
SAÍDA ___/___ ÀS ___ H. RÚB. ______

RESERVAS E OBSERVAÇÕES DO TRANSPORTADOR
Preço de referência do combustível 1.899 *€/l. (valor de litro)*
(n.º 4, Art.º 4 - A, DL 239/2003 de 4/10 alterado pelo DL 145/2008 de 28/7)

RESERVAS E OBSERVAÇÕES DO DESTINATÁRIO

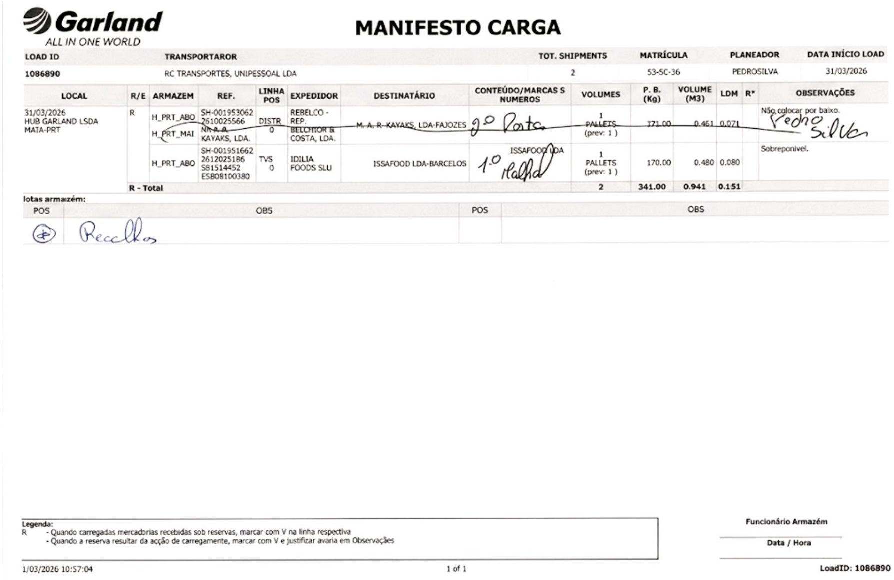
VALOR A PAGAR	EXPEDIDOR	DESTINATÁRIO
TRANSPORTE	€ ,	€ ,
ESPERAS	€ ,	€ ,
PESAGEM	€ ,	€ ,
OP. CARGA E DESCARGA	€ ,	€ ,
TOTAL	€ ,	€ ,
TAXA COMB. %	€ ,	€ ,
IVA %	€ ,	€ ,
TOTAL + IVA	€ ,	€ ,

ASSINATURA DO EXPEDIDOR | ASSINATURA DO TRANSPORTADOR | LOCAL, DATA E ASSINATURA DO DESTINATÁRIO

C/4X50 (DO Nº39001 AO Nº42000)

Preenchimento obrigatório — Preenchimento Facultativo — DESPACHO DGTT N.º 21 994/99 - 2.ª SÉRIE

Figure B.4: Transport guide in pick-ups



Garland ALL IN ONE WORLD

MANIFESTO CARGA

LOAD ID	TRANSPORTAROR	TOT. SHIPMENTS	MATRÍCULA	PLANEADOR	DATA INÍCIO LOAD
1086890	RC TRANSPORTES, UNIPESSOAL LDA	2	53-SC-36	PEDROSILVA	31/03/2026

LOCAL	R/E	ARMAZEM	REF.	LINHA POS	EXPEDIDOR	DESTINATÁRIO	CONTEÚDO/MARCAS S NUMEROS	VOLUMES	P. B. (Kg)	VOLUME (M3)	LDM	R*	OBSERVAÇÕES
31/03/2026 HUB GARLAND LSDA MATA-PRT	R	H_PRT_ABO H_PRT_MAI	SH-001953062 2610025566 NR A.A. KAYAKS, LDA.	DISTR 0	REBELCO - REP. BELCHIOR & COSTA, LDA.	M. A. R. KAYAKS, LDA-FAJOZES	2º Porto	1 PALLETS (prev: 1)	171.00	0.461	0.071		Não colocar por baixo. Pedro Silva
		H_PRT_ABO	SH-001951662 2612025186 S81514452 ESB08100380	TVS 0	IDILIA FOODS SLU	ISSAFOOD LDA-BARCELOS	ISSAFOOD LDA 1.º [illegible]	1 PALLETS (prev: 1)	170.00	0.480	0.080		Sobreponível.
	R - Total							2	341.00	0.941	0.151		

lotas armazém:

POS	OBS	POS	OBS
⊕	Recolha		

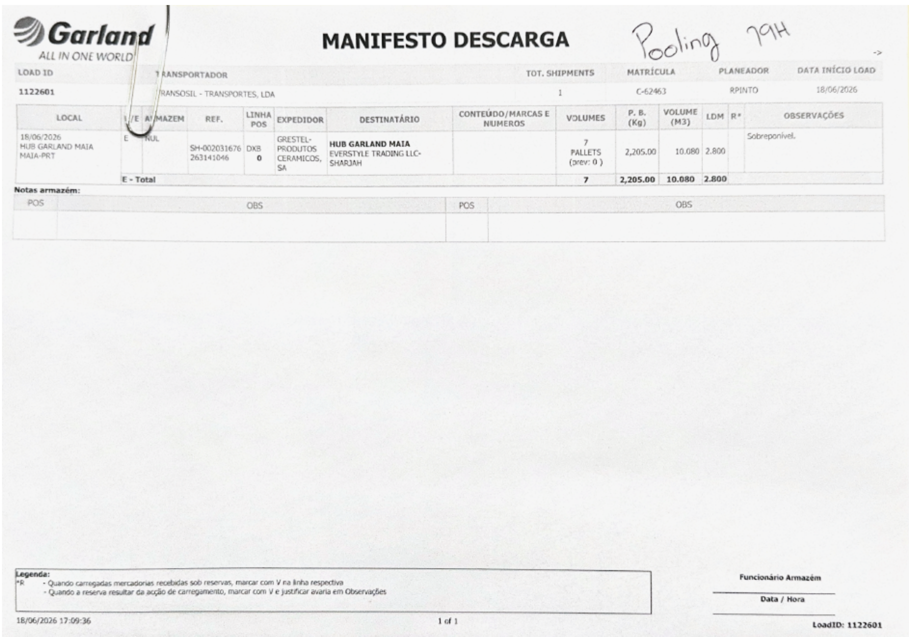
Legenda:
R - Quando carregadas mercadorias recebidas sob reservas, marcar com V na linha respectiva
- Quando a reserva resultar da acção de carregamente, marcar com V e justificar avaria em Observações

Funcionário Armazém

Data / Hora

1/03/2026 10:57:04 1 of 1 LoadID: 1086890

Figure B.5: Cargo manifest



Garland ALL IN ONE WORLD

MANIFESTO DESCARGA Pooling 79H

->

LOAD ID	TRANSPORTADOR	TOT. SHIPMENTS	MATRÍCULA	PLANEADOR	DATA INÍCIO LOAD
1122601	TRANSOSIL - TRANSPORTES, LDA	1	C-62463	RPINTO	18/06/2026

LOCAL	R/E	ARMAZEM	REF.	LINHA POS	EXPEDIDOR	DESTINATÁRIO	CONTEÚDO/MARCAS E NUMEROS	VOLUMES	P. B. (Kg)	VOLUME (M3)	LDM	R*	OBSERVAÇÕES
18/06/2026 HUB GARLAND MAIA MAIA-PRT	E	NUL	SH-002031676 263141046	DXB 0	GRESTEL-PRODUTOS CERAMICOS, SA	**HUB GARLAND MAIA** EVERSTYLE TRADING LLC-SHARJAH		7 PALLETS (prev: 0)	2,205.00	10.080	2.800		Sobreponível.
	E - Total							7	2,205.00	10.080	2.800		

Notas armazém:

POS	OBS	POS	OBS

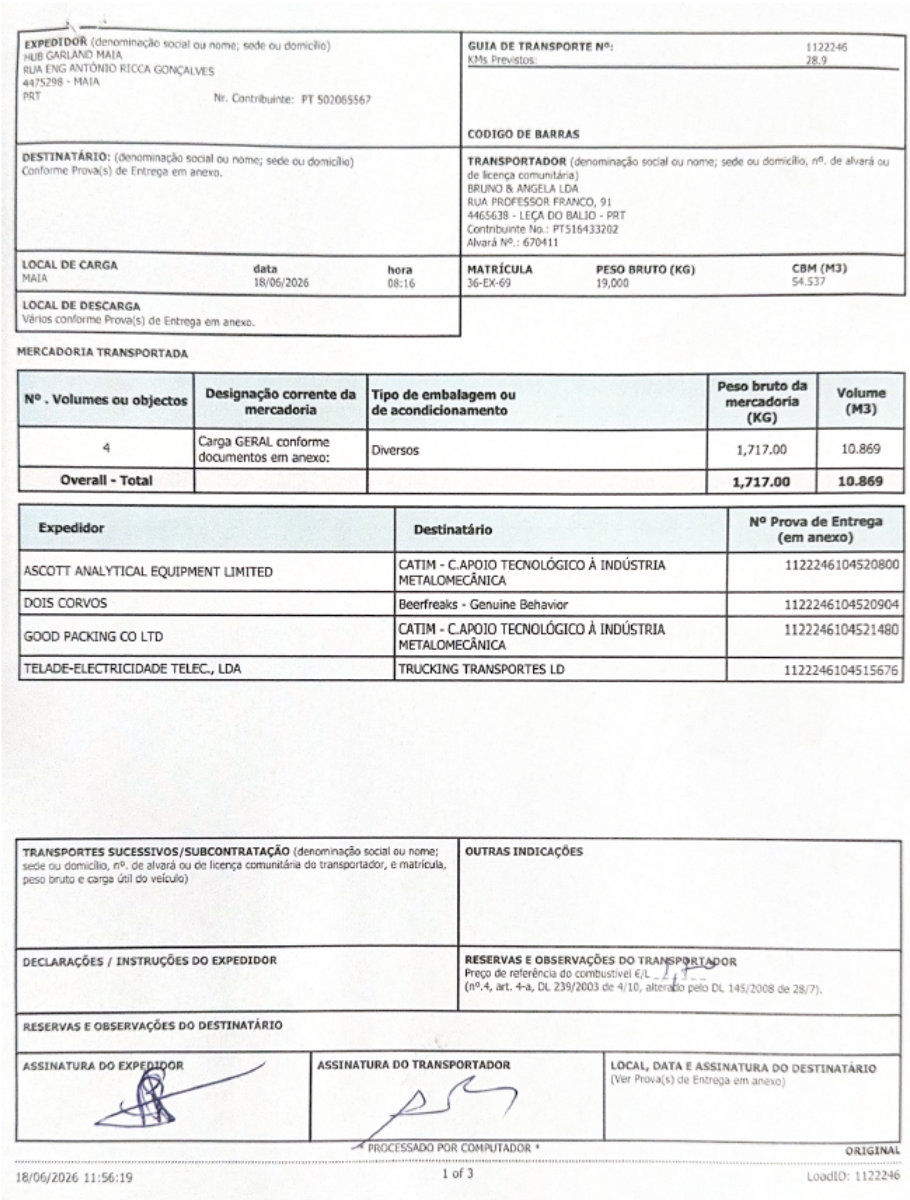
Legenda:
*R - Quando carregadas mercadorias recebidas sob reservas, marcar com V na linha respectiva
- Quando a reserva resultar da acção de carregamento, marcar com V e justificar avaria em Observações

Funcionário Armazém

Data / Hora

18/06/2026 17:09:36 1 of 1 LoadID: 1122601

Figure B.6: Discharge manifest



EXPEDIDOR (denominação social ou nome; sede ou domicílio)
HUB GARLAND MAIA
RUA ENG ANTÓNIO RICCA GONÇALVES
4475298 - MAIA
PRT
Nr. Contribuinte: PT 502065567

GUIA DE TRANSPORTE Nº: 1122246
KMs Previstos: 28.9

CODIGO DE BARRAS

DESTINATÁRIO: (denominação social ou nome; sede ou domicílio)
Conforme Prova(s) de Entrega em anexo.

TRANSPORTADOR (denominação social ou nome; sede ou domicílio, nº. de alvará ou de licença comunitária)
BRUNO & ANGELA LDA
RUA PROFESSOR FRANCO, 91
4465638 - LEÇA DO BALIO - PRT
Contribuinte No.: PT516433202
Alvará Nº.: 670411

LOCAL DE CARGA MAIA — **data** 18/06/2026 — **hora** 08:16

MATRÍCULA 36-EX-69 — **PESO BRUTO (KG)** 19,000 — **CBM (M3)** 54.537

LOCAL DE DESCARGA
Vários conforme Prova(s) de Entrega em anexo.

MERCADORIA TRANSPORTADA

Nº . Volumes ou objectos	Designação corrente da mercadoria	Tipo de embalagem ou de acondicionamento	Peso bruto da mercadoria (KG)	Volume (M3)
4	Carga GERAL conforme documentos em anexo:	Diversos	1,717.00	10.869
Overall - Total			**1,717.00**	**10.869**

Expedidor	Destinatário	Nº Prova de Entrega (em anexo)
ASCOTT ANALYTICAL EQUIPMENT LIMITED	CATIM - C.APOIO TECNOLÓGICO À INDÚSTRIA METALOMECÂNICA	1122246104520800
DOIS CORVOS	Beerfreaks - Genuine Behavior	1122246104520904
GOOD PACKING CO LTD	CATIM - C.APOIO TECNOLÓGICO À INDÚSTRIA METALOMECÂNICA	1122246104521480
TELADE-ELECTRICIDADE TELEC., LDA	TRUCKING TRANSPORTES LD	1122246104515676

TRANSPORTES SUCESSIVOS/SUBCONTRATAÇÃO (denominação social ou nome; sede ou domicílio, nº. de alvará ou de licença comunitária do transportador, e matrícula, peso bruto e carga útil do veículo)

OUTRAS INDICAÇÕES

DECLARAÇÕES / INSTRUÇÕES DO EXPEDIDOR

RESERVAS E OBSERVAÇÕES DO TRANSPORTADOR
Preço de referência do combustível €/L 1,7
(nº.4, art. 4-a, DL 239/2003 de 4/10, alterado pelo DL 145/2008 de 28/7).

RESERVAS E OBSERVAÇÕES DO DESTINATÁRIO

ASSINATURA DO EXPEDIDOR

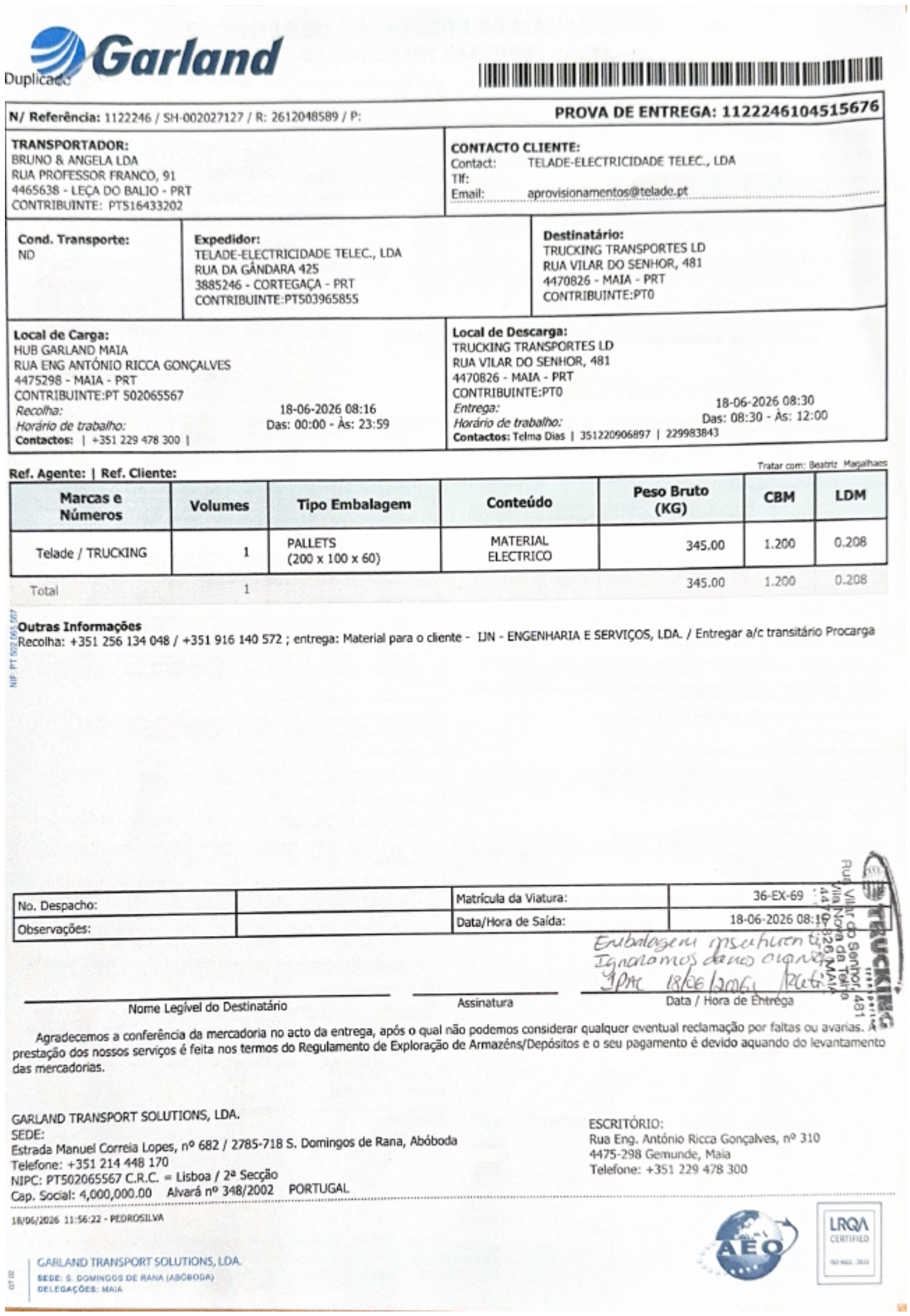
ASSINATURA DO TRANSPORTADOR

LOCAL, DATA E ASSINATURA DO DESTINATÁRIO
(Ver Prova(s) de Entrega em anexo)

* PROCESSADO POR COMPUTADOR *
ORIGINAL

18/06/2026 11:56:19 — 1 of 3 — LoadID: 1122246

Figure B.7: Transport guide for deliveries



Duplicado

N/ Referência: 1122246 / SH-002027127 / R: 2612048589 / P:

PROVA DE ENTREGA: 1122246104515676

TRANSPORTADOR:
BRUNO & ANGELA LDA
RUA PROFESSOR FRANCO, 91
4465638 - LEÇA DO BALIO - PRT
CONTRIBUINTE: PT516433202

CONTACTO CLIENTE:
Contact: TELADE-ELECTRICIDADE TELEC., LDA
Tlf:
Email: aprovisionamentos@telade.pt

Cond. Transporte:
ND

Expedidor:
TELADE-ELECTRICIDADE TELEC., LDA
RUA DA GÂNDARA 425
3885246 - CORTEGAÇA - PRT
CONTRIBUINTE:PT503965855

Destinatário:
TRUCKING TRANSPORTES LD
RUA VILAR DO SENHOR, 481
4470826 - MAIA - PRT
CONTRIBUINTE:PT0

Local de Carga:
HUB GARLAND MAIA
RUA ENG ANTÓNIO RICCA GONÇALVES
4475298 - MAIA - PRT
CONTRIBUINTE:PT 502065567
Recolha: 18-06-2026 08:16
Horário de trabalho: Das: 00:00 - Às: 23:59
Contactos: | +351 229 478 300 |

Local de Descarga:
TRUCKING TRANSPORTES LD
RUA VILAR DO SENHOR, 481
4470826 - MAIA - PRT
CONTRIBUINTE:PT0
Entrega: 18-06-2026 08:30
Horário de trabalho: Das: 08:30 - Às: 12:00
Contactos: Telma Dias | 351220906897 | 229983843

Ref. Agente: | Ref. Cliente:

Tratar com: Beatriz Magalhaes

Marcas e Números	Volumes	Tipo Embalagem	Conteúdo	Peso Bruto (KG)	CBM	LDM
Telade / TRUCKING	1	PALLETS (200 x 100 x 60)	MATERIAL ELECTRICO	345.00	1.200	0.208
Total	1			345.00	1.200	0.208

NIF: PT 502 065 567

Outras Informações
Recolha: +351 256 134 048 / +351 916 140 572 ; entrega: Material para o cliente - IJN - ENGENHARIA E SERVIÇOS, LDA. / Entregar a/c transitário Procarga

No. Despacho:		Matrícula da Viatura:	36-EX-69
Observações:		Data/Hora de Saída:	18-06-2026 08:10

Embalagem insuficiente
Ignoramos danos

Nome Legível do Destinatário — Assinatura — Data / Hora de Entrega

TRUCKING
Rua Vilar do Senhor, 481
Vila Nova da Telha
4470-826 MAIA

Agradecemos a conferência da mercadoria no acto da entrega, após o qual não podemos considerar qualquer eventual reclamação por faltas ou avarias. A prestação dos nossos serviços é feita nos termos do Regulamento de Exploração de Armazéns/Depósitos e o seu pagamento é devido aquando do levantamento das mercadorias.

GARLAND TRANSPORT SOLUTIONS, LDA.
SEDE:
Estrada Manuel Correia Lopes, nº 682 / 2785-718 S. Domingos de Rana, Abóboda
Telefone: +351 214 448 170
NIPC: PT502065567 C.R.C. = Lisboa / 2ª Secção
Cap. Social: 4,000,000.00 Alvará nº 348/2002 PORTUGAL

ESCRITÓRIO:
Rua Eng. António Ricca Gonçalves, nº 310
4475-298 Gemunde, Maia
Telefone: +351 229 478 300

18/06/2026 11:56:22 - PEDROSILVA

GARLAND TRANSPORT SOLUTIONS, LDA.
SEDE: S. DOMINGOS DE RANA (ABÓBODA)
DELEGAÇÕES: MAIA

AEO

LRQA CERTIFIED

Figure B.8: Proof of Delivery (POD)

Appendix C

Labelling and Scanning Infrastructure

This appendix presents the identification and scanning infrastructure used to support cargo traceability and warehouse operations, including the portable data terminals (Figure C.1), cargo labels (Figure C.2), label printers (Figure C.3), warehouse worktables (Figure C.4), QR codes used to identify rack positions (Figure C.5), barcode labels used on worktables to register storage locations in the WMS (Figure C.6), and *BKS* labels generated for non-manifested cargo received during inbound operations (Figure C.7), as discussed in Section 3.5.

Figure C.1: Portable Data Terminals

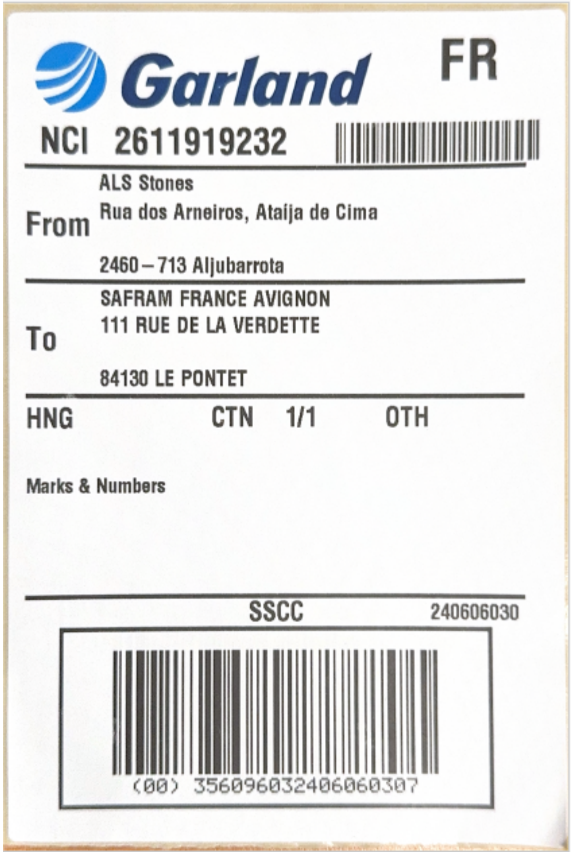


Figure C.2: Cargo identification labels

Figure C.3: Label printers

Figure C.4: Worktables

Figure C.5: QR codes identifying individual rack positions

Figure C.6: Barcode labels used on warehouse worktables to register cargo storage locations in the WMS

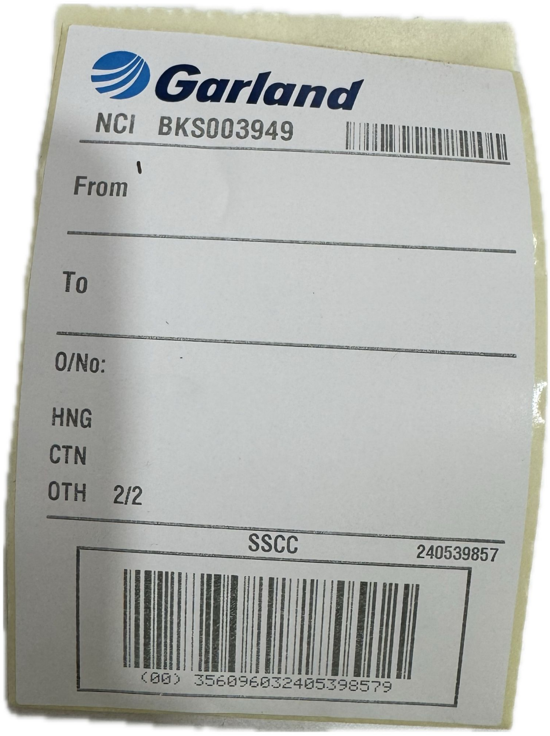
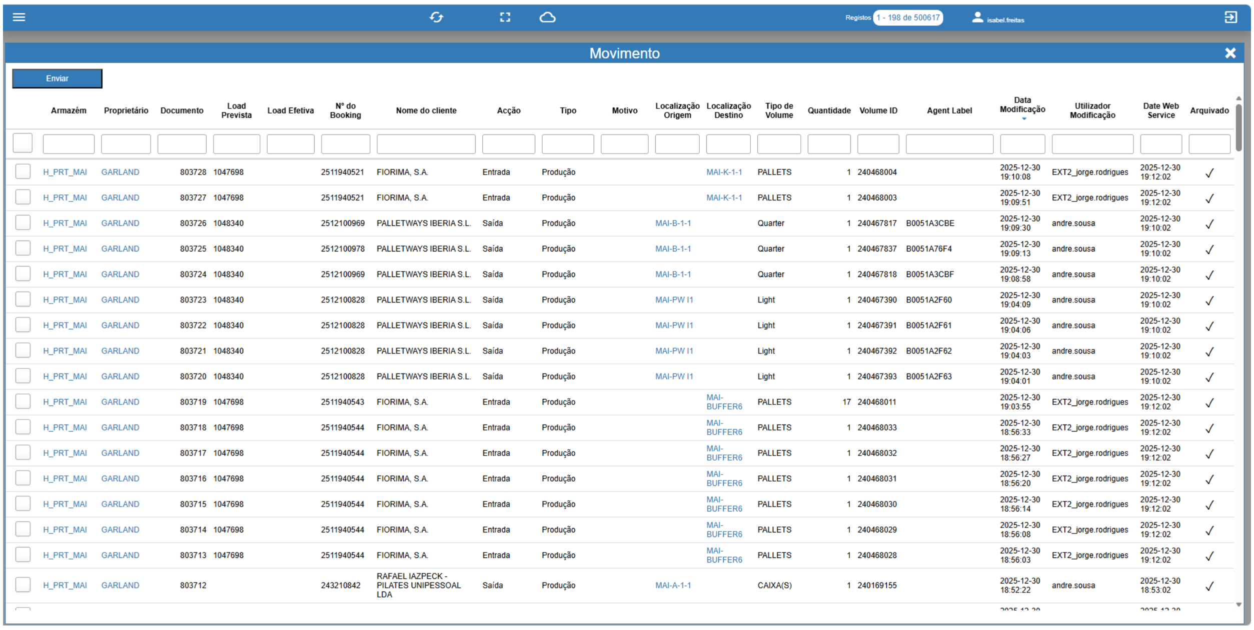


Figure C.7: BKS labels

Appendix D

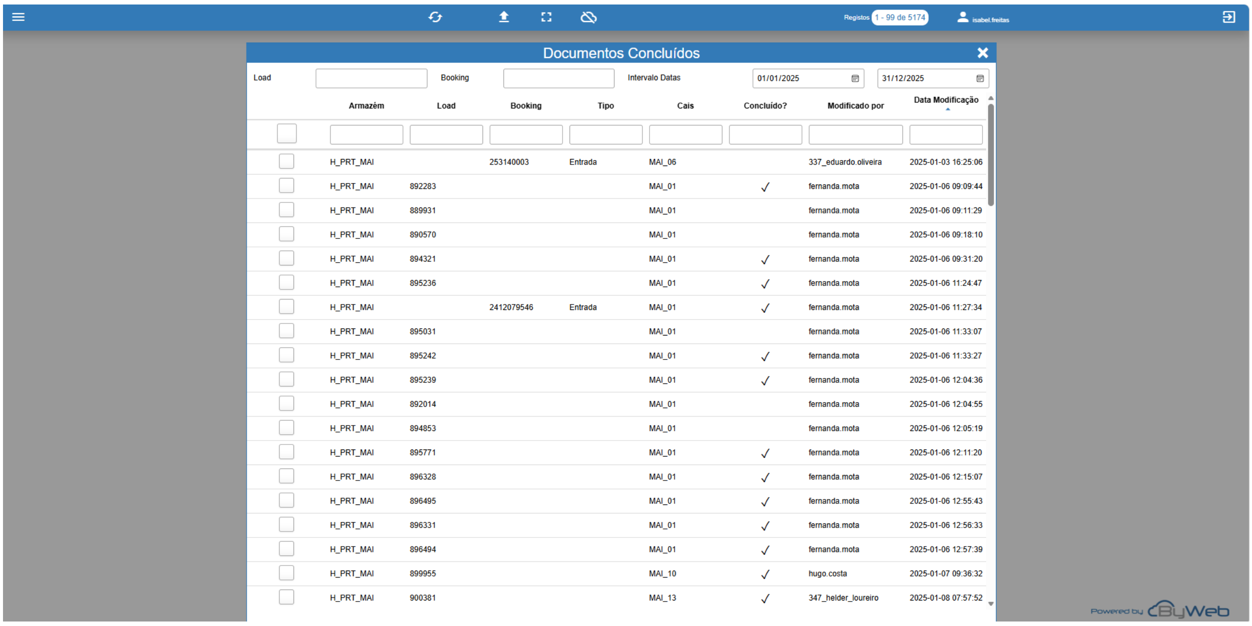
WMS Data Sources

This appendix presents the WMS interfaces corresponding to the datasets used during the data extraction process: *Movements*, *Completed Documents*, *Bookings* and *Loads* (Figures D.1 to D.4), as discussed in Section 4.1.



Armazém	Proprietário	Documento	Load Prevista	Load Efetiva	Nº do Booking	Nome do cliente	Acção	Tipo	Motivo	Localização Origem	Localização Destino	Tipo de Volume	Quantidade	Volume ID	Agent Label	Data Modificação	Utilizador Modificação	Date Web Service	Arquivado
H_PRT_MAI	GARLAND	803728	1047698		2511940521	FIORIMA, S.A.	Entrada	Produção			MAI-K-1-1	PALLETS	1	240468004		2025-12-30 19:10:08	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803727	1047698		2511940521	FIORIMA, S.A.	Entrada	Produção			MAI-K-1-1	PALLETS	1	240468003		2025-12-30 19:09:51	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803726	1048340		2512100969	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-B-1-1		Quarter	1	240467817	B0051A3CBE	2025-12-30 19:09:30	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803725	1048340		2512100978	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-B-1-1		Quarter	1	240467837	B0051A76F4	2025-12-30 19:09:13	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803724	1048340		2512100969	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-B-1-1		Quarter	1	240467818	B0051A3CBF	2025-12-30 19:08:58	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803723	1048340		2512100828	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-PW I1		Light	1	240467390	B0051A2F60	2025-12-30 19:04:09	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803722	1048340		2512100828	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-PW I1		Light	1	240467391	B0051A2F61	2025-12-30 19:04:06	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803721	1048340		2512100828	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-PW I1		Light	1	240467392	B0051A2F62	2025-12-30 19:04:03	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803720	1048340		2512100828	PALLETWAYS IBERIA S.L.	Saída	Produção		MAI-PW I1		Light	1	240467393	B0051A2F63	2025-12-30 19:04:01	andre.sousa	2025-12-30 19:10:02	✓
H_PRT_MAI	GARLAND	803719	1047698		2511940543	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	17	240468011		2025-12-30 19:03:55	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803718	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468033		2025-12-30 18:56:33	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803717	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468032		2025-12-30 18:56:27	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803716	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468031		2025-12-30 18:56:20	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803715	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468030		2025-12-30 18:56:14	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803714	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468029		2025-12-30 18:56:08	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803713	1047698		2511940544	FIORIMA, S.A.	Entrada	Produção			MAI-BUFFER6	PALLETS	1	240468028		2025-12-30 18:56:03	EXT2_jorge.rodrigues	2025-12-30 19:12:02	✓
H_PRT_MAI	GARLAND	803712			243210842	RAFAEL IAZPECK - PILATES UNIPESSOAL LDA	Saída	Produção		MAI-A-1-1		CAIXA(S)	1	240169155		2025-12-30 18:52:22	andre.sousa	2025-12-30 18:53:02	✓

Figure D.1: WMS Movements table.



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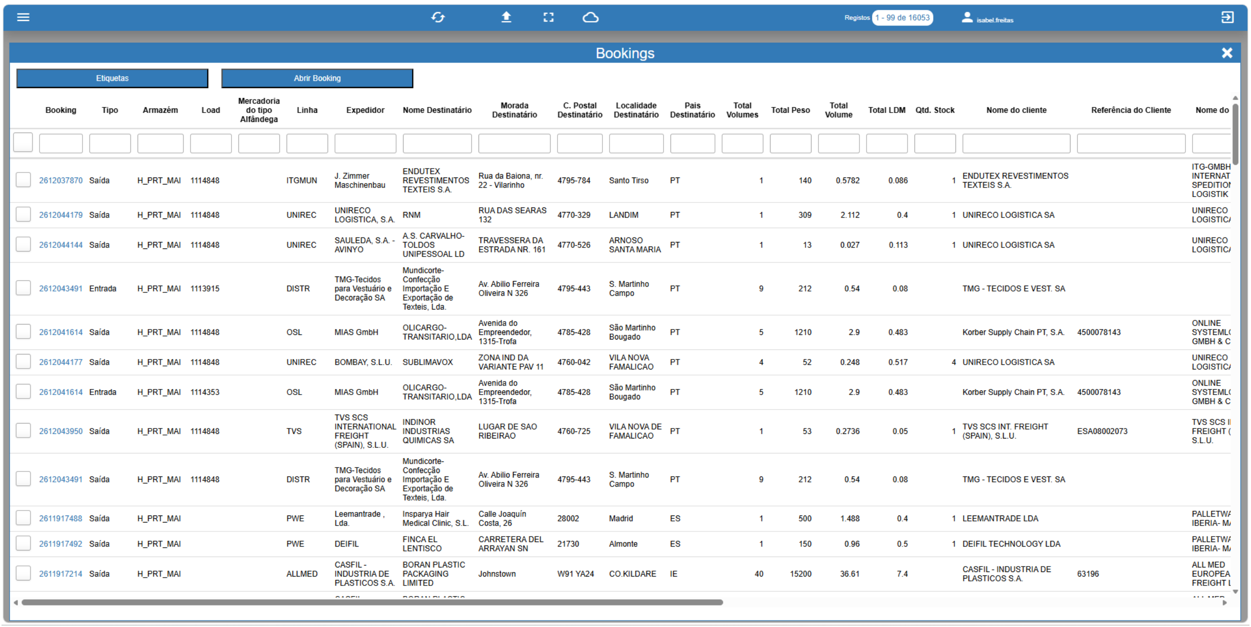
Documentos Concluídos

Load | Booking | Intervalo Datas 01/01/2025 – 31/12/2025

Armazém	Load	Booking	Tipo	Cais	Concluído?	Modificado por	Data Modificação
H_PRT_MAI		253140003	Entrada	MAI_06		337_eduardo.oliveira	2025-01-03 16:25:06
H_PRT_MAI	892283			MAI_01	✓	fernanda.mota	2025-01-06 09:09:44
H_PRT_MAI	889931			MAI_01		fernanda.mota	2025-01-06 09:11:29
H_PRT_MAI	890570			MAI_01		fernanda.mota	2025-01-06 09:18:10
H_PRT_MAI	894321			MAI_01	✓	fernanda.mota	2025-01-06 09:31:20
H_PRT_MAI	895236			MAI_01	✓	fernanda.mota	2025-01-06 11:24:47
H_PRT_MAI		2412079546	Entrada	MAI_01	✓	fernanda.mota	2025-01-06 11:27:34
H_PRT_MAI	895031			MAI_01		fernanda.mota	2025-01-06 11:33:07
H_PRT_MAI	895242			MAI_01	✓	fernanda.mota	2025-01-06 11:33:27
H_PRT_MAI	895239			MAI_01	✓	fernanda.mota	2025-01-06 12:04:36
H_PRT_MAI	892014			MAI_01		fernanda.mota	2025-01-06 12:04:55
H_PRT_MAI	894853			MAI_01		fernanda.mota	2025-01-06 12:05:19
H_PRT_MAI	895771			MAI_01	✓	fernanda.mota	2025-01-06 12:11:20
H_PRT_MAI	896328			MAI_01	✓	fernanda.mota	2025-01-06 12:15:07
H_PRT_MAI	896495			MAI_01	✓	fernanda.mota	2025-01-06 12:55:43
H_PRT_MAI	896331			MAI_01	✓	fernanda.mota	2025-01-06 12:56:33
H_PRT_MAI	896494			MAI_01	✓	fernanda.mota	2025-01-06 12:57:39
H_PRT_MAI	899955			MAI_10	✓	hugo.costa	2025-01-07 09:36:32
H_PRT_MAI	900381			MAI_13	✓	347_helder_loureiro	2025-01-08 07:57:52

Figure D.2: WMS Completed Documents table.



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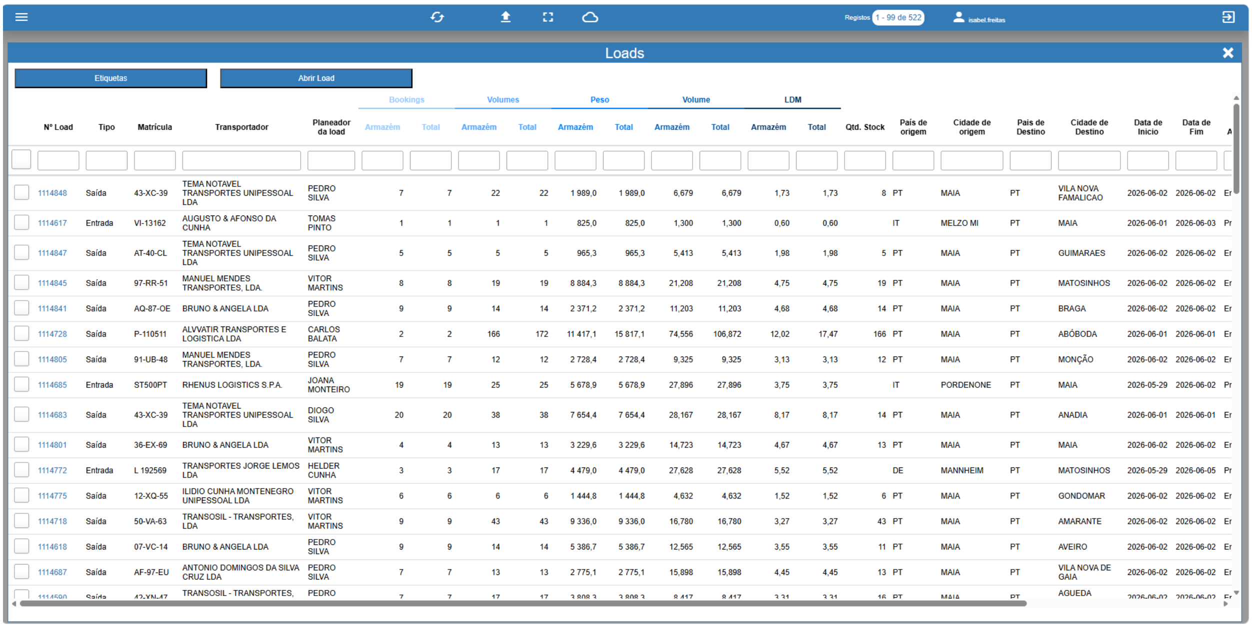
Bookings

Etiquetas | Abrir Booking

Booking	Tipo	Armazém	Load	Mercadoria do tipo Alfândega	Linha	Expedidor	Nome Destinatário	Morada Destinatário	C. Postal Destinatário	Localidade Destinatário	Pais Destinatário	Total Volumes	Total Peso	Total Volume	Total LDM	Qtd. Stock	Nome do cliente	Referência do Cliente	Nome do
2612037870	Saída	H_PRT_MAI	1114848		ITGMUN	J. Zimmer Maschinenbau	ENDUTEX REVESTIMENTOS TEXTEIS S.A.	Rua da Baiona, nr. 22 - Vilarinho	4795-784	Santo Tirso	PT	1	140	0.5782	0.086	1	ENDUTEX REVESTIMENTOS TEXTEIS S.A.		ITG-GMBH INTERNAT SPEDITIOI LOGISTIK
2612044179	Saída	H_PRT_MAI	1114848		UNIREC	UNIRECO LOGISTICA, S.A.	RNM	RUA DAS SEARAS 132	4770-329	LANDIM	PT	1	309	2.112	0.4	1	UNIRECO LOGISTICA SA		UNIRECO LOGISTIC/
2612044144	Saída	H_PRT_MAI	1114848		UNIREC	SAULEDA, S.A. - AVINYO	A.S. CARVALHO-TOLDOS UNIPESSOAL LD	TRAVESSERA DA ESTRADA NR. 161	4770-526	ARNOSO SANTA MARIA	PT	1	13	0.027	0.113	1	UNIRECO LOGISTICA SA		UNIRECO LOGISTIC/
2612043491	Entrada	H_PRT_MAI	1113915		DISTR	TMG-Tecidos para Vestuário e Decoração SA	Mundicorte-Confecção Importação E Exportação de Texteis, Lda.	Av. Abilio Ferreira Oliveira N 326	4795-443	S. Martinho Campo	PT	9	212	0.54	0.08		TMG - TECIDOS E VEST. SA		
2612041614	Saída	H_PRT_MAI	1114848		OSL	MIAS GmbH	OLICARGO-TRANSITARIO,LDA	Avenida do Empreendedor, 1315-Trofa	4785-428	São Martinho Bougado	PT	5	1210	2.9	0.483		Korber Supply Chain PT, S.A.	4500078143	ONLINE SYSTEML(GMBH & C
2612044177	Saída	H_PRT_MAI	1114848		UNIREC	BOMBAY, S.L.U.	SUBLIMAVOX	ZONA IND DA VARIANTE PAV 11	4760-042	VILA NOVA FAMALICAO	PT	4	52	0.248	0.517	4	UNIRECO LOGISTICA SA		UNIRECO LOGISTIC/
2612041614	Entrada	H_PRT_MAI	1114353		OSL	MIAS GmbH	OLICARGO-TRANSITARIO,LDA	Avenida do Empreendedor, 1315-Trofa	4785-428	São Martinho Bougado	PT	5	1210	2.9	0.483		Korber Supply Chain PT, S.A.	4500078143	ONLINE SYSTEML(GMBH & C
2612043950	Saída	H_PRT_MAI	1114848		TVS	TVS SCS INTERNATIONAL FREIGHT (SPAIN), S.L.U.	INDINOR INDUSTRIAS QUIMICAS SA	LUGAR DE SAO RIBEIRAO	4760-725	VILA NOVA DE FAMALICAO	PT	1	53	0.2736	0.05	1	TVS SCS INT. FREIGHT (SPAIN), S.L.U.	ESA08002073	TVS SCS I FREIGHT (S.L.U.
2612043491	Saída	H_PRT_MAI	1114848		DISTR	TMG-Tecidos para Vestuário e Decoração SA	Mundicorte-Confecção Importação E Exportação de Texteis, Lda.	Av. Abilio Ferreira Oliveira N 326	4795-443	S. Martinho Campo	PT	9	212	0.54	0.08		TMG - TECIDOS E VEST. SA		
2611917488	Saída	H_PRT_MAI			PWE	Leemantrade , Lda.	Insparya Hair Medical Clinic, S.L.	Calle Joaquín Costa, 26	28002	Madrid	ES	1	500	1.488	0.4	1	LEEMANTRADE LDA		PALLETW/ IBERIA- M/
2611917492	Saída	H_PRT_MAI			PWE	DEIFIL	FINCA EL LENTISCO	CARRETERA DEL ARRAYAN SN	21730	Almonte	ES	1	150	0.96	0.5	1	DEIFIL TECHNOLOGY LDA		PALLETW/ IBERIA- M/
2611917214	Saída	H_PRT_MAI			ALLMED	CASFIL - INDUSTRIA DE PLASTICOS S.A.	BORAN PLASTIC PACKAGING LIMITED	Johnstown	W91 YA24	CO.KILDARE	IE	40	15200	36.61	7.4		CASFIL - INDUSTRIA DE PLASTICOS S.A.	63196	ALL MED EUROPEA FREIGHT L

Figure D.3: WMS Bookings table.



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Loads

Etiquetas
Abrir Load

N° Load	Tipo	Matrícula	Transportador	Planeador da load	Bookings Armazém	Bookings Total	Volumes Armazém	Volumes Total	Peso Armazém	Peso Total	Volume Armazém	Volume Total	LDM Armazém	LDM Total	Qtd. Stock	País de origem	Cidade de origem	País de Destino	Cidade de Destino	Data de Início	Data de Fim	A
1114848	Saída	43-XC-39	TEMA NOTAVEL TRANSPORTES UNIPESSOAL LDA	PEDRO SILVA	7	7	22	22	1 989,0	1 989,0	6,679	6,679	1,73	1,73	8	PT	MAIA	PT	VILA NOVA FAMALICAO	2026-06-02	2026-06-02	Er
1114617	Entrada	VI-13162	AUGUSTO & AFONSO DA CUNHA	TOMAS PINTO	1	1	1	1	825,0	825,0	1,300	1,300	0,60	0,60		IT	MELZO MI	PT	MAIA	2026-06-01	2026-06-03	Pr
1114847	Saída	AT-40-CL	TEMA NOTAVEL TRANSPORTES UNIPESSOAL LDA	PEDRO SILVA	5	5	5	5	965,3	965,3	5,413	5,413	1,98	1,98	5	PT	MAIA	PT	GUIMARAES	2026-06-02	2026-06-02	Er
1114845	Saída	97-RR-51	MANUEL MENDES TRANSPORTES, LDA.	VITOR MARTINS	8	8	19	19	8 884,3	8 884,3	21,208	21,208	4,75	4,75	19	PT	MAIA	PT	MATOSINHOS	2026-06-02	2026-06-02	Er
1114841	Saída	AQ-87-OE	BRUNO & ANGELA LDA	PEDRO SILVA	9	9	14	14	2 371,2	2 371,2	11,203	11,203	4,68	4,68	14	PT	MAIA	PT	BRAGA	2026-06-02	2026-06-02	Er
1114728	Saída	P-110511	ALVVATIR TRANSPORTES E LOGISTICA LDA	CARLOS BALATA	2	2	166	172	11 417,1	15 817,1	74,556	106,872	12,02	17,47	166	PT	MAIA	PT	ABÓBODA	2026-06-01	2026-06-01	Er
1114805	Saída	91-UB-48	MANUEL MENDES TRANSPORTES, LDA.	PEDRO SILVA	7	7	12	12	2 728,4	2 728,4	9,325	9,325	3,13	3,13	12	PT	MAIA	PT	MONÇÃO	2026-06-02	2026-06-02	Er
1114685	Entrada	ST500PT	RHENUS LOGISTICS S.P.A.	JOANA MONTEIRO	19	19	25	25	5 678,9	5 678,9	27,896	27,896	3,75	3,75		IT	PORDENONE	PT	MAIA	2026-05-29	2026-06-02	Pr
1114683	Saída	43-XC-39	TEMA NOTAVEL TRANSPORTES UNIPESSOAL LDA	DIOGO SILVA	20	20	38	38	7 654,4	7 654,4	28,167	28,167	8,17	8,17	14	PT	MAIA	PT	ANADIA	2026-06-01	2026-06-01	Er
1114801	Saída	36-EX-69	BRUNO & ANGELA LDA	VITOR MARTINS	4	4	13	13	3 229,6	3 229,6	14,723	14,723	4,67	4,67	13	PT	MAIA	PT	MAIA	2026-06-02	2026-06-02	Er
1114772	Entrada	L 192569	TRANSPORTES JORGE LEMOS LDA	HELDER CUNHA	3	3	17	17	4 479,0	4 479,0	27,628	27,628	5,52	5,52		DE	MANNHEIM	PT	MATOSINHOS	2026-05-29	2026-06-05	Pr
1114775	Saída	12-XQ-55	ILIDIO CUNHA MONTENEGRO UNIPESSOAL LDA	VITOR MARTINS	6	6	6	6	1 444,8	1 444,8	4,632	4,632	1,52	1,52	6	PT	MAIA	PT	GONDOMAR	2026-06-02	2026-06-02	Er
1114718	Saída	50-VA-63	TRANSOSIL - TRANSPORTES, LDA	VITOR MARTINS	9	9	43	43	9 336,0	9 336,0	16,780	16,780	3,27	3,27	43	PT	MAIA	PT	AMARANTE	2026-06-02	2026-06-02	Er
1114618	Saída	07-VC-14	BRUNO & ANGELA LDA	PEDRO SILVA	9	9	14	14	5 386,7	5 386,7	12,565	12,565	3,55	3,55	11	PT	MAIA	PT	AVEIRO	2026-06-02	2026-06-02	Er
1114687	Saída	AF-97-EU	ANTONIO DOMINGOS DA SILVA CRUZ LDA	PEDRO SILVA	7	7	13	13	2 775,1	2 775,1	15,898	15,898	4,45	4,45	13	PT	MAIA	PT	VILA NOVA DE GAIA	2026-06-02	2026-06-02	Er
1114590	Saída	42-XN-47	TRANSOSIL - TRANSPORTES,	PEDRO	7	7	17	17	3 808,3	3 808,3	8,417	8,417	3,31	3,31	16	PT	MAIA	PT	AGUEDA	2026-06-02	2026-06-02	Er

Figure D.4: WMS Loads table.

Appendix E

Historical Dock Redistribution by Storage Location

E.1 Inbound Movements (Storage Entry)

This appendix details the redistribution rules applied to movements originally assigned to *MAI_01* during inbound operations, as discussed in Section 4.2.7. To ensure consistency with operational reality, where a single truck operates through a single dock door, the redistribution was performed at the load level: all rows belonging to the same load were reassigned to the same dock.

For each load, the dominant storage location, defined as the location with the highest share of pallet quantity within that load, was used to identify the set of valid alternative dock doors. Docks representing more than 10% of the historical movement volume for that specific storage location were considered eligible. From this set, an alternative door was selected with a probability proportional to its historical usage share. This procedure was applied independently to inbound and outbound flows. Table E.1 summarizes the redistribution impact.

Table E.1: Inbound redistribution: storage location to alternative dock doors

Storage Location	Alternative Docks — Redistribution Weight
MAI-B-1-1	MAI_06 (100%)
MAI-BUFFER1	MAI_11 (33%), MAI_16 (33%), MAI_17 (33%)
MAI-BUFFER2	MAI_04 (59%), MAI_06 (41%)
MAI-BUFFER3	MAI_11 (26%), MAI_13 (58%), MAI_14 (16%)
MAI-BUFFER4	MAI_15 (17%), MAI_17 (22%), MAI_18 (16%), MAI_19 (30%), MAI_21 (16%)
MAI-BUFFER6	MAI_17 (53%), MAI_18 (17%), MAI_19 (30%)
MAI-BUFFER7	MAI_24 (100%)
MAI-C-1-1	MAI_06 (52%), MAI_07 (48%)
MAI-D-1-1	MAI_02 (100%)
MAI-E-1-1	MAI_02 (100%)
MAI-EB-1-1	MAI_02 (39%), MAI_04 (25%), MAI_05 (36%)
MAI-EB-1-2	MAI_02 (38%), MAI_09 (62%)
MAI-EC-1-1	MAI_02 (30%), MAI_03 (37%), MAI_04 (33%)
MAI-EC-1-2	MAI_03 (100%)
MAI-ED-1-1	MAI_02 (43%), MAI_06 (35%), MAI_16 (22%)

(continued from previous page)

Storage Location	Alternative Docks — Redistribution Weight
MAI-ED-1-2	MAI_02 (57%), MAI_16 (17%), MAI_22 (26%)
MAI-EE-1-1	MAI_05 (31%), MAI_16 (69%)
MAI-EE-1-2	MAI_02 (52%), MAI_22 (48%)
MAI-EF-1-1	MAI_23 (16%), MAI_24 (23%), MAI_25 (27%), MAI_26 (34%)
MAI-EF-1-2	MAI_04 (59%), MAI_25 (27%), MAI_26 (14%)
MAI-EG-1-1	MAI_08 (17%), MAI_24 (21%), MAI_25 (36%), MAI_26 (25%)
MAI-EG-1-2	MAI_24 (49%), MAI_25 (19%), MAI_26 (32%)
MAI-EH-1-1	MAI_25 (56%), MAI_26 (44%)
MAI-EH-1-2	MAI_03 (37%), MAI_05 (41%), MAI_26 (22%)
MAI-EI-1-1	MAI_23 (26%), MAI_24 (27%), MAI_26 (47%)
MAI-EI-1-2	MAI_07 (27%), MAI_14 (17%), MAI_26 (56%)
MAI-F-1-1	MAI_18 (23%), MAI_19 (46%), MAI_21 (30%)
MAI-G-1-1	MAI_19 (100%)
MAI-H-1-1	MAI_19 (100%)
MAI-J-1-1	MAI_02 (50%), MAI_03 (50%)
MAI-K-1-1	MAI_02 (44%), MAI_03 (56%)
MAI-L-1-1	MAI_05 (29%), MAI_16 (41%), MAI_17 (30%)
MAI-PENDURADOS	MAI_04 (35%), MAI_09 (39%), MAI_29 (26%)
MAI-PW E1	MAI_04 (25%), MAI_05 (21%), MAI_15 (21%), MAI_16 (33%)
MAI-PW E2	MAI_04 (18%), MAI_05 (21%), MAI_13 (25%), MAI_15 (37%)
MAI-PW I1	MAI_06 (48%), MAI_07 (52%)
MAI-PW I2	MAI_06 (100%)
MAI-W-1-1	MAI_02 (56%), MAI_03 (44%)
MAI-X-1-1	MAI_02 (55%), MAI_03 (45%)
MAI-Y-1-1	MAI_29 (100%)
Mai-A-1-1	MAI_04 (100%)
Maia-ARR	MAI_02 (67%), MAI_03 (33%)

E.2 Outbound Movements (Storage Exit)

This section presents the redistribution rules applied to outbound movements originally associated with *MAI_01*. The same redistribution logic based on historical dock usage was applied, as presented in Table E.2.

Table E.2: Outbound redistribution: storage location to alternative dock doors

Storage Location	Alternative Docks — Redistribution Weight
MAI-A-1-1	MAI_06 (56%), MAI_14 (44%)
MAI-B-1-1	MAI_09 (39%), MAI_14 (61%)
MAI-BUFFER1	MAI_09 (33%), MAI_16 (33%), MAI_20 (33%)

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Storage Location	Alternative Docks — Redistribution Weight
MAI-BUFFER2	MAI_12 (60%), MAI_14 (40%)
MAI-BUFFER3	MAI_07 (83%), MAI_15 (17%)
MAI-BUFFER4	MAI_15 (45%), MAI_16 (55%)
MAI-BUFFER7	MAI_24 (100%)
MAI-C-1-1	MAI_10 (100%)
MAI-D-1-1	MAI_14 (100%)
MAI-E-1-1	MAI_14 (100%)
MAI-EB-1-1	MAI_23 (25%), MAI_24 (58%), MAI_26 (17%)
MAI-EB-1-2	MAI_24 (100%)
MAI-EC-1-1	MAI_23 (28%), MAI_24 (32%), MAI_25 (12%), MAI_26 (28%)
MAI-EC-1-2	MAI_24 (66%), MAI_25 (34%)
MAI-ED-1-1	MAI_24 (55%), MAI_25 (45%)
MAI-ED-1-2	MAI_24 (41%), MAI_26 (26%), MAI_29 (33%)
MAI-EE-1-1	MAI_22 (22%), MAI_22A (21%), MAI_23 (22%), MAI_24 (35%)
MAI-EE-1-2	MAI_17 (42%), MAI_24 (58%)
MAI-EF-1-1	MAI_10 (46%), MAI_24 (54%)
MAI-EF-1-2	MAI_24 (100%)
MAI-EG-1-1	MAI_08 (31%), MAI_15 (30%), MAI_16 (38%)
MAI-EG-1-2	MAI_08 (21%), MAI_15 (54%), MAI_18 (26%)
MAI-EH-1-1	MAI_08 (100%)
MAI-EH-1-2	MAI_02 (19%), MAI_12 (24%), MAI_16 (26%), MAI_20 (30%)
MAI-EI-1-2	MAI_11 (37%), MAI_24 (42%), MAI_25 (22%)
MAI-F-1-1	MAI_15 (51%), MAI_16 (49%)
MAI-G-1-1	MAI_15 (53%), MAI_16 (47%)
MAI-I-1-1	MAI_13 (100%)
MAI-J-1-1	MAI_19 (100%)
MAI-K-1-1	MAI_18 (40%), MAI_19 (35%), MAI_20 (25%)
MAI-L-1-1	MAI_18 (75%), MAI_20 (25%)
MAI-PENDURADOS	MAI_14 (50%), MAI_29 (50%)
MAI-PW E1	MAI_06 (100%)
MAI-PW E2	MAI_06 (100%)
MAI-PW I1	MAI_05 (22%), MAI_08 (30%), MAI_09 (23%), MAI_10 (24%)
MAI-PW I2	MAI_04 (19%), MAI_05 (35%), MAI_08 (23%), MAI_14 (23%)
MAI-W-1-1	MAI_29 (100%)
MAI-X-1-1	MAI_29 (100%)
MAI-Y-1-1	MAI_14 (33%), MAI_20 (34%), MAI_29 (33%)
Mai-A-1-1	MAI_13 (100%)
Mai-BUFFER7	MAI_24 (100%)
Maia-ARR	MAI_05 (100%)

Appendix F

Warehouse Distance Matrix

To support the analysis of internal warehouse movements, a distance matrix was developed based on the physical warehouse layout, as discussed in Section 4.3.3. The matrix contains the calculated distances (in meters) between dock doors and storage locations used during inbound and outbound operations.

These distances were integrated into the simulation model and used to estimate internal travel distances associated with cargo handling activities between dock areas and storage locations. The matrix served as one of the main spatial inputs for evaluating internal flow efficiency and operator movement within the warehouse.

Figure F.1 presents the measured warehouse dimensions and the operational reference points used to construct the matrix, combining CAD documentation with on-site laser measurements.

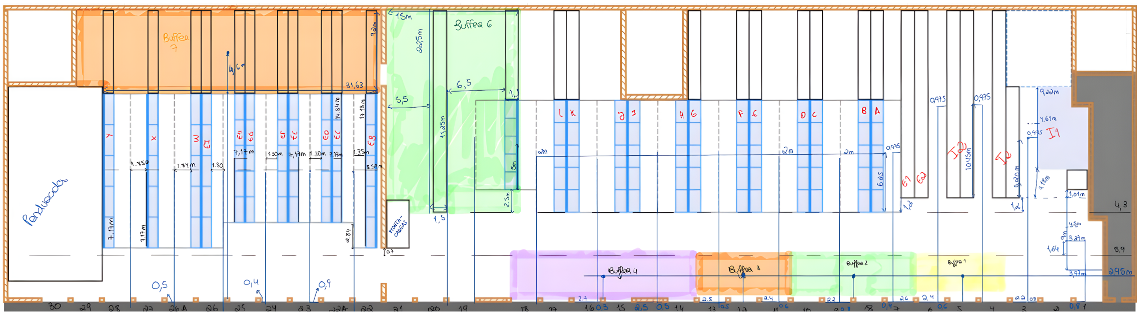

Figure F.1: Measured warehouse dimensions and operational reference points used in the development of the distance matrix

Tables F.1 and F.2 present the distance matrix used in the simulation model, covering dock doors MAI_01 to MAI_16 and MAI_17 to MAI_30, respectively.

Table F.1: Distance matrix (meters) – storage locations vs. dock doors MAI_01 to MAI_16

Storage Location	MAI_01	MAI_02	MAI_03	MAI_04	MAI_05	MAI_06	MAI_07	MAI_08	MAI_09	MAI_10	MAI_11	MAI_12	MAI_13	MAI_14	MAI_15	MAI_16
MAI-A-1-1	39,53	36,03	32,53	29,03	25,53	22,03	18,53	19,83	23,33	26,83	30,33	33,83	37,33	40,83	47,83	51,33
MAI-B-1-1	45,25	42,25	37,73	35,25	31,75	28,25	24,75	21,25	18,45	22,65	26,15	29,65	33,15	36,65	43,65	47,15
MAI-C-1-1	45,25	42,35	37,73	35,25	31,75	28,25	24,75	21,25	18,45	22,65	26,15	29,65	33,15	36,65	43,65	47,15
MAI-D-1-1	52,05	49,05	44,53	42,05	38,55	35,05	31,55	28,05	24,55	21,05	18,45	22,85	26,35	29,85	36,85	40,35
MAI-E-1-1	52,05	49,05	44,53	42,05	38,55	35,05	31,55	28,05	24,55	21,05	18,45	22,85	26,35	29,85	36,85	40,35
MAI-F-1-1	58,95	55,95	51,43	48,95	45,45	41,95	38,45	34,95	31,45	27,95	24,45	20,95	19,45	22,95	29,95	33,45
MAI-G-1-1	58,95	55,95	51,43	48,95	45,45	41,95	38,45	34,95	31,45	27,95	24,45	20,95	19,45	22,95	29,95	33,45
MAI-H-1-1	65,95	62,95	58,43	55,95	52,45	48,95	45,45	41,95	38,45	34,95	31,45	27,95	24,45	20,95	22,95	26,45
MAI-I-1-1	65,95	62,95	58,43	55,95	52,45	48,95	45,45	41,95	38,45	34,95	31,45	27,95	24,45	20,95	22,95	26,45
MAI-J-1-1	72,75	69,75	65,23	62,75	59,25	55,75	52,25	48,75	45,25	41,75	38,25	34,75	31,25	27,75	20,75	19,65
MAI-K-1-1	72,75	69,75	65,23	62,75	59,25	55,75	52,25	48,75	45,25	41,75	38,25	34,75	31,25	27,75	20,75	19,65
MAI-L-1-1	79,45	76,45	71,93	69,45	65,95	62,45	58,95	55,45	51,95	48,45	44,95	41,45	37,95	34,45	27,45	23,95
MAI-EB-1-1	98,54	95,04	91,54	88,04	84,54	81,04	77,54	74,04	70,54	67,04	63,54	60,04	56,54	53,04	46,04	42,54
MAI-EB-1-2	100,54	97,04	93,54	90,04	86,54	83,04	79,54	76,04	72,54	69,04	65,54	62,04	58,54	55,04	48,04	44,54
MAI-EC-1-1	99,96	96,46	92,96	89,46	85,96	82,46	78,96	75,46	71,96	68,46	64,96	61,46	57,96	54,46	47,46	43,96
MAI-EC-1-2	101,96	98,46	94,96	91,46	87,96	84,46	80,96	77,46	73,96	70,46	66,96	63,46	59,96	56,46	49,46	45,96
MAI-ED-1-1	104,81	101,31	97,81	94,31	90,81	87,31	83,81	80,31	76,81	73,31	69,81	66,31	62,81	59,31	52,31	48,81
MAI-ED-1-2	106,81	103,31	99,81	96,31	92,81	89,31	85,81	82,31	78,81	75,31	71,81	68,31	64,81	61,31	54,31	50,81
MAI-EE-1-1	104,81	101,31	96,51	94,31	90,81	87,31	83,81	80,31	76,81	73,31	69,81	66,31	62,81	59,31	52,31	48,81
MAI-EE-1-2	106,81	103,31	99,81	96,31	92,81	89,31	85,81	82,31	78,81	75,31	71,81	68,31	64,81	61,31	54,31	50,81
MAI-EF-1-1	110,01	106,51	103,01	99,51	96,01	92,51	89,01	85,51	82,01	78,51	75,01	71,51	68,01	64,51	57,51	54,01
MAI-EF-1-2	112,01	108,51	105,01	101,51	98,01	94,51	91,01	87,51	84,01	80,51	77,01	73,51	70,01	66,51	59,51	56,01
MAI-EG-1-1	110,01	106,51	103,01	99,51	96,01	92,51	89,01	85,51	82,01	78,51	75,01	71,51	68,01	64,51	57,51	54,01
MAI-EG-1-2	112,01	108,51	105,01	101,51	98,01	94,51	91,01	87,51	84,01	80,51	77,01	73,51	70,01	66,51	59,51	56,01
MAI-EH-1-1	114,41	110,91	107,41	103,91	100,41	96,91	93,41	89,91	86,41	82,91	79,41	75,91	72,41	68,91	61,91	58,41
MAI-EH-1-2	116,41	112,91	109,41	105,91	102,41	98,91	95,41	91,91	88,41	84,91	81,41	77,91	74,41	70,91	63,91	60,41
MAI-EI-1-1	112,99	109,49	105,99	102,49	98,99	95,49	91,99	88,49	84,99	81,49	77,99	74,49	70,99	67,49	60,49	56,99
MAI-EI-1-2	114,99	111,49	107,99	104,49	100,99	97,49	93,99	90,49	86,99	83,49	79,99	76,49	72,99	69,49	62,49	58,99
MAI-W-1-1	119,53	116,03	112,53	109,03	105,53	102,03	98,53	95,03	91,53	88,03	84,53	81,03	77,53	74,03	67,03	63,53
MAI-X-1-1	119,53	116,03	112,53	109,03	105,53	102,03	98,53	95,03	91,53	88,03	84,53	81,03	77,53	74,03	67,03	63,53
MAI-Y-1-1	124,04	120,54	117,04	113,54	110,04	106,54	103,04	99,54	96,04	92,54	89,04	85,54	82,04	78,54	71,54	68,04
Maia-ARR	7,54	10,34	13,84	17,34	20,84	24,34	27,84	31,34	34,84	38,34	41,84	45,34	48,84	52,34	59,34	62,84
MAI-BUFFER1	16,95	13,45	9,95	6,45	2,95	6,45	9,95	13,45	16,95	20,45	23,95	27,45	30,95	34,45	41,45	44,95
MAI-BUFFER2	29,20	25,70	22,20	18,70	15,20	11,70	8,20	4,70	4,70	8,20	11,70	15,20	18,70	22,20	29,20	32,70
MAI-BUFFER3	41,45	37,95	34,45	30,95	27,45	23,95	20,45	16,95	12,95	9,95	6,45	2,95	6,45	9,95	16,95	20,45
MAI-BUFFER4	57,20	53,70	50,20	46,70	43,20	39,70	36,20	32,70	29,20	25,70	22,20	18,70	15,20	11,70	4,70	4,70
MAI-BUFFER6	74,70	71,20	67,70	64,20	60,70	57,20	53,70	50,20	46,70	43,20	39,70	36,20	32,70	29,20	22,20	18,70
MAI-BUFFER7	124,63	121,13	117,63	114,13	110,63	107,13	103,63	100,13	96,63	93,13	89,63	86,13	82,63	79,13	72,13	68,63
MAI-PW I1	26,47	22,97	20,87	24,37	27,87	31,37	34,87	38,37	41,87	45,37	48,87	52,37	55,87	59,37	66,37	69,87
MAI-PW I2	33,49	29,99	27,74	25,09	25,34	27,54	31,04	34,54	38,04	41,54	45,04	48,54	52,04	55,51	62,54	66,04
MAI-PW E2	39,43	35,93	33,63	28,93	25,43	23,73	27,23	30,73	34,23	37,73	41,23	44,73	48,23	51,73	58,73	62,23
MAI-PW E1	43,73	41,43	39,13	34,43	30,93	27,43	23,93	25,23	28,73	32,23	35,73	39,23	42,73	46,23	53,23	56,73
MAI-PENDURADOS	121,40	117,90	114,40	110,90	107,40	103,90	100,40	96,90	93,40	89,90	86,40	82,90	79,40	75,90	68,90	65,40

Table F.2: Distance matrix (meters) – storage locations vs. dock doors MAI_17 to MAI_30

Storage Location	MAI_17	MAI_18	MAI_19	MAI_20	MAI_21	MAI_22	MAI_22A	MAI_23	MAI_24	MAI_25	MAI_26	MAI_26A	MAI_27	MAI_28	MAI_29	MAI_30
MAI-A-1-1	54,83	58,33	65,33	68,83	72,33	75,83	79,33	82,83	86,33	89,83	93,33	96,83	100,33	103,83	107,33	110,83
MAI-B-1-1	50,65	54,15	61,15	64,65	68,15	71,65	75,15	78,65	82,15	85,65	89,15	92,65	96,15	99,65	103,15	106,65
MAI-C-1-1	50,65	54,15	61,15	64,65	68,15	71,65	75,15	78,65	82,15	85,65	89,15	92,65	96,15	99,65	103,15	106,65
MAI-D-1-1	43,85	47,35	54,35	57,85	61,35	64,85	68,35	71,85	75,35	78,85	82,35	85,85	89,35	92,85	96,35	99,85
MAI-E-1-1	43,85	47,35	54,35	57,85	61,35	64,85	68,35	71,85	75,35	78,85	82,35	85,85	89,35	92,85	96,35	99,85
MAI-F-1-1	36,95	40,45	47,45	50,95	54,45	57,95	61,45	64,95	68,45	71,95	75,45	78,95	82,45	85,95	89,45	92,95
MAI-G-1-1	36,95	40,45	47,45	50,95	54,45	57,95	61,45	64,95	68,45	71,95	75,45	78,95	82,45	85,95	89,45	92,95
MAI-H-1-1	29,95	33,45	40,45	43,95	47,45	50,95	54,45	57,95	61,45	64,95	68,45	71,95	75,45	78,95	82,45	85,95
MAI-I-1-1	29,95	33,45	40,45	43,95	47,45	50,95	54,45	57,95	61,45	64,95	68,45	71,95	75,45	78,95	82,45	85,95
MAI-J-1-1	23,15	26,65	33,65	37,15	40,65	44,15	47,65	51,15	54,65	58,15	61,65	65,15	68,65	72,15	75,65	79,15
MAI-K-1-1	23,15	26,65	33,65	37,15	40,65	44,15	47,65	51,15	54,65	58,15	61,65	65,15	68,65	72,15	75,65	79,15
MAI-L-1-1	20,45	19,95	26,95	30,45	33,95	37,45	40,95	44,45	47,95	51,45	54,95	58,45	61,95	65,45	68,95	72,45
MAI-EB-1-1	39,04	35,54	28,54	25,04	21,54	18,04	18,54	22,04	25,54	29,04	32,54	36,04	39,54	43,04	46,54	50,04
MAI-EB-1-2	41,04	37,54	30,54	27,04	23,54	20,04	20,54	24,04	27,54	31,04	34,54	38,04	41,54	45,04	48,54	52,04
MAI-EC-1-1	40,46	36,96	29,96	26,46	22,96	19,46	19,96	23,46	26,96	30,46	33,96	37,46	40,96	44,46	47,96	51,46
MAI-EC-1-2	42,46	38,96	31,96	28,46	24,96	24,96	21,96	25,46	28,96	32,46	35,96	39,46	42,96	46,46	49,96	53,46
MAI-ED-1-1	45,31	41,81	34,81	31,31	27,81	27,81	21,31	19,01	22,51	26,01	29,51	33,01	36,51	40,01	43,51	47,01
MAI-ED-1-2	47,31	43,81	36,81	33,31	29,81	29,81	23,31	21,01	24,51	28,01	31,51	35,01	38,51	42,01	45,51	49,01
MAI-EE-1-1	45,31	41,81	34,81	31,31	27,81	27,81	21,31	19,01	22,51	26,01	29,51	33,01	36,51	40,01	43,51	47,01
MAI-EE-1-2	47,31	43,81	36,81	33,31	29,81	29,81	23,31	21,01	24,51	28,01	31,51	35,01	38,51	42,01	45,51	49,01
MAI-EF-1-1	50,51	47,01	40,01	36,51	33,01	33,01	26,51	23,01	19,51	20,81	24,31	27,81	31,31	34,81	38,31	41,81
MAI-EF-1-2	52,51	49,01	42,01	38,51	35,01	35,01	28,51	25,01	21,51	22,81	26,31	29,81	33,31	36,81	40,31	43,81
MAI-EG-1-1	50,51	47,01	40,01	36,51	33,01	33,01	26,51	23,01	19,51	20,81	24,31	27,81	31,31	34,81	38,31	41,81
MAI-EG-1-2	52,51	49,01	42,01	38,51	35,01	35,01	28,51	25,01	21,51	22,81	26,31	29,81	33,31	36,81	40,31	43,81
MAI-EH-1-1	54,91	51,41	44,41	40,91	37,41	37,41	30,41	26,91	23,41	19,91	19,41	22,91	26,41	29,91	33,41	36,91
MAI-EH-1-2	56,91	53,41	46,41	42,91	39,41	39,41	32,41	28,91	25,41	21,91	21,41	24,91	28,41	31,91	35,41	38,91
MAI-EI-1-1	53,49	49,99	42,99	39,49	35,99	35,99	28,99	25,49	21,99	18,49	17,99	21,49	24,99	28,49	31,99	35,49
MAI-EI-1-2	55,49	51,99	44,99	41,49	37,99	37,99	30,99	27,49	23,99	20,49	19,99	23,49	26,99	30,49	33,99	37,49
MAI-W-1-1	60,03	56,53	49,53	46,03	42,53	42,53	36,03	32,53	29,03	25,53	22,03	18,53	20,03	23,53	27,03	30,53
MAI-X-1-1	60,03	56,53	49,53	46,03	42,53	42,53	36,03	32,53	29,03	25,53	22,03	18,53	20,03	23,53	27,03	30,53
MAI-Y-1-1	64,54	61,04	54,04	50,54	47,04	47,04	40,04	36,54	33,04	29,54	26,04	22,54	19,04	18,54	22,04	25,54
Maia-ARR	66,34	69,84	76,84	80,34	83,84	87,34	90,84	94,34	97,84	101,34	104,84	108,34	111,84	115,34	118,84	122,34
MAI-BUFFER1	48,45	51,95	58,95	62,45	65,95	69,45	72,95	76,45	79,95	83,45	86,95	90,45	93,95	97,45	100,95	104,45
MAI-BUFFER2	36,20	39,70	46,70	50,20	53,70	57,20	60,70	64,20	67,70	71,20	74,70	78,20	81,70	85,20	88,70	92,20
MAI-BUFFER3	23,95	27,45	34,45	37,95	41,45	44,95	48,45	51,95	55,45	58,95	62,45	65,95	69,45	72,95	76,45	79,95
MAI-BUFFER4	8,20	11,70	18,70	22,20	25,70	29,20	32,70	36,20	39,70	43,20	29,20	50,20	53,70	57,20	60,70	64,20
MAI-BUFFER6	15,20	11,70	4,70	4,70	8,20	11,70	15,20	18,70	22,20	25,70	29,20	32,70	36,20	39,70	43,20	46,70
MAI-BUFFER7	65,13	61,63	54,63	51,13	47,63	44,13	40,63	37,13	33,63	30,13	30,13	33,63	37,13	40,63	44,13	47,63
MAI-PW I1	73,37	76,87	83,87	87,37	90,87	94,37	97,87	101,37	104,87	108,37	111,87	115,37	118,87	122,37	125,87	129,37
MAI-PW I2	69,54	73,04	80,04	83,54	87,04	90,54	94,04	97,54	101,04	104,54	108,91	112,41	115,91	119,41	122,91	126,41
MAI-PW E2	65,73	69,23	76,23	79,73	83,23	86,73	90,23	93,73	97,23	100,73	107,73	111,23	114,73	118,23	121,73	125,23
MAI-PW E1	60,23	63,73	70,73	74,23	77,73	81,23	84,73	88,23	91,73	95,23	98,73	102,23	105,73	109,23	112,73	116,23
MAI-PENDURADOS	61,90	58,40	54,90	47,90	44,40	40,90	37,40	33,90	30,40	26,90	23,40	19,90	16,40	12,90	9,40	5,90

Appendix G

Maximum Dwell Time per Storage Location

As described in Section 4.3.8, the *storageDelay* block used within the simulation model required a maximum dwell time to be estimated for each storage location, in order to match inbound pallet movements with their corresponding outbound movements through the *storageExitIndex* indexing structure.

For each storage location, all available inbound-outbound pairs were identified based on the historical *StorageEntry* and *StorageExit* records. The maximum dwell time threshold was computed once against the full population of pairs for each subzone, using the raw average dwell time ($\mu_{raw,subzone}$). This value served simultaneously as the outlier threshold and the final calibrated matching window, with pairs exceeding this average being classified as outliers and excluded from the indexing process.

Across all storage locations, a total of 78658 inbound-outbound pairs were identified, of which 24721 (approximately 31%) exceeded the location-specific threshold and were treated as outliers.

Table G.1 presents, for each storage location, the total number of inbound-outbound pairs identified, the number of pairs within and exceeding the location-specific threshold, the corresponding percentage of pairs within this limit, and the resulting mean dwell time used as the matching window.

Table G.1: Inbound-outbound pair matching and outlier identification per storage location

Storage Location	**Total Pairs**	**Bookings within Mean**	**Bookings Exceeding Mean**	**% within Mean**	**Mean Dwell Time (days)**
MAI-EB-1-1	922	575	347	62,40	4,04
MAI-EB-1-2	752	486	266	64,60	4,03
MAI-EC-1-2	151	88	63	58,30	3,75
MAI-EC-1-1	229	128	101	55,90	3,71
MAI-EI-1-2	88	67	21	76,10	3,62
MAI-ED-1-2	74	47	27	63,50	3,44
MAI-EI-1-1	501	353	148	70,50	3,26
MAI-ED-1-1	116	74	42	63,80	3,25
MAI-EH-1-1	286	184	102	64,30	3,25
MAI-EE-1-2	69	40	29	58,00	3,07
MAI-EE-1-1	92	54	38	58,70	3,03

(continued from previous page)

Storage Location	Total Pairs	Bookings within Mean	Bookings Exceeding Mean	% within Mean	Mean Dwell Time (days)
MAI-EG-1-1	315	216	99	68,60	2,98
MAI-EF-1-1	344	231	113	67,20	2,98
MAI-BUFFER7	1543	1004	539	65,10	2,68
MAI-EH-1-2	72	43	29	59,70	2,68
MAI-EG-1-2	67	40	27	59,70	2,60
MAI-EF-1-2	49	32	17	65,30	2,26
MAI-J-1-1	2104	1351	753	64,20	1,77
MAI-K-1-1	6434	3919	2515	60,90	1,73
MAI-W-1-1	1254	832	422	66,30	1,63
MAI-BUFFER3	3	1	2	33,30	1,60
MAI-B-1-1	2830	1917	913	67,70	1,56
MAI-I-1-1	2504	1608	896	64,20	1,53
MAI-X-1-1	1870	1238	632	66,20	1,52
MAI-H-1-1	2237	1469	768	65,70	1,51
MAI-C-1-1	2892	1955	937	67,60	1,43
MAI-L-1-1	1688	1151	537	68,20	1,41
MAI-D-1-1	3733	2524	1209	67,60	1,38
MAI-PW I1	10455	7146	3309	68,40	1,38
MAI-PW I2	53	38	15	71,70	1,36
MAI-E-1-1	2959	2003	956	67,70	1,35
Maia-ARR	70	49	21	70,00	1,16
MAI-Y-1-1	215	157	58	73,00	1,10
MAI-BUFFER4	1121	787	334	70,20	1,05
MAI-F-1-1	4683	3457	1226	73,80	0,97
MAI-PENDURADOS	61	50	11	82,00	0,97
MAI-BUFFER2	67	50	17	74,60	0,93
MAI-G-1-1	5324	3964	1360	74,50	0,91
MAI-BUFFER6	10542	7444	3098	70,60	0,86
MAI-A-1-1	7393	5283	2110	71,50	0,75
MAI-PW E2	623	430	193	69,00	0,72
MAI-PW E1	1870	1450	420	77,50	0,67
MAI-BUFFER1	3	2	1	66,70	0,30
Total	**78658**	**53937**	**24721**	–	–

Table G.2 further details the distribution of the outlier pairs identified for each storage location, grouped into dwell-time ranges (up to 4 days, 4–7 days, 7–14 days, 14–30 days, and more than 30 days), together with the total number of outlier pairs per location.

Table G.2: Distribution of outlier inbound-outbound pairs per storage location, by dwell-time range

Storage Location	Mean Dwell Time (days)	Bookings within Mean	$\leq$ 4 days	4–7 days	7–14 days	14–30 days	> 30 days	Total Outliers
MAI-A-1-1	0,75	5283	1935	130	31	10	4	2110
MAI-B-1-1	1,56	1917	684	186	35	6	2	913
MAI-BUFFER1	0,30	2	1	0	0	0	0	1
MAI-BUFFER2	0,93	50	15	1	1	0	0	17
MAI-BUFFER3	1,60	1	2	0	0	0	0	2
MAI-BUFFER4	1,05	787	287	44	3	0	0	334
MAI-BUFFER6	0,86	7444	2826	234	32	6	0	3098
MAI-BUFFER7	2,68	1004	201	226	89	19	4	539
MAI-C-1-1	1,43	1955	768	144	17	8	0	937
MAI-D-1-1	1,38	2524	979	193	33	3	1	1209
MAI-E-1-1	1,35	2003	788	145	19	3	1	956
MAI-EB-1-1	4,04	575	0	212	113	20	2	347
MAI-EB-1-2	4,03	486	0	177	69	17	3	266
MAI-EC-1-1	3,71	128	17	55	27	1	1	101
MAI-EC-1-2	3,75	88	12	35	14	1	1	63
MAI-ED-1-1	3,25	74	8	22	9	3	0	42
MAI-ED-1-2	3,44	47	10	9	6	2	0	27
MAI-EE-1-1	3,03	54	11	19	7	1	0	38
MAI-EE-1-2	3,07	40	9	17	2	1	0	29
MAI-EF-1-1	2,98	231	22	53	32	6	0	113
MAI-EF-1-2	2,26	32	9	6	1	1	0	17
MAI-EG-1-1	2,98	216	22	50	22	5	0	99
MAI-EG-1-2	2,60	40	14	7	6	0	0	27
MAI-EH-1-1	3,25	184	27	54	18	1	2	102
MAI-EH-1-2	2,68	43	12	14	3	0	0	29
MAI-EI-1-1	3,26	353	23	70	37	17	1	148
MAI-EI-1-2	3,62	67	1	11	8	0	1	21
MAI-F-1-1	0,97	3457	1059	130	26	8	3	1226
MAI-G-1-1	0,91	3964	1201	117	32	8	2	1360
MAI-H-1-1	1,51	1469	615	116	35	1	1	768
MAI-I-1-1	1,53	1608	709	159	27	1	0	896
MAI-J-1-1	1,77	1351	601	127	21	3	1	753
MAI-K-1-1	1,73	3919	2050	395	59	10	1	2515
MAI-L-1-1	1,41	1151	444	74	16	3	0	537
MAI-PENDURADOS	0,97	50	7	2	2	0	0	11
MAI-PW E1	0,67	1450	385	31	4	0	0	420
MAI-PW E2	0,72	430	181	9	3	0	0	193
MAI-PW I1	1,38	7146	2720	499	73	17	0	3309
MAI-PW I2	1,36	38	12	2	1	0	0	15
MAI-W-1-1	1,63	832	324	69	25	4	0	422
MAI-X-1-1	1,52	1238	501	98	27	5	1	632
MAI-Y-1-1	1,10	157	50	7	1	0	0	58
Maia-ARR	1,16	49	18	1	2	0	0	21
Total	–	**53937**	**19560**	**3950**	**988**	**191**	**32**	**24721**

Appendix H

Maximum Dwell Time per Subzone - Scenario 2

As described in Section 5.1.3.1, the redesigned storage layout adopted in Scenario 2 organizes storage locations into subzones defined by cargo destination, rather than the individual storage locations used in the baseline scenario and in Scenario 1. Consequently, the *storageDelay* matching mechanism used to estimate the maximum dwell time for the *storageExitIndex* indexing structure (Section 4.3.8) was recalculated at the subzone level for this scenario, following the same procedure described in Appendix G.

For each subzone, all available inbound-outbound pairs were identified based on the historical *StorageEntry* and *StorageExit* records, aggregated according to the subzone assigned to each storage location under the Scenario 2 layout, and a single, non-iterative baseline average dwell time was computed across all matched pairs. Pairs exceeding this average were flagged as outliers; the threshold was computed once, against the full population, and not recalculated after the flagging. This single average therefore served as both the outlier classification threshold and the maximum dwell time used as the matching window for that subzone.

Across all subzones, the same total of 78658 inbound-outbound pairs identified in the baseline scenario was obtained, since pair identification depends only on the underlying booking and storage records and not on the spatial aggregation used for matching. Of these, 24515 (approximately 31%) exceeded their subzone's threshold and were flagged as outliers, leaving 54143 pairs within the calibrated window.

Table H.1 presents, for each subzone, the total number of inbound-outbound pairs identified, the number of pairs within and exceeding the subzone-specific threshold, the corresponding percentage of pairs within the threshold, and the resulting mean dwell time used as the matching window.

Table H.1: Inbound-outbound pair matching and outlier identification per subzone (Scenario 2)

Subzone	Total Pairs	Bookings within Mean	Bookings Exceeding Mean	% within Mean	Mean Dwell Time (days)
Z1_NACIONAL	46142	32334	13808	70,00	1,35
Z1_SHUTTLE	5203	3804	1399	73,00	0,70
Z2_FRANCE_GENERAL	2815	2146	669	76,00	0,64
Z2_SAFRAM	64	39	25	61,00	1,34
Z3_GERMANY_GENERAL	1578	1193	385	76,00	0,88

(continued from previous page)

Subzone	**Total Pairs**	**Bookings within Mean**	**Bookings Exceeding Mean**	**% within Mean**	**Mean Dwell Time (days)**
Z3_OSL	5224	2862	2362	55,00	1,92
Z3_SCHMALZ	356	233	123	65,00	1,33
Z4_ITA	1416	804	612	57,00	1,90
Z4_SWE_NOR	991	725	266	73,00	0,83
Z5_SPAIN_GENERAL	920	629	291	68,00	1,28
Z5_PALLETWAYS	6211	4392	1819	71,00	0,60
Z5_UNIRECO	310	188	122	61,00	1,56
Z6_BENELUX	2648	1695	953	64,00	1,30
Z6_CENTRAL_EUROPE	701	473	228	67,00	1,05
Z6_OTHERS_EU	802	486	316	61,00	2,75
Z7_USA_CH	955	664	291	70,00	2,61
Z7_UK	1994	1239	755	62,00	4,40
Z7_REST_WORLD	328	237	91	72,00	3,72
Total	**78658**	**54143**	**24515**	–	–

Table H.2 further details the distribution of the outlier pairs identified for each subzone, grouped into dwell-time ranges (up to 4 days, 4–7 days, 7–14 days, 14–30 days, and more than 30 days), together with the total number of outlier pairs per subzone.

Table H.2: Distribution of outlier inbound-outbound pairs per subzone, by dwell-time range (Scenario 2)

Subzone	**Mean Dwell Time (days)**	**Bookings within Mean**	**≤ 4 days**	**4–7 days**	**7–14 days**	**14–30 days**	**> 30 days**	**Total Outliers**
Z1_NACIONAL	1,35	32334	11060	2205	427	100	16	13808
Z1_SHUTTLE	0,70	3804	1282	74	33	8	2	1399
Z2_FRANCE_GENERAL	0,64	2146	614	49	6	0	0	669
Z2_SAFRAM	1,34	39	21	4	0	0	0	25
Z3_GERMANY_GENERAL	0,88	1193	313	41	27	4	0	385
Z3_OSL	1,92	2862	1981	349	28	4	0	2362
Z3_SCHMALZ	1,33	233	99	18	6	0	0	123
Z4_ITA	1,90	804	453	125	32	2	0	612
Z4_SWE_NOR	0,83	725	246	14	5	1	0	266
Z5_SPAIN_GENERAL	1,28	629	247	32	11	1	0	291
Z5_PALLETWAYS	0,60	4392	1762	55	2	0	0	1819
Z5_UNIRECO	1,56	188	100	19	3	0	0	122
Z6_BENELUX	1,30	1695	799	146	7	1	0	953
Z6_CENTRAL_EUROPE	1,05	473	204	16	8	0	0	228
Z6_OTHERS_EU	2,75	486	110	132	68	6	0	316
Z7_USA_CH	2,61	664	156	61	58	14	2	291
Z7_UK	4,40	1239	0	475	229	42	9	755
Z7_REST_WORLD	3,72	237	6	36	38	8	3	91
Total	–	**54143**	**19453**	**3851**	**988**	**191**	**32**	**24515**

Appendix I

Distance Matrix – Scenario 2

As described in Section 5.1.3.1, the redesigned storage layout adopted in Scenario 2 organizes storage locations into physical subzones, derived from the 18 logical subzones split into individual lanes to preserve the spatial granularity of the original storage locations.

This distance matrix comprises 34 physical subzones $\times$ 32 dock doors (1088 distance values), measured following operational reference points and circulation paths adapted to the spatial configuration of the redesigned, zone-based layout. The complete matrix is loaded into the simulation model through the `distanceIndex` structure and used directly by the `getBestDockForLoad()` function to determine the available dock door that minimizes the quantity-weighted average travel distance for each load.

Due to the number of dock doors, the matrix is presented across two tables. Table I.1 presents the distances between each physical subzone and dock doors MAI_01 to MAI_16, and Table I.2 presents the remaining dock doors, MAI_17 to MAI_30.

Table I.1: Distance matrix (meters) between physical subzones and dock doors – MAI_01 to MAI_16 (Scenario 2)

Subzone	MAI_01	MAI_02	MAI_03	MAI_04	MAI_05	MAI_06	MAI_07	MAI_08	MAI_09	MAI_10	MAI_11	MAI_12	MAI_13	MAI_14	MAI_15	MAI_16
Z1_NACIONAL1	57,25	53,75	50,25	46,75	43,25	39,75	36,25	32,75	29,25	25,75	22,25	21,75	25,25	28,75	39,25	42,75
Z1_NACIONAL2	50,85	47,35	43,85	40,35	36,85	33,35	29,85	26,35	22,85	21,15	24,65	28,15	31,65	35,15	42,15	45,65
Z1_NACIONAL3	50,85	47,35	43,85	40,35	36,85	33,35	29,85	26,35	22,85	21,15	24,65	28,15	31,65	35,15	42,15	45,65
Z1_NACIONAL4	45,65	42,15	38,65	35,15	31,65	28,15	24,65	21,15	22,85	26,35	29,85	33,35	36,85	40,35	47,35	50,85
Z1_NACIONAL5	45,65	42,15	38,65	35,15	31,65	28,15	24,65	21,15	22,85	26,35	29,85	33,35	36,85	40,35	47,35	50,85
Z1_NACIONAL6	39,75	36,25	32,75	29,25	25,75	22,25	21,75	25,25	28,75	32,25	35,75	39,25	42,75	46,25	53,25	56,75
Z1_NACIONAL7	39,75	36,25	32,75	29,25	25,75	22,25	21,75	25,25	28,75	32,25	35,75	39,25	42,75	46,25	53,25	56,75
Z1_SHUTTLE1	63,55	60,05	56,55	53,05	49,55	46,05	42,55	39,05	35,55	32,05	28,55	25,05	21,55	22,45	29,45	32,95
Z1_SHUTTLE2	57,25	53,75	50,25	46,75	43,25	39,75	36,25	32,75	29,25	25,75	22,25	21,75	25,25	28,75	39,25	42,75
Z2_GERAL1	64,25	60,75	57,25	53,75	50,25	46,75	43,25	39,75	36,25	32,75	29,25	25,75	22,25	18,75	18,75	22,25
Z2_GERAL2	64,25	60,75	57,25	53,75	50,25	46,75	43,25	39,75	36,25	32,75	29,25	25,75	22,25	18,75	18,75	22,25
Z2_GERAL3	75,35	71,85	68,35	64,85	61,35	57,85	54,35	50,85	47,35	43,85	40,35	36,85	33,35	29,85	22,85	21,15
Z2_GERAL4	75,35	71,85	68,35	64,85	61,35	57,85	54,35	50,85	47,35	43,85	40,35	36,85	33,35	29,85	22,85	21,15
Z2_GERAL5	82,05	78,55	75,05	71,55	68,05	64,55	61,05	57,55	54,05	50,55	47,05	43,55	40,05	36,55	29,55	26,05
Z2_SAFRAM	58,55	55,05	51,55	48,05	44,55	41,05	37,55	34,05	30,55	27,05	23,55	20,05	16,55	17,45	24,45	27,95
Z3_DEU_GERAL1	82,05	78,55	75,05	71,55	68,05	64,55	61,05	57,55	54,05	50,55	47,05	43,55	40,05	36,55	29,55	26,05
Z3_DEU_GERAL2	88,25	84,75	81,25	77,75	74,25	70,75	67,25	63,75	60,25	56,75	53,25	49,75	46,25	42,75	35,75	32,25
Z3_OSL	88,25	84,75	81,25	77,75	74,25	70,75	67,25	63,75	60,25	56,75	53,25	49,75	46,25	42,75	35,75	32,25
Z3_SCHMALZ	95,65	92,15	88,65	85,15	81,65	78,15	74,65	71,15	67,65	64,15	60,65	57,15	53,65	50,15	43,15	39,65
Z4_ITA	106,65	103,15	99,65	96,15	92,65	89,15	85,65	82,15	78,65	75,15	71,65	68,15	64,65	61,15	54,15	50,65
Z4_SWE_NOR1	102,35	98,85	95,35	91,85	88,35	84,85	81,35	77,85	74,35	70,85	67,35	63,85	60,35	56,85	49,85	46,35
Z4_SWE_NOR2	102,35	98,85	95,35	91,85	88,35	84,85	81,35	77,85	74,35	70,85	67,35	63,85	60,35	56,85	49,85	46,35
Z5_GERAL	31,95	28,45	24,95	21,45	22,55	26,05	29,55	33,05	36,55	40,05	43,55	47,05	50,55	54,05	61,05	64,55
Z5_PALLETWAYS	31,95	28,45	24,95	21,45	22,55	26,05	29,55	33,05	36,55	40,05	43,55	47,05	50,55	54,05	61,05	64,55
Z5_UNIRECO	22,10	18,60	16,90	20,40	23,90	27,40	30,90	34,40	37,90	41,40	44,90	48,40	51,90	55,40	62,40	65,90
Z6_BENELUX	111,35	107,85	104,35	100,85	97,35	93,85	90,35	86,85	83,35	79,85	76,35	72,85	69,35	65,85	58,85	55,35
Z6_EUROPA_CENTRAL	116,05	112,55	109,05	105,55	102,05	98,55	95,05	91,55	88,05	84,55	81,05	77,55	74,05	70,55	63,55	60,05
Z6_OUTROS_UE	121,85	118,35	114,85	111,35	107,85	104,35	100,85	97,35	93,85	90,35	86,85	83,35	79,85	76,35	69,35	65,85
Z7_AMERICAS_CHE1	132,05	128,55	125,05	121,55	118,05	114,55	111,05	107,55	104,05	100,55	97,05	93,55	90,05	86,55	79,55	76,05
Z7_AMERICAS_CHE2	127,80	124,30	120,80	117,30	113,80	110,30	106,80	103,30	99,80	96,30	92,80	89,30	85,80	82,30	75,30	71,80
Z7_GBR1	121,85	118,35	114,85	111,35	107,85	104,35	100,85	97,35	93,85	90,35	86,85	83,35	79,85	76,35	69,35	65,85
Z7_GBR2	126,55	123,05	119,55	116,05	112,55	109,05	105,55	102,05	98,55	95,05	91,55	88,05	84,55	81,05	74,05	70,55
Z7_RESTO_MUNDO1	133,50	130,00	126,50	123,00	119,50	116,00	112,50	109,00	105,50	102,00	98,50	95,00	91,50	88,00	81,00	77,50
Z7_RESTO_MUNDO2	133,50	130,00	126,50	123,00	119,50	116,00	112,50	109,00	105,50	102,00	98,50	95,00	91,50	88,00	81,00	77,50

Table I.2: Distance matrix (meters) between physical subzones and dock doors – MAI_17 to MAI_30 (Scenario 2)

Subzone	MAI_17	MAI_18	MAI_19	MAI_20	MAI_21	MAI_22	MAI_22A	MAI_23	MAI_24	MAI_25	MAI_26	MAI_26A	MAI_27	MAI_28	MAI_29	MAI_30
Z1_NACIONAL1	46,25	49,75	56,75	60,25	63,75	67,25	70,75	74,25	77,75	81,25	84,75	88,25	91,75	95,25	98,75	102,25
Z1_NACIONAL2	49,15	52,65	59,65	63,15	66,65	70,15	73,65	77,15	80,65	84,15	87,65	91,15	94,65	98,15	101,65	105,15
Z1_NACIONAL3	49,15	52,65	59,65	63,15	66,65	70,15	73,65	77,15	80,65	84,15	87,65	91,15	94,65	98,15	101,65	105,15
Z1_NACIONAL4	54,35	57,85	64,85	68,35	71,85	75,35	78,85	82,35	85,85	89,35	92,85	96,35	99,85	103,35	106,85	110,35
Z1_NACIONAL5	54,35	57,85	64,85	68,35	71,85	75,35	78,85	82,35	85,85	89,35	92,85	96,35	99,85	103,35	106,85	110,35
Z1_NACIONAL6	60,25	63,75	70,75	74,25	77,75	81,25	84,75	88,25	91,75	95,25	98,75	102,25	105,75	109,25	112,75	116,25
Z1_NACIONAL7	60,25	63,75	70,75	74,25	77,75	81,25	84,75	88,25	91,75	95,25	98,75	102,25	105,75	109,25	112,75	116,25
Z1_SHUTTLE1	36,45	39,95	46,95	50,45	53,95	57,45	60,95	64,45	67,95	67,95	71,45	74,95	78,45	81,95	85,45	88,95
Z1_SHUTTLE2	46,25	49,75	56,75	60,25	63,75	67,25	70,75	74,25	77,75	81,25	84,75	88,25	91,75	95,25	98,75	102,25
Z2_GERAL1	25,75	29,25	36,25	39,75	43,25	46,75	50,25	53,75	57,25	60,75	64,25	67,75	71,25	74,75	81,75	85,25
Z2_GERAL2	25,75	29,25	36,25	39,75	43,25	46,75	50,25	53,75	57,25	60,75	64,25	67,75	71,25	74,75	81,75	85,25
Z2_GERAL3	24,65	28,15	35,15	38,65	42,15	45,65	49,15	52,65	56,15	59,65	63,15	66,65	70,15	73,65	77,15	80,65
Z2_GERAL4	24,65	28,15	35,15	38,65	42,15	45,65	49,15	52,65	56,15	59,65	63,15	66,65	70,15	73,65	77,15	80,65
Z2_GERAL5	22,55	21,45	28,45	31,95	35,45	38,95	42,45	45,95	49,45	52,95	56,45	59,95	63,45	66,95	70,45	73,95
Z2_SAFRAM	31,45	34,95	41,95	45,45	48,95	52,45	55,95	59,45	62,95	62,95	66,45	69,95	73,45	76,95	80,45	83,95
Z3_DEU_GERAL1	22,55	21,45	28,45	31,95	35,45	38,95	42,45	45,95	49,45	52,95	56,45	59,95	63,45	66,95	70,45	73,95
Z3_DEU_GERAL2	28,75	25,25	21,75	25,75	29,25	32,75	36,25	39,75	43,25	46,75	50,25	53,75	57,25	60,75	64,25	67,75
Z3_OSL	28,75	25,25	21,75	25,75	29,25	32,75	36,25	39,75	43,25	46,75	50,25	53,75	57,25	60,75	64,25	67,75
Z3_SCHMALZ	36,15	32,65	25,65	24,35	27,85	31,35	34,85	38,35	41,85	45,35	48,85	52,35	55,85	59,35	62,85	66,35
Z4_ITA	47,15	43,65	36,65	33,15	29,65	26,15	22,15	21,35	24,85	28,35	31,85	35,35	38,85	42,35	45,85	49,35
Z4_SWE_NOR1	42,85	39,35	32,35	28,85	25,35	21,85	22,15	25,65	29,15	32,65	36,15	39,65	43,15	46,65	50,15	53,65
Z4_SWE_NOR2	42,85	39,35	32,35	28,85	25,35	21,85	22,15	25,65	29,15	32,65	36,15	39,65	43,15	46,65	50,15	53,65
Z5_GERAL	68,05	71,55	78,55	82,05	85,55	89,05	92,55	96,05	99,55	103,05	106,55	110,05	113,55	117,05	120,55	124,05
Z5_PALLETWAYS	68,05	71,55	78,55	82,05	85,55	89,05	92,55	96,05	99,55	103,05	106,55	110,05	113,55	117,05	120,55	124,05
Z5_UNIRECO	69,40	72,90	79,90	83,40	86,90	90,40	93,90	97,40	100,90	104,40	107,90	111,40	114,90	118,40	121,90	125,40
Z6_BENELUX	51,85	48,35	41,35	37,85	34,35	30,85	27,35	23,85	20,35	23,65	27,15	30,65	34,15	37,65	41,15	44,65
Z6_EUROPA_CENTRAL	56,55	53,05	46,05	41,35	37,85	34,35	30,85	27,35	25,05	21,55	22,45	25,95	29,45	32,95	36,45	39,95
Z6_OUTROS_UE	62,35	58,85	51,85	48,35	44,85	41,35	37,85	34,35	30,85	27,35	23,85	20,35	23,65	27,15	30,65	34,15
Z7_AMERICAS_CHE1	72,55	69,05	62,05	58,55	55,05	51,55	48,05	46,05	42,55	39,05	35,55	32,05	28,55	23,55	20,45	23,95
Z7_AMERICAS_CHE2	68,30	64,80	57,80	54,30	50,80	47,30	43,80	41,80	38,30	34,80	31,30	27,80	24,30	19,30	16,20	19,70
Z7_GBR1	62,35	58,85	51,85	48,35	44,85	41,35	37,85	34,35	30,85	27,35	23,85	20,35	23,65	27,15	30,65	34,15
Z7_GBR2	67,05	63,55	56,55	53,05	49,55	46,05	42,55	39,05	35,55	32,05	28,55	25,05	21,55	22,45	25,95	29,45
Z7_RESTO_MUNDO1	74,00	70,50	63,50	60,00	56,50	53,00	49,50	46,00	42,50	39,00	35,50	32,00	28,50	25,00	21,50	18,00
Z7_RESTO_MUNDO2	74,00	70,50	63,50	60,00	56,50	53,00	49,50	46,00	42,50	39,00	35,50	32,00	28,50	25,00	21,50	18,00

Appendix J

Simulation Model and Scenario Analysis

This appendix provides supporting visual material and detailed documentation for the simulation model and scenario analysis described in Chapters 4 and 5. It is organised into two parts.

Part I — Simulation Model Interface

The first part provides illustrations of the simulation model interface. Figure J.1 presents the 2D floor plan view, while Figure J.2 illustrates the 3D warehouse environment, both showing storage locations, dock doors, and agents under baseline conditions. Figure J.3 details the model logic structure, encompassing the four core process flows (Pallet Inbound, Truck Inbound, Pallet Outbound, and Truck Outbound), alongside the resource pools, functions, events and schedules implemented in *AnyLogic*.

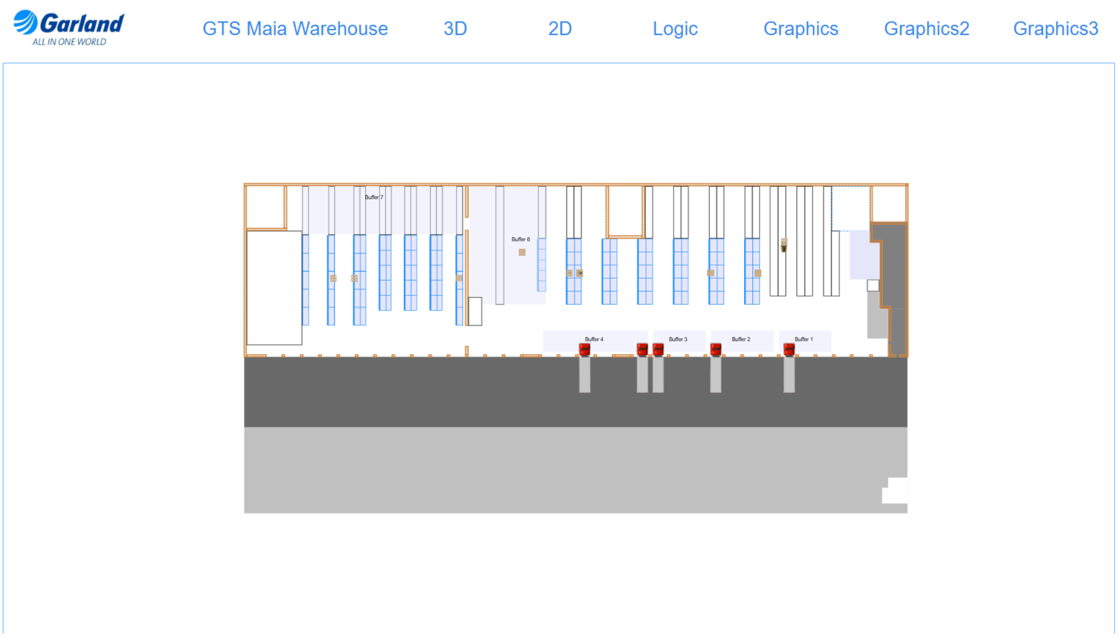

Figure J.1: 2D view of the GTS Maia warehouse simulation model in *AnyLogic*, showing the warehouse storage locations, dock doors, and pallet agents during the baseline simulation run.

Figure J.2: 3D view of the GTS Maia warehouse simulation model in *AnyLogic*, showing the physical layout, racking structures, dock doors, and truck and forklift agents during the baseline simulation run.

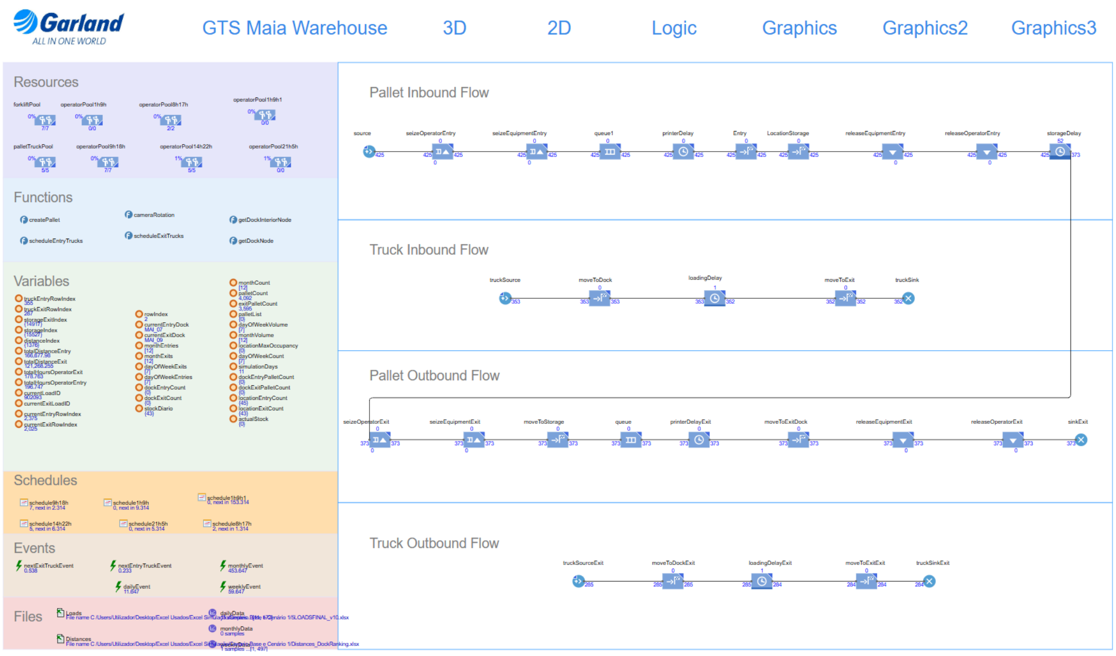

Figure J.3: Logic view of the simulation model in *AnyLogic*, showing the four process flows (Pallet Inbound, Truck Inbound, Pallet Outbound, and Truck Outbound), resource pools, functions, variables, schedules, events, and data files.

Part II — Scenario Ranking Figures

The second part presents the full-size ranking figures for storage locations and dock doors across the three scenarios.

J.1 Baseline Scenario

Figures J.4 and J.5 correspond to the current, unmodified operational configuration described in Section 5.1.1.1, and support the ranking indicators discussed in Section 5.1.1.2. Figure J.4 ranks all 43 storage locations by pallet entry volume and average daily occupancy, reflecting the historical dock-door and storage assignments recorded in *StorageEntry* and *StorageExit*. Figure J.5 presents the equivalent ranking across all 32 dock doors, by both entry and exit pallet volume.

Figure J.4: Baseline scenario: pallet entries and average daily occupancy by storage location

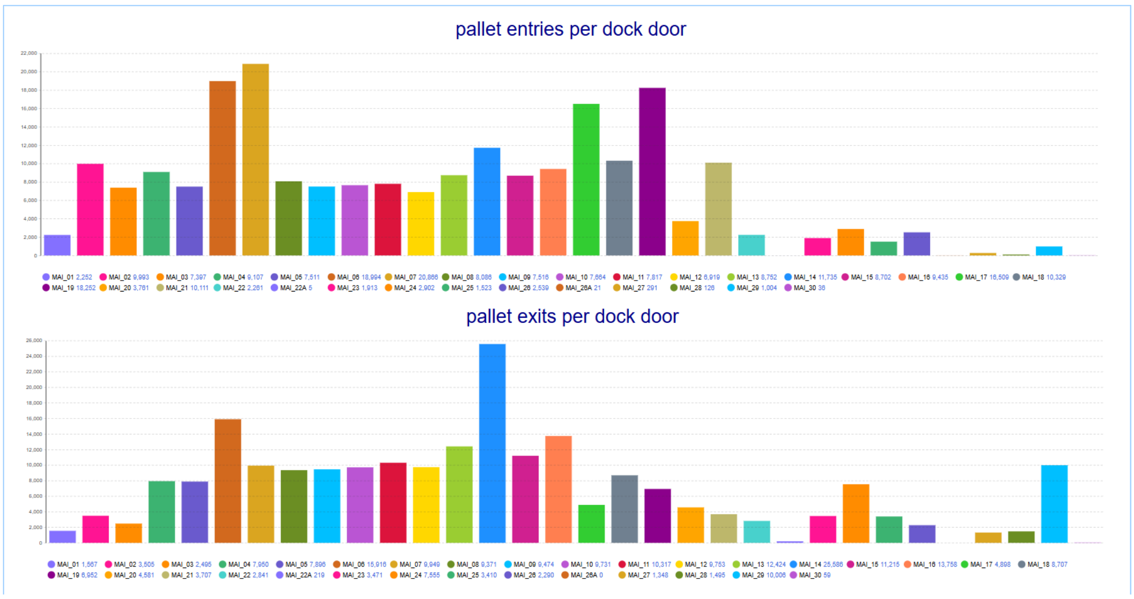

Figure J.5: Baseline scenario: pallet entries and exits per dock door

J.2 Scenario 1

Figures J.6 and J.7 correspond to the dynamic, proximity-based dock assignment policy described in Section 5.1.2.1, and support the ranking indicators discussed in Section 5.1.2.2. Since Scenario 1 leaves the storage layout itself unchanged, Figure J.6 is directly comparable to its baseline counterpart, location by location. Figure J.7, by contrast, reflects the redistribution of traffic across dock doors that results from replacing the historical assignment with the proximity-based policy.

Figure J.6: Scenario 1: pallet entries and average daily occupancy by storage location

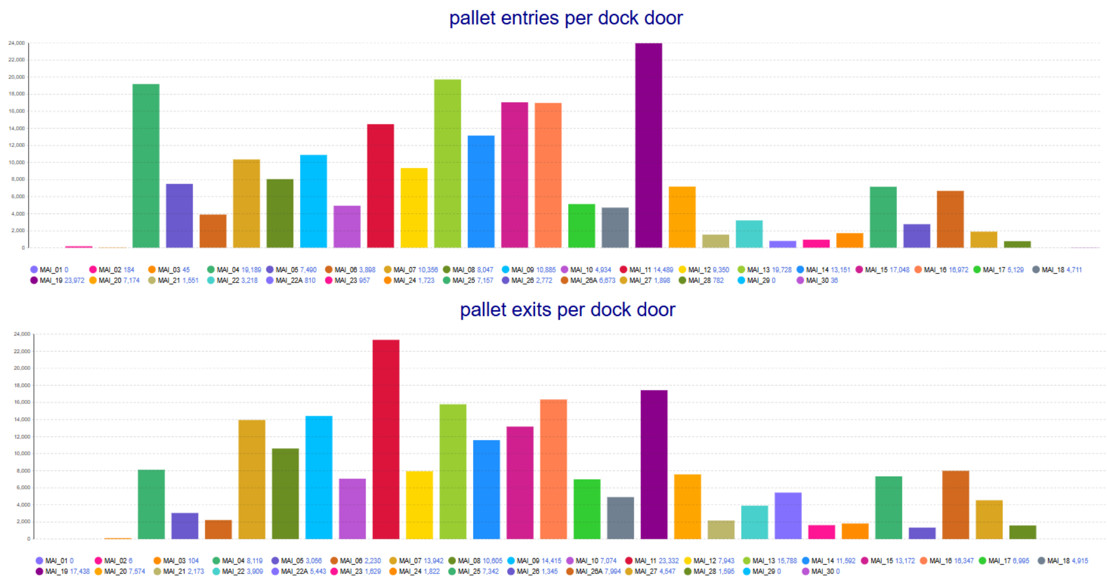

Figure J.7: Scenario 1: pallet entries and exits per dock door

J.3 Scenario 2

Tables J.1, J.2, and J.3 present the three dimensions of historical data used to define the seven destination zones, as described in Section 5.1.3.1: inbound pallet volume by destination country, pallet volume by operational direction, and pallet volume by consolidating agent.

Figures J.8, J.9, and J.10 correspond to the redesigned, zone-based warehouse layout described in Section 5.1.3.1, combined with the same proximity-based dock assignment logic as Scenario 1. Figure J.8 shows the redesigned layout itself, with the seven destination zones, their constituent physical subzones, and the fixed reference points used to compute the distance matrix described in Section 5.1.3.1. Figures J.9 and J.10 present the resulting subzone occupancy and dock door rankings, discussed in Section 5.1.3.2; unlike the baseline and Scenario 1, these are not directly comparable location by location to the current layout, since the physical subzones themselves are new.

Table J.1: Inbound pallet volume by destination country

Destination Country	**Pallets**	**% of Total**
Portugal	109736	48,92%
France	26833	11,96%
Germany	22825	10,17%
Spain	12994	5,79%
Sweden	11270	5,02%
United Kingdom	11080	4,94%
Netherlands	5158	2,30%
United States	4202	1,87%
Italy	3687	1,64%
Poland	2679	1,19%
Czech Republic	2321	1,03%
Belgium	2195	0,98%
Switzerland	1968	0,88%
Ireland	1626	0,72%
Austria	1220	0,54%
Other (52 countries)	4537	2,02%

Table J.2: Pallet volume by operational direction

Direction	**Pallets**	**% of Total**	**Description**
Export	101538	45,26%	Cargo originating in Maia, destined for a foreign country.
Iberian	71063	31,68%	Distribution in Portugal and flows to/from Spain.
Import	51660	23,03%	Cargo originating abroad, with final destination in Portugal.
Foreign	70	0,03%	Residual volume, not classified above.

Table J.3: Pallet volume by consolidating agent

Agent	Associated Line	Pallets	% of Total
Palletways Iberia	Palletways	23092	10,29%
Unireco Logistica	Unireco	15555	6,93%
Online Systemlogistik (OSL)	OSL	11835	5,28%
Mainfreight Forwarding Netherlands	Mainfreight Holland	10809	4,82%
BHS Logistics	First Cargo Sweden	10688	4,76%
Nuova Transports	Nuova Transports	8336	3,72%
Rhenus Logistics Limited	Rhenus UK Cannock/Hinckley	6497	2,90%
ITG GmbH	ITG Munich	5943	2,65%
Mainfreight Forwarding Belgium	Mainfreight Belgium	3814	1,70%
TVS SCS Int. Freight (Spain)	TVS Spain	3595	1,60%
Rhenus Logistics SpA	Rhenus Italy	2663	1,19%
Mainfreight Poland	Mainfreight Poland	2091	0,93%
Schmalz+Schoen Logistics	Schmalz+Schoen	1912	0,85%
Navis Schiffahrts und Speditions	Navis	1793	0,80%
Streck	Streck	1774	0,79%
Other agents (122)	N/A	9491	4,23%
No agent identified	N/A	104443	46,56%

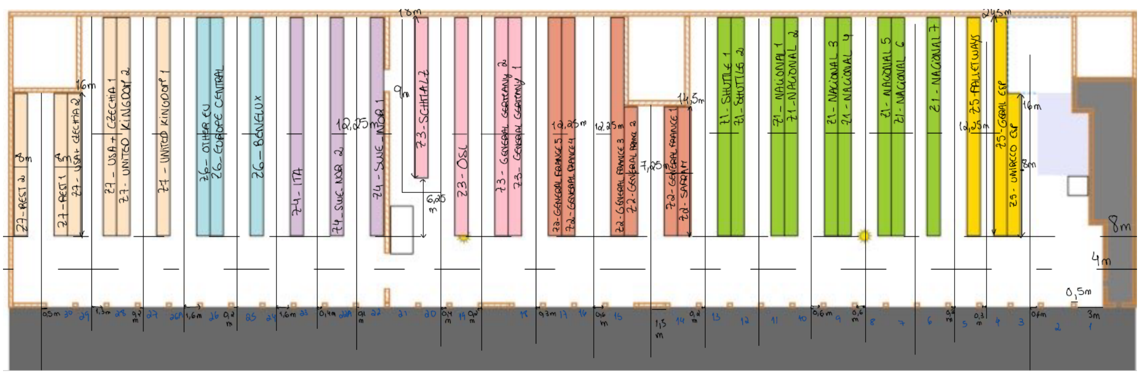

Figure J.8: Redesigned, zone-based warehouse layout for Scenario 2, showing the physical sub-zones and reference points used to compute the distance matrix

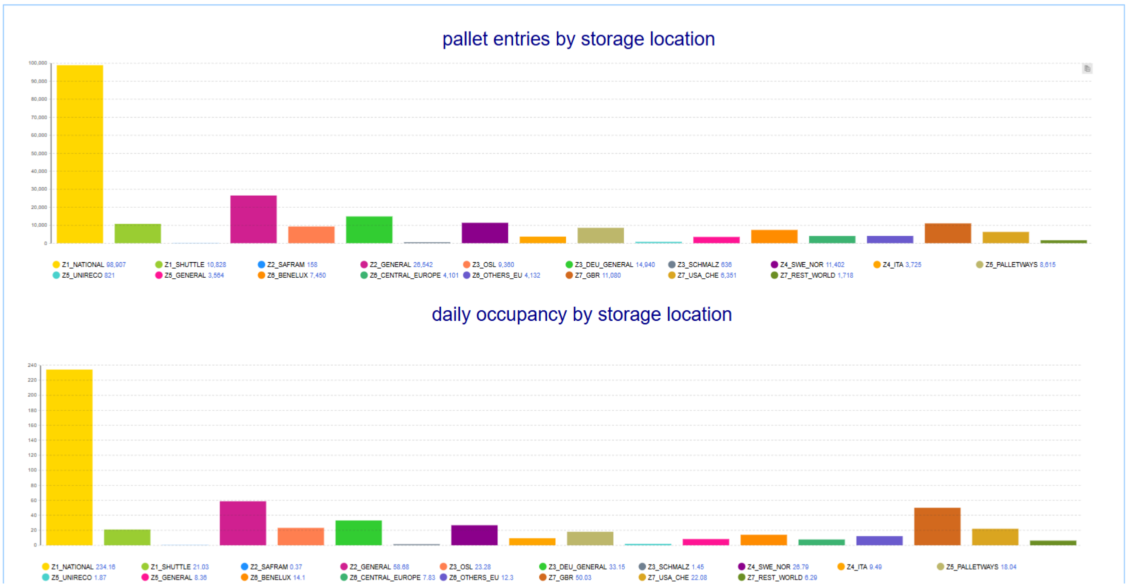

Figure J.9: Scenario 2: pallet entries and average daily occupancy by storage location

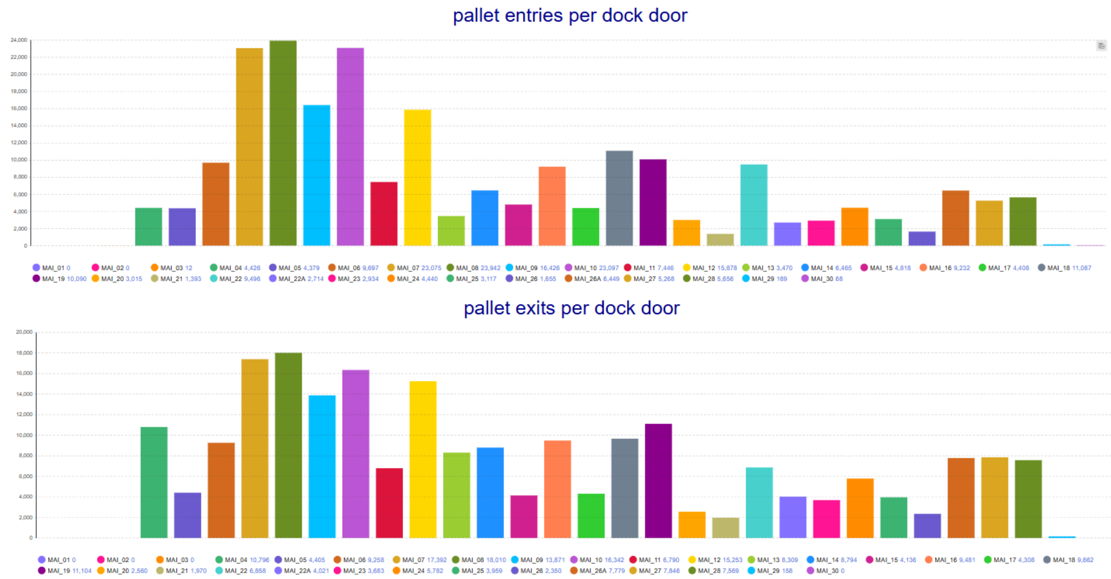

Figure J.10: Scenario 2: pallet entries and exits per dock door

Appendix K

Dock-Door Assignment Prototype Interface

This appendix presents figures of the *Excel*-based dock-door assignment prototype described in Section 5.3, illustrating its main interface, data structures, and supporting reference sheets.

Figure K.1 shows the *Critérios seleção Zonas* sheet, a static reference table generated by *PreencherCriteriosZonas()* documenting, for each of the eighteen logical subzones, the line, agent, destination country, and direction patterns used by *GetSubzona()* to classify a booking.

Subzona	Serviço	Linha	Agente	PaisDestino	Sentido	Critérios de Seleção
Z1_SHUTTLE	Contém SHUTTLE	Contém SHUTTLE				Linha/Serviço contém SHUTTLE (ex: SHUTTLE Maia -> Abóboda)
Z1_NACIONAL	CARRO DÍA Range 0002	DISTRIBUICAO, NACIONAL BROKER, PORTO, LISBOA...		PRT	Ibérico ou Importacao	PaisDestino=PRT e Sentido={Ibérico,Importacao} OU Linhas de distribuição nacional
Z2_SAFRAM		SAFRAM	Contém SAFRAM		Exportacao	Linha=SAFRAM ou Agente contém SAFRAM, Sentido=Exportacao
Z2_GERAL		FRANCA GERAL, FRACHT FRANCE...		FRA	Exportacao	Linha contém FRANCA/FRANCE/FRACHT ou PaisDestino=FRA, Sentido=Exportacao
Z3_OSL		OSL	ONLINE SYSTEMLOGISTIK		Exportacao	Linha=OSL e Agente=ONLINE SYSTEMLOGISTIK, Sentido=Exportacao
Z3_DEU_GERAL		ALEMANHA GERAL, ALEMANHA BROKER, ITG MUNICH			Exportacao	Linha contém ALEMANHA ou =ITG MUNICH, Sentido=Exportacao
Z3_SCHMALZ		SCHMALZ+SCHOEN	Contém SCHMALZ ou SCHOEN		Exportacao	Linha/Agente contém SCHMALZ ou SCHOEN, Sentido=Exportacao
Z4_SWE_NOR		FIRST CARGO-SWEDEN	Contém FIRST CARGO	SWE, NOR		Linha/Agente=FIRST CARGO e PaisDestino={SWE,NOR}
Z4_ITA		ITALIA GERAL, NUOVA TRANSPORTS, RHENUS ITALY	Contém NUOVA	ITA, GRC, MLT		Linha contém ITALIA/NUOVA/RHENUS ITALY ou Agente contém NUOVA, PaisDestino={ITA,GRC,MLT}
Z5_PALLETWAYS		PALLETWAYS		ESP	Ibérico	Linha=PALLETWAYS e PaisDestino=ESP
Z5_UNIRECO		UNIRECO, TVS SPAIN, FVA	Contém UNIRECO	ESP	Ibérico	Linha={UNIRECO,TVS SPAIN,FVA} ou Agente contém UNIRECO, PaisDestino=ESP
Z5_GERAL		ESPANHA GERAL, GTS SPAIN, BILBAO...		ESP	Ibérico	PaisDestino=ESP não enquadrado em Z5_PALLETWAYS ou Z5_UNIRECO
Z6_BENELUX		MAINFREIGHT HOLLAND, MAINFREIGHT BELGIUM...	Contém MAINFREIGHT	NLD, BEL, LUX		Linha Mainfreight NL/BE ou Holanda/Bélgica Geral e PaisDestino={NLD,BEL,LUX}
Z6_EUROPA_CENTRAL		MAINFREIGHT POLAND, POLONIA GERAL, REP. CHECA...	Contém MAINFREIGHT POLAND	POL, CZE, SVK, HUN		Linha Mainfreight Poland ou Polónia/Rep.Checa/Eslováquia/Hungria, PaisDestino={POL,CZE,SVK,HUN}
Z6_OUTROS_UE		ALLMED, NAVIS, NTG ROAD, AUSTRIA GERAL	Contém ALLMED ou NAVIS	IRL, AUT		Linha/Agente={ALLMED,NAVIS,NTG ROAD,AUSTRIA} e PaisDestino={IRL,AUT}
Z7_GBR		UK GERAL, UK BROKER, NEXT, RHENUS UK-*	Contém RHENUS UK	GBR		Linha={UK GERAL,UK BROKER,NEXT,RHENUS UK-*} ou Agente contém RHENUS UK, PaisDestino=GBR
Z7_AMERICAS_CHE		NORTH AMERICA, SOUTH AMERICA, SUICA GERAL...	Contém STRECK	USA, CAN, MEX, CHE...		Linha Américas/Suíça ou Agente=STRECK, PaisDestino={USA,CAN,MEX,CHE,...}
Z7_RESTO_MUNDO		ASIA + OCEANIA, TURQUIA GERAL, SERTRANS...		CHN, JPN, TUR, MAR...		Linha Ásia/África/Oceania ou PaisDestino não enquadrado nas zonas anteriores

Figure K.1: Subzone selection criteria reference sheet (*Critérios seleção Zonas*)

Figure K.2 shows an excerpt of the *Distâncias* sheet, listing the recorded travel distance between each physical subzone and each dock door, the source table consumed by *BuildDistDict()* (Section 5.3.3).

	Subzona	Zona	Dock_Door	Distance
2	Z1_SHUTTLE1	Z1	MAI_01	63,55
3	Z1_SHUTTLE1	Z1	MAI_02	60,05
4	Z1_SHUTTLE1	Z1	MAI_03	56,55
5	Z1_SHUTTLE1	Z1	MAI_04	53,05
6	Z1_SHUTTLE1	Z1	MAI_05	49,55
7	Z1_SHUTTLE1	Z1	MAI_06	46,05
8	Z1_SHUTTLE1	Z1	MAI_07	42,55
9	Z1_SHUTTLE1	Z1	MAI_08	39,05
10	Z1_SHUTTLE1	Z1	MAI_09	35,55
11	Z1_SHUTTLE1	Z1	MAI_10	32,05
12	Z1_SHUTTLE1	Z1	MAI_11	28,55
13	Z1_SHUTTLE1	Z1	MAI_12	25,05
14	Z1_SHUTTLE1	Z1	MAI_13	21,55
15	Z1_SHUTTLE1	Z1	MAI_14	22,45
16	Z1_SHUTTLE1	Z1	MAI_15	29,45
17	Z1_SHUTTLE1	Z1	MAI_16	32,95
18	Z1_SHUTTLE1	Z1	MAI_17	36,45
19	Z1_SHUTTLE1	Z1	MAI_18	39,95
20	Z1_SHUTTLE1	Z1	MAI_19	46,95
21	Z1_SHUTTLE1	Z1	MAI_20	50,45
22	Z1_SHUTTLE1	Z1	MAI_21	53,95
23	Z1_SHUTTLE1	Z1	MAI_22	57,45
24	Z1_SHUTTLE1	Z1	MAI_22A	60,95
25	Z1_SHUTTLE1	Z1	MAI_23	64,45
26	Z1_SHUTTLE1	Z1	MAI_24	67,95
27	Z1_SHUTTLE1	Z1	MAI_25	67,95
28	Z1_SHUTTLE1	Z1	MAI_26	71,45
29	Z1_SHUTTLE1	Z1	MAI_26A	74,95
30	Z1_SHUTTLE1	Z1	MAI_27	78,45
31	Z1_SHUTTLE1	Z1	MAI_28	81,95
32	Z1_SHUTTLE1	Z1	MAI_29	85,45
33	Z1_SHUTTLE1	Z1	MAI_30	88,95
34	Z1_SHUTTLE2	Z1	MAI_01	57,25
35	Z1_SHUTTLE2	Z1	MAI_02	53,75
36	Z1_SHUTTLE2	Z1	MAI_03	50,25
37	Z1_SHUTTLE2	Z1	MAI_04	46,75
38	Z1_SHUTTLE2	Z1	MAI_05	43,25

Plano do Dia | Ocupação de Portas | Dados | Critérios seleção Zonas | Distâncias

Figure K.2: Excerpt of the physical subzone to dock-door distance sheet (*Distâncias*)

Figure K.3 shows the *Dados* sheet produced by *ImportarDados()*, consolidating the raw *Loads/Legs/Bookings* records for both directions into a single working table, including the classified storage subzone and the direction flag (Entrada/Saída) for each record.

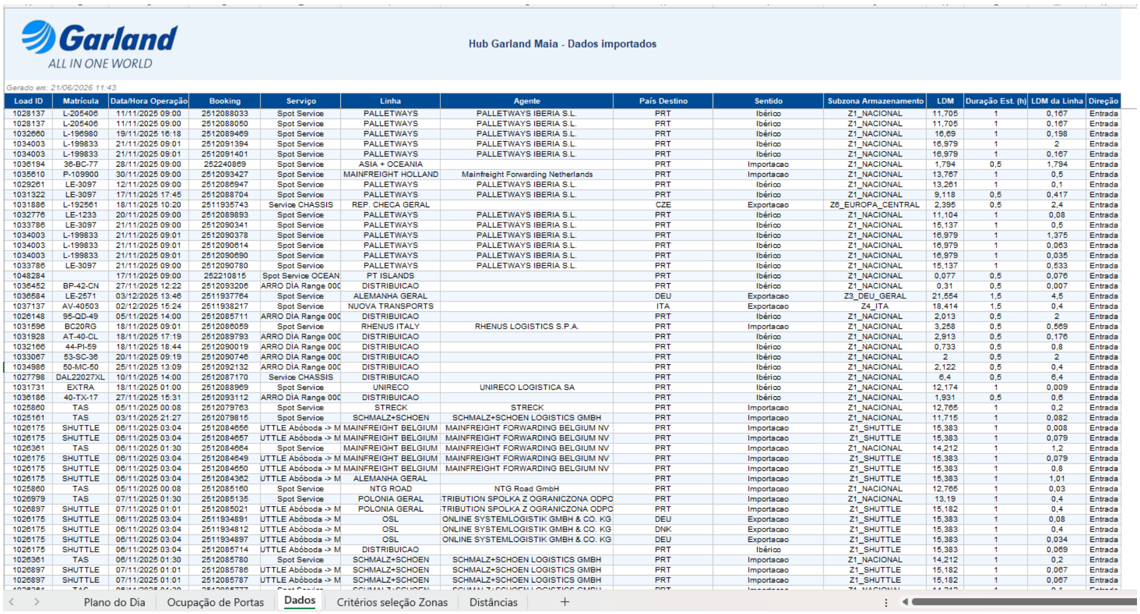

Figure K.3: Imported and consolidated data sheet (*Dados*), including the classified storage sub-zone for each record

Figure K.4 shows the date-selection form displayed when running *GerarPlanoPonderado()*, allowing the user to choose, among the dates available in the imported data, the day for which the dock-door plan should be generated.

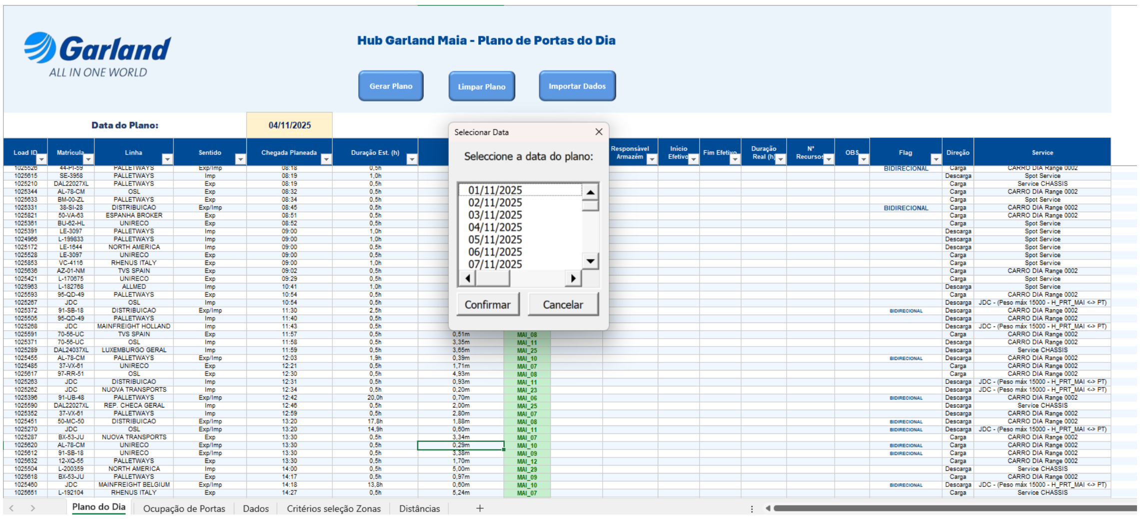

Figure K.4: Date selection form (*frmSelecionarData*) used to choose the day for which the plan is generated

Figure K.5 shows the *Plano do Dia* sheet after running *GerarPlanoPonderado()* for 04/11/2025, listing each load's matricula, line, planned arrival, estimated duration, LDM, suggested dock door, bidirectional flag, direction, and service.

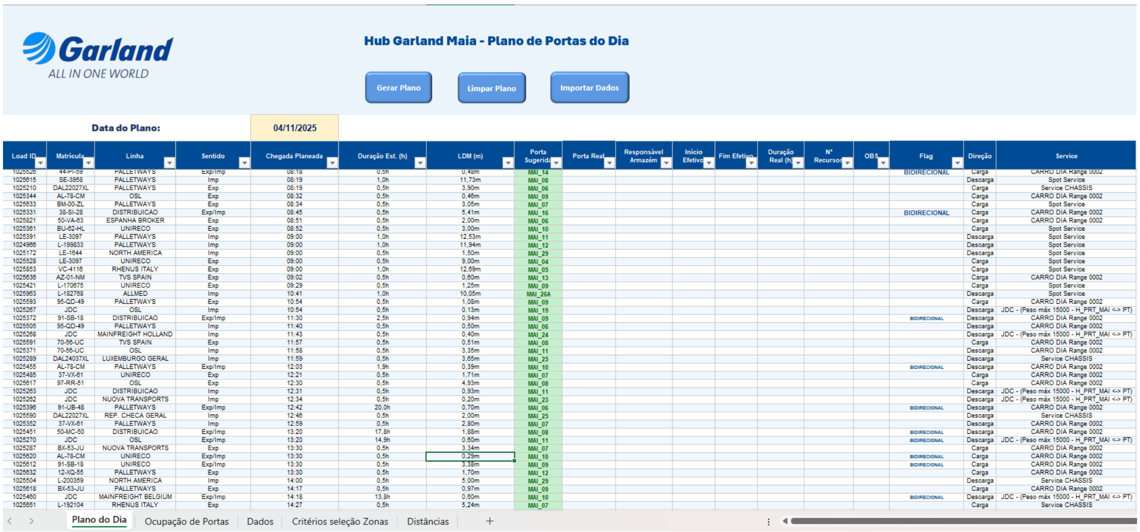

Figure K.5: Daily plan sheet (*Plano do Dia*) after generating the dock-door assignment for a selected day

Figure K.6 shows the *Ocupação de Portas* sheet generated by *AtualizarGrelhaOcupacao()*, displaying the 24-hour occupancy grid for every dock door on a selected day, in 30-minute increments.

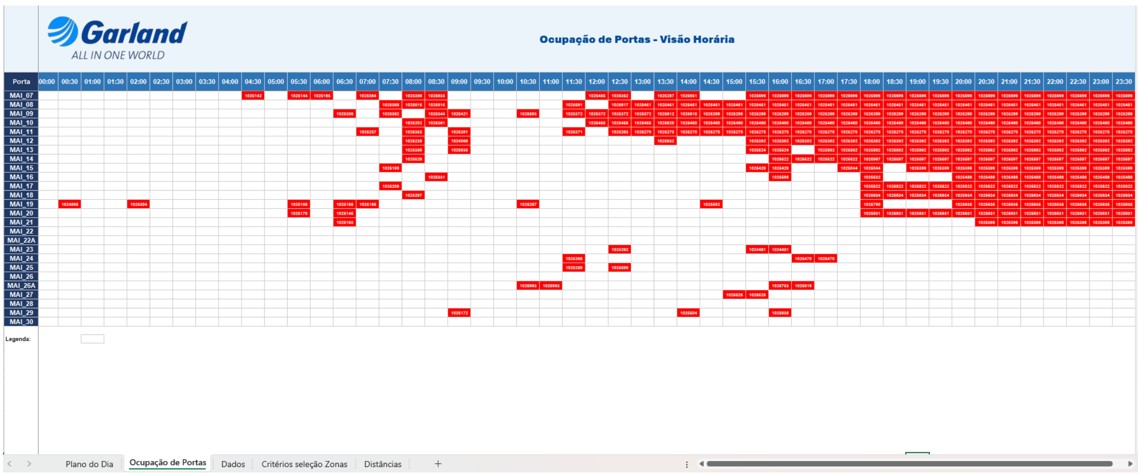

Figure K.6: 24-hour dock-door occupancy grid (*Ocupação de Portas*), generated for a selected day

Figure K.7 shows the confirmation prompt displayed by *BotaoLimparPlano()* before clearing the daily plan, preventing accidental data loss.

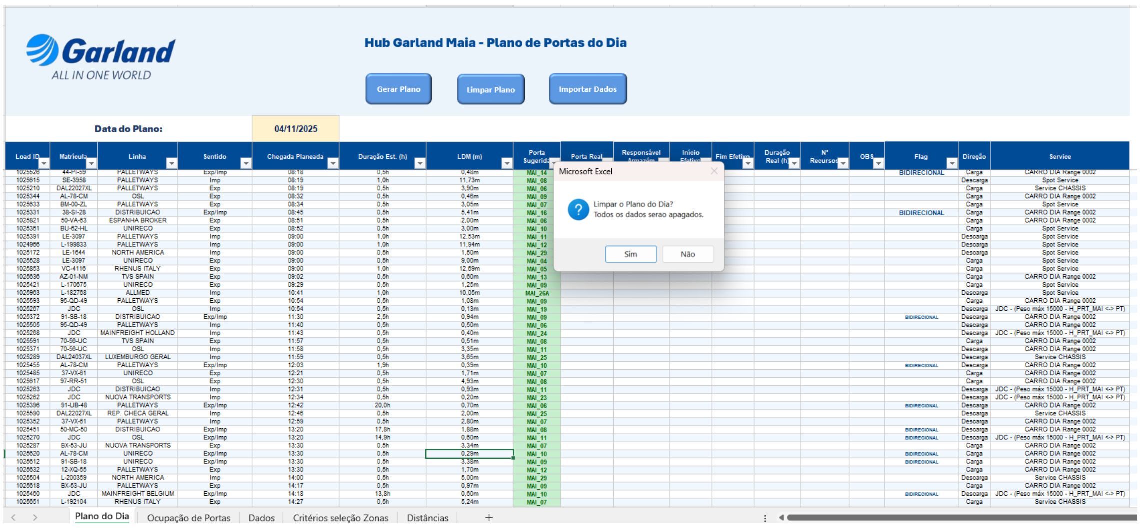

Figure K.7: Confirmation dialog displayed before clearing the daily plan sheet