Adaptive layout and stacking strategies for improving an empty container depot

MSc. Thesis

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Adaptive layout and stacking strategies for improving an empty container depot

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Cover: Empty Container Depot MedRepair Smirnoffweg (Credits: MedRepair Rotterdam)

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TU Delft

Preface

What a journey it has been. That was the first thing that came to my mind. It was not always easy, especially when dealing with setbacks at the beginning of my studies. But eventually something changed. This journey has taken me to many beautiful places, introduced me to inspiring people, and led me through enriching internships and experiences. Looking back, would I have done things differently if I had the opportunity? Maybe yes, maybe no.

What lies before you is my master thesis, part of the Master's program in Transport, Infrastructure and Logistics at the TU Delft, conducted in collaboration with MSC Netherlands and MedRepair. For those interested in empty container logistics and its dynamic developments, this report might be of interest to you. I already wish you a pleasant and insightful reading experience!

First, I want to thank all the people who supported me throughout this project. A special thanks goes to Stefano Fazi and Edwin van Hassel for their guidance as supervisors, which helped shape the outcomes of this research. Your feedback allowed me to reflect on my work in a meaningful way, opening up discussions that elevated the project to a higher level. I really appreciated your support and enjoyed working on this project with you.

I am also very grateful to my daily supervisor Piero de Peverelli Luschi, who provided me with all the relevant information to make a solid start in this research area. Our conversations during (lunch) meetings were incredibly valuable. They opened up discussions that led to new ideas and a deeper understanding of the topic. All those "broodjes", as you called them, were the perfect fuel for a good dialogue. I believe those moments helped me better understand the complexity of the research.

Adding to this, there are many more people that I would like to thank. In no particular order, Casper and Giuseppe, thank you both for your support during the initial phases and for your sharp questions that helped strengthen the research. Renee and Daniel, thank you for the tours at Smirnoffweg, the laughs and for answering all my detailed questions during our online calls.

Finally, a big thank you to my parents, brothers, close friends and study friends. You kept believing in me, supported me often, and were always there to discuss many topics that I encountered over the years. You pushed me to reach a level that at the beginning felt out of reach and I deeply appreciate that. For those not mentioned by name, you are not forgotten. You crossed my mind, and I thank you for being part of this journey.

Olivier J.M. Klein Schiphorst
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Summary

Despite their critical role in maintaining container availability, Empty Container Depot (ECD) operations remain underexplored in academic research, specifically when focused on layout design and stacking strategies. This research presents a comprehensive simulation framework that helps to improve ECD operations and understanding of system dynamics. By applying the approach to a real-world case, the MedRepair Smirnoffweg depot, this study not only contributes to this academic understanding of ECD operations, but also supports informed decision-making for improving depot efficiency. By developing a generic model and applying the theories discussed, this research provide valuable support for planning both existing and new depot facilities with similar operational characteristics and challenges.

The simulation framework created throughout the research serves as a practical guideline for researchers aiming to identify operational inefficiencies, test different operational, tactical and strategic scenarios, and focus on improving facilities. Structured into five distinct phases the framework enables a comprehensive analysis of ECD systems. Phase 1 reveals that while principles from related logistical domains offers insights, they are not sufficiently tailored to the unique complexities of ECDs. Therefore, expert consultation is essential to gain operational understanding. In the first two phases, literature and expert inputs are combined to conduct a layered system and data analysis, using the IDEF0 method to map subsystem interactions and identify bottlenecks. These analyses clarify real-world depot procedures and form the foundation for the conceptual modelling.

Phase 3 translates this understanding into a flexible simulation model capable of adapting to various layout configurations, stacking strategies and operational policies. The model supports analysis of internal movement dynamics, such as congestion and flow disruptions, and enables comparative evaluation of layout alternatives using defined KPIs like throughput, subsystem occupation rates and ECH usage. Evaluating the selected KPIs together is essential to fully understand system dynamics and model outcomes. This integrated perspective forms the basis for evaluating and refining configurations in the following phases.

In the final phases 4 and 5, nine different settings are tested across four scenarios to explore performance improvements. The results show that iterative scenario testing can overcome bottlenecks, improve ECH usage and maintain or improve system throughput. These improvements are achieved through targeted changes in the layout and operational settings. A key insight is that internal container movements account for only a small portion of total dwell time, making their impact on throughput less direct. Instead, throughput is more influenced by bottleneck occurrence and subsystem process durations. Adding to these findings, settings with similar bottleneck dynamics can still differ in ECH usage due to variations in driving distances between subsystems, although these differences are relatively small due to consistent container flows. These findings confirm that bottleneck prevention is a key driver of throughput improvement and that even subtle layout adjustments can influence equipment efficiency. Together, this framework provides a structured and insightful approach to understanding and improving ECD operations, directly addressing the research goal of simulation-driven layout design.

As shown, adaptive layout configurations and stacking strategies help depots respond better to seasonal demand fluctuations and varying truck interarrival patterns. By testing different designs in realistic scenarios, improvements can be made in equipment use, driving distances and bottleneck control within the system. Shipping companies that own their own depots are advised to apply the framework to proactively manage layout transitions and stacking strategies in alignment with forecasted flows. This enables more resilient operations and improves the coordination between logistics agents and depot personnel.

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Nomenclature

Abbreviations

Abbreviation	Definition
ARC	Activity Relationship Chart
BI	Business Intelligence
DES	Discrete-Event Simulation
ECD	Empty Container Depot
ECDF	Empirical Cumulative Distribution Function
ECH	Empty Container Handler
EPTI	Electronic Pre-Trip Inspection
FEU	Forty-foot Equivalent Unit
FLP	Facility Layout Planning
IPO	Input, Process and Output
KPI	Key Performance Indicator
K-S	Kolmogorov-Smirnov
MLE	Maximum Likelihood Estimator
MR	Machinery Repair
M&R	Maintenance & repair
PEM	Pairwise Exchange Method
PDF	Probability Density Function
PTI	Pre-Trip Inspection
SLP	Systematic Layout Planning
SSAM	Storage Space Allocation Problem
TEU	Twenty-foot Equivalent Unit
UNCTAD	United Nations Conference on Trade And Development
VV&T	Validation, Verification and Testing

1 Introduction

Container transport is expected to grow in the years to come. This is confirmed by the United Nations Conference on Trade and Development (UNCTAD), projecting an average annual increase of 2.7% between 2025 and 2029 [1]. This growth is driven by the recovery of global trade, technological progress and infrastructure developments. This development has direct implications for the infrastructure and operational processes within maritime and hinterland logistics. This expected growth will particularly put pressure on existing resources, like container terminals, yards and depots.

To maintain operational efficiency under these conditions, strategies are needed to manage future container flows effectively. These strategies must not only consider the handling of full containers, but also the handling of empty containers, because they account for a significant share of the total container movements. Especially in Europe this share is high, due to higher import volumes compared to export volumes. The extra-EU export trade that happened via sea is almost half of the total amount of goods transported between EU and other continents, from an import perspective this share is even larger than 50% of the total imported amount value of goods [2].

For shipping lines, tailored empty container management is essential in keeping operational costs under control. This is about both the strategic repositioning of empty containers across terminals and the handling of containers that arrive at depots for storage and maintenance & repair (M&R) activities. Empty container depots play a vital role in the logistic chain as they are responsible for inspecting, maintaining and if necessary repairing containers before they are redeployed. The expected increase in container volume implies that depots will face a significant rise in the number of container units processed as well. Factors such as yard configuration, spatial organisation of stacking areas and container stacking strategies are becoming more important in overall facility performance. Given the diversity of container types, conditions and handling requirements, this calls for an integrated and flexible approach. It is therefore important for shipping companies that operate their own depots to consider how these processes can be improved in order to support more efficient and scalable container handling.

While container terminals and repositioning of empty containers has received considerable attention in existing research, the depot side of operations has received comparatively less focus. The depot context introduces a different type of operational complexity. Due to their limited space, depots depend heavily on efficient operational processes. Depot operations have to deal with different seasonal supply and demand situations and strategic decisions related to movements of empty containers within the supply chain network itself [3]. In this context there is a need to reconsider depot layout and internal logistics to manage future operational needs. Studies that researched this topic are the papers by: *Hidalgo et al. (2017) [4]*, *Pascual and Smith (2020) [5]* and *Karakaya et al. (2023) [6]*. While Hidalgo et al. explore fixed layout and policy scenarios at an operational level, and Karakaya et al. focus on layout design for top-lifter operated yards, this research shifts the focus to tactical-level layout and stacking strategies for different container types and conditions.

1.1. Current depot operations

In the world of container transport, an Empty Container Depot (ECD) acts as an important facility where containers are temporarily stored, maintained and/or repaired if needed. In this research a fully MSC-operated depot will be analysed for understanding depot systems. MedRepair Smirnoffweg (Rotterdam) is managed entirely in-house (except from M&R activities which are partially carried out by another company on site, regulated by MSC). The main challenge for a depot lies in maintaining smooth internal flows and sufficient throughput to meet export-driven demand. In other words, the depot must ensure that the right container is available at the right time. Current operations are focused on the arrival, storage and release of containers. As well as, organising maintenance and repair activities.

A yard area is usually structured into storage blocks with corresponding Twenty-foot Equivalent Unit (TEU) ground slots, separated by driving lanes that allow equipment to move between blocks. Within each storage block, specific actions can be performed on containers. The first step when a container enters the depot is the qualification of that container in the inspection area. Depending on the container's characteristics and condition, the container is allocated a sequence of required actions that must be executed before the container gates out. Per container a specific operational path must be followed. A simplified version of path configurations is provided in Figure 1.1 and Figure 1.2 for both dry containers and refrigerated containers (reefers), which require specialised handling.

The performance of depot operations is closely related to the spatial requirements and the utilisation of the depot. When the depot is operating close to its capacity, operations become less efficient. To mitigate these effects, it is crucial to operate based on well-designed strategies that help maintain reliable and efficient performance. Based on literature, the most common layouts for terminals and depots are parallel and perpendicular configurations, where storage blocks are aligned along or across from the gate [6]. Based on the use of top-lifters as the primary handling equipment, the parallel layout is most suitable for ECDs. These vehicles can only access containers from the front row, making narrower blocks and more driving lanes effective for reducing travel distances and reshuffling. However, this comes at the cost of storage density and requires careful spatial planning.

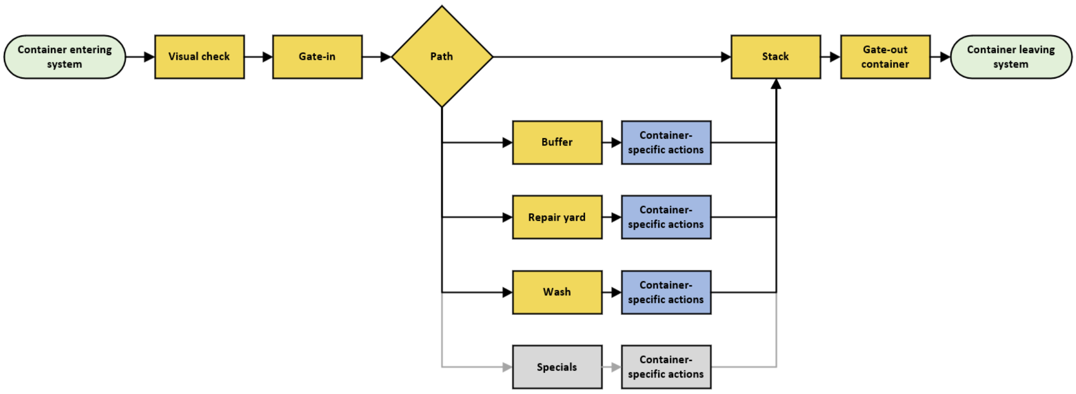


Figure 1.1: Simplified flowchart of container flow inside the depot of MedRepair Smirnoffweg

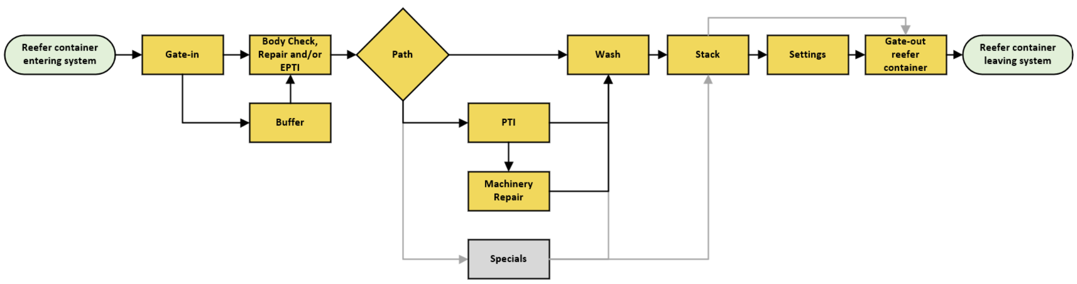


Figure 1.2: Simplified flowchart of reefer container flow inside the depot of MedRepair Smirnoffweg

1.2. Research problem

Land is becoming increasingly scarce and expensive, while MSC's container volumes is projected to increase in the years to come. The combination of these two opposite dynamics poses a serious challenge and increased pressure on depot and terminal operations. While stacking and grouping containers based on their gate-out requirements is a common approach, this strategy proves difficult for empty containers due to the wide range and variability of activities inside the depot. The layout of the depot must therefore accommodate all the different services efficiently, making sure high yard utilisation without over-fragmenting the space, which will eventually lead to operational inefficiencies. At the same time, recent global disruptions such as the COVID-19 pandemic and the Red Sea crisis have shown that depots must also support flexibility when market conditions change. Depending on the situation, carriers may choose to absorb flows using extra storage capacity or evacuate container more rapidly by adjusting routing and scheduling. In both cases, ECDs play a critical role. This raises the question of how operational efficiency can be improved under high capacity utilisation, while still allowing the depot to adapt to changing market conditions with sufficient flexibility.

1.3. Research objective

The goal of this research is to improve operational processes within an ECD facility that only handles empty containers. Figure 1.3 shows the high-over process of general depot operations for a single facility. The research will primarily focus on the implementation of different tactical strategies, under different operational conditions.

Based upon historical data of MedRepair Smirnoffweg, different realistic operational scenarios will be constructed, researched and simulated using a model. The model should simulate different yard layouts and stacking strategies for a depot which is restricted to spatial constraints. From a layout perspective, layout configurations should be adaptive, meaning that storage blocks could change shape and size or even locations within the depot to best fit the specific needs of each operational scenario. This adaptiveness support operational flexibility, accounts for infrastructural constraints and enables the depot to respond effectively to shifts in container flows and regional repositioning needs. Adaptations to the model should be easily made to simulate different yard sizes and operational conditions. Well-known simulation concepts should be used to validate the results, along with insights from the container industry and related fields. To measure the efficiency of different layout and stacking strategies under varying operational scenarios, several performance indicators will be used. Indicators that will be used are, container throughput, driving distance per Empty Container Handler (ECH) and occupation rates. These indicators form the basis of the evaluation framework.

Figure 1.3 presents a graphical overview of the operational activities of a general ECD, with an indication of the proposed research contribution. The research focuses on improving depot layouts and strategies by using a model to identify improved configurations tailored to specific operational needs. These contributions are highlighted in the blue/grey box, and they highlight where the research adds value to current depot operations.

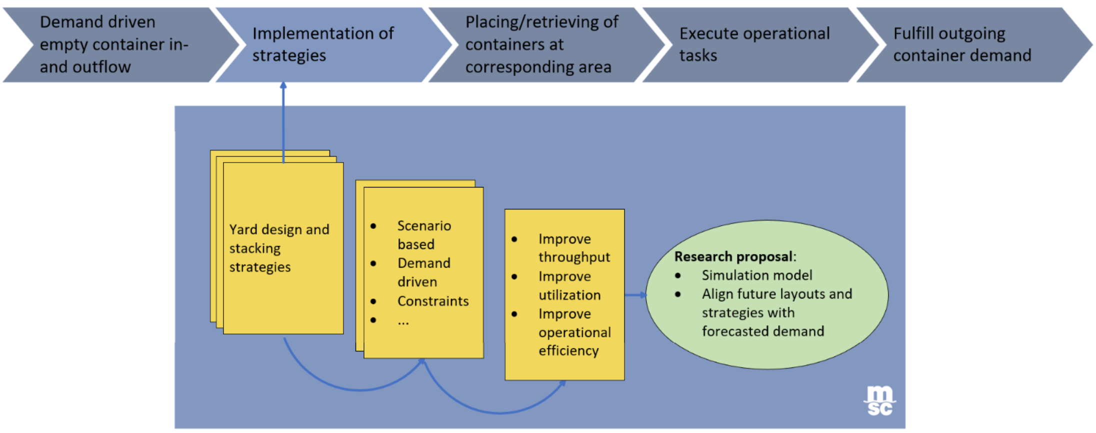


Figure 1.3: Graphical representation of empty container depot operations, unfolding research topic

1.4. Research questions

According to the previous introduction, the research will address the following question:

"How can adaptive layout configurations and stacking strategies contribute to the improvement of operations within an empty container depot, considering global/regional logistics strategies, demand requirements and infrastructural constraints?"

Data collection and scenario-based simulation will provide valuable insights into depot operations. These insights can support tactical decision-making to improve operational performance. Several sub-questions have been formulated to guide the research.

Sub-questions:

1. What insights into empty container depot operations can be drawn from literature and real-world operational practices?
2. How does existing knowledge on layout and stacking strategies apply to empty container depots, and in what ways do empty container flows differ from full container flows?
3. What are the main operational challenges and capacity limitations in current empty container depot processes?
4. What trends in historical data and expert insights support future operational planning for depot operations?
5. Which operational scenarios should be modelled to evaluate the impact of layout and stacking strategies under varying depot conditions, including logistics strategies, demand requirements and infrastructural constraints?
6. Which modelling technique can be used to effectively evaluate the impact of different layout and stacking strategies on depot performance?
7. What lessons can be drawn regarding the effectiveness of adaptive layout and stacking strategies under different operational scenarios?

1.5. Research deliverables

This research produces three key deliverables. First, a general framework for analysing and improving operations within ECDs, focusing on layout adaptability, process efficiency and scenario-based planning. Second, a simulation model developed as part of the framework, capable of evaluating different layout configurations and stacking strategies under various operational scenarios and different depot environments. Third, the application of the framework and the model in a case study at MedRepair Smirnoffweg (Rotterdam), evaluating different layout configurations and stacking strategies under various operational scenarios in a real-world context. By focusing on these three deliverables, a comprehensive answer to the main research question can be given.

1.6. Research structure

This research has the following structure. In chapter 2, a thorough literature review will be presented on ECD related literature, in relation with different methods used for the analysis of similar systems. Followed by chapter 3, which build on this gap found by introducing a research and simulation framework that is tailored to break down ECD and similar systems. In chapter 4 this framework is applied by analysing system relationships in combination with a data analysis. Followed by chapter 5, which builds on this analysis by implementing these findings into a Discrete-Event Simulation (DES) model tailored to the case study depot. This model then is applied to several constructed scenarios and settings in chapter 6. Finally, chapter 7 states the conclusion and discussion of the research. In this chapter key findings are mentioned, as well as, strategic recommendations for key stakeholders and future research directions.

2 Literature review

The methodology for the review of the literature follows a semi-systematic approach presented by *Snyder (2019)* [7] to identify theoretical frameworks and literature gaps. Furthermore, techniques used in the paper of *Wee & Banister (2016)* [8] are used to extract relevant literature. This section will review (recent) literature on container depot operations, simulation methods, empty container handlings and similar processes in other fields.

Based on the literature, gaps will be identified and discussed. For each section, the corresponding references will be given with associated search terms. For this research, two different search engines are used, Google Scholar (Primarily) and Scopus. Along with knowledge gathered through conducted consultations with experts from the company MSC, in order to retrieve relevant search terms.

Based on different techniques like forward and backward snowballing, within relevant papers, the literature time interval is mainly set to papers published after 2016. Meaningful theories from earlier studies, grounded in the literature, will also be included in this literature review.

2.1. Academic perspectives on ECD operations

The reviewed literature for this section is presented in Table 2.1, where each reference is listed with corresponding search words or search technique. This approach follows the methodology described in the introduction section of this chapter.

Table 2.1: Search terms used for section 2.1

Reference	Section	Search terms	Date
Snyder [7]	2	Write literature review paper	since 2016
Wee and Banister [8]	2	Literature research	since 2016
United Nations Conference on Trade and Development (UNCTAD) [1]	2	Maritime transport review	-
Hidalgo et al. [4]	2.1	Container depot operations	since 2016
Pascual and Smith [5]	2.1	Forward snowballing in [4]	-
Carlo, Vis, and Roodbergen [9]	2.1.1	Backward snowballing in [4]	-
Bierwirth and Meisel [10]	2.1.1	Backward snowballing in [4]	-
Kim, Park, and Jin [11]	2.1.1	Backward snowballing in [4]	-
Kim and Kim [12]	2.1.1	Backward snowballing in [5]	-
Kang et al. [13]	2.1.1	Backward snowballing in [4]	-
Lee and Hsu [14]	2.1.1	Backward snowballing in [4]	-
Park et al. [15]	2.1.1	Backward snowballing in [5]	-
Chen and Lu [16]	2.1.1	Backward snowballing in [5]	-
Wiese, Suhl, and Kliewer [17]	2.1.1	Backward snowballing in [4]	-
Ranau [18]	2.1.1	Backward snowballing in [5]	-
Lee and Kim [19]	2.1.1	Backward snowballing in [5]	-

Reference	Section	Search terms	Date
Kemme [20]	2.1.1	Backward snowballing in [5]	-
Wiese, Suhl, and Kliewer [21]	2.1.1	Backward snowballing in [5]	-
Taner, Kulak, and Koyuncuo□lu [22]	2.1.1	Backward snowballing in [5]	-
Kress, Meiswinkel, and Pesch [23]	2.1.2	Forward snowballing in [12]	-
Dkhil, Yassine, and Chabchoub [24]	2.1.2	Forward snowballing in [12]	-
Majoral, Reyes, and Saurí [25]	2.1.2	Forward snowballing in [12]	-
Yan et al. [26]	2.1.2	Forward snowballing in [12]	-
Mutters [27]	2.1.2	Forward snowballing in [12]	-
Zhou, Wang, and Li [28]	2.1.2	Forward snowballing in [13]	-
Yu et al. [29]	2.1.2	Forward snowballing in [13]	-
Maniezzo, Boschetti, and Gutjahr [30]	2.1.2	Forward snowballing in [13]	-
Oelschlägel and Knust [31]	2.1.2	Forward snowballing in [13]	-
Lehnfeld and Knust [32]	2.1.2	Forward snowballing in [13]	-
Karakaya [33]	2.1.2	Forward snowballing in [14]	-
Karakaya, Vinel, and Smith [34]	2.1.2	Forward snowballing in [11]	-
Ryan Alvita [35]	2.1.2	Forward snowballing in [11]	-
Mili [36]	2.1.2	Forward snowballing in [17]	-
Gharehgozli, Zaerpour, and Koster [37]	2.1.3	container terminal layout	since 2016

According to projections of the UNCTAD, container transport is expected to grow steadily in the coming years, with global trade recovery driving increased volumes [1]. As a result, the whole container supply chain will face increased operational pressure. Despite the attention of the handling of full containers, and repositioning of empty containers between terminals, empty container depot operations are under-explored in academic literature. A case study of an ECD in Valparaiso Chile emphasises this as well [4]. ECDs are responsible for storage, inspection and M&R activities of empty containers, which are of great importance for the operations of shipping lines. These facilities can contribute to an efficient global supply chain and are therefore interesting to investigate further.

2.1.1. Research gaps in empty container depot literature

Although the importance of ECDs in global container logistics is well known, academic research on these facilities remains limited.

Literature on container terminal operations can be grouped into three categories based on the level of decision-making involved: operational, tactical and strategic. This structure is based on the classification given in the paper by *Pascual and Smith (2020)* [5] about their study on ECDs, which offers a structured overview of the distinct decision levels involved in yard operations. The work by *Carlo et al. (2014)* [9] touches on all three of the levels, which gives an overview of port storage yard operations. Within this paper four main topics are discussed: yard design, storage space assignment for containers, routing and dispatching of equipment and the optimisation of container remarshalling. This insights are also mentioned in the paper by *Hidalgo et al. (2017)* [4].

At the operational and tactical level, multiple studies have concentrated on container stacking policies and the Storage Space Allocation Problem (SSAM). Going into more detail, the SSAM included detailed subtopics like pre-marshalling and block relocation problems. This has been explored in studies such as *Kim and Kim [12]*, *Kang et al. [13]*, *Lee and Hsu [14]*, *Bierwirth and Meisel [10] Park et al. [15]* and *Chen and Lu [16]*.

Looking into the strategic level, research is more focused on long term decision-making. Topics are particularly focused on yard layout design and equipment acquisition at port terminals. These topics have been explored in various studies, such as those by *Kim, Park, and Jin [11]*, *Wiese, Suhl, and Kliewer [17]*, *Ranau [18]*, *Lee and Kim [19]*, *Kemme [20]*, *Wiese, Suhl, and Kliewer [21]* and *Taner et al.* [22]. While these studies primarily focus on (full) container terminal operations, this research deviates by examining empty container operations. Full and empty containers require different handling processes and machinery, making operational challenges and layout considerations different.

The lack of focus on ECDs is both mentioned in the paper of *Hidalgo et al. (2017)* [4] and *Pascual and Smith (2020)* [5] , who states that until that moment no quantitative research has been conducted to assess operational policies with ECDs. However, some of the approaches in the reviewed terminal studies may still offer relevant insights, despite not focusing on ECDs. Pre-marshalling and block relocation strategies described by *Lee and Hsu [14]* could be adapted for off-hire container operations, where specific containers need to be retrieved from storage. Yard layout principles from *Kim, Park, and Jin [11]*, including the configuration of storage blocks, aisle width, stack height, and other relevant design parameters, may support more efficient space usage in ECDs. Lastly, strategic grouping of different container types may benefit ECD operations, as presented in *Wiese, Suhl, and Kliewer [17]*, in their study on bundling reefers and dry containers.

However, key differences remain. ECDs rely on different handling equipment, typically lack automation, are not constrained by weight of containers and primarily deal with truck-based in- and outflow. Furthermore, ECD operations often involve simpler processes, with less need for container-specific retrieval and more structured allocation by container type. These characteristics reduce the direct applicability of terminal-based models and highlight the need for research specifically tailored to ECD operations.

2.1.2. Relevant operational and tactical insights from terminal and warehousing literature

Building on the identified gap in quantitative research on ECDs, this section explores contributions (primarily) published after the year 2017. This section will provide an overview of relevant studies that offer insights into closely related logistical challenges.

Operational-level contributions

The research conducted by *Kress et al. (2019)* [23] is focused on operational improvements of container terminals. Key finding of this paper is that the dynamic assignment of straddle carriers to quay cranes, instead of fixed assignment, could improve operational processes. This is closely related to ECD operations, where ECHs are assigned to incoming containers via trucks. Predetermination of ECHs that serve incoming trucks, or forcing a strict sequence for container pickups, would likely limit the depot's efficiency.

Looking more into stacking protocols, the research conducted by *Oelschlägel and Knust (2021)* [31] focus on directly minimising poorly placed containers during the first storage process, in order to minimise later reallocation of containers. The paper by *Lehnfeld and Knust (2014)* [32] also explores the strategic placement of container to minimise later repositioning. This could be applicable for ECD operations when the utilisation of the yard is high, and different container types are bundled in the same stacking area. Making the findings in these two papers relevant for ECD operations.

Tactical-level contributions

From a tactical point of view, relevant insides could be found in related fields. The paper of *Dkhil et al. (2018)* [24] shows that combining location assignment and vehicle scheduling into a single multi-objective optimisation model leads to more efficient operations. Compared to ECD operations, such techniques could be beneficial in better utilising storage space inside the depot. Another paper that focus on available space inside container terminal is the research conducted by *Zhou et al. (2020)* [28], they underline the importance of taking extra space into account for reshuffling container activities. Layouts without reshuffling adjustment possibilities will lead to underperforming operations. These findings are applicable in ECD operations, especially important for situations where the density of the yard is close to maximum capacity. Neglecting buffer space will impact the operational efficiency of the depot.

Another paper of *Majoral et al. (2024)* [25] underlines that stacking strategies contribute to better operational efficiency inside terminals, as poor strategies lead to more unproductive housekeeping moves. In relation to ECD operations, the implementation of a proper stacking strategy could improve operational processes. A research conducted by *Mutters, N. (2019)* [27], also states the importance of stacking strategies. Specifically, the analysis of housekeeping moves inside terminals, including stochasticity in container retrieval times and types. Key findings of this research is that proactive housekeeping could help improve operational efficiency for container terminals. This is also highly applicable on ECD operations where the stochastic arrival and retrieval of different container types influence operational efficiency. The repositioning process is most beneficial when stochasticity is low. Similarly, *Yu et al. (2021)* [29] highlight that under conditions of retrieval uncertainty, flexible yard layout outperform fixed yard layouts within export container terminals. As mentioned earlier, similar uncertainties exist in the arrival and retrieval processes of containers within ECDs. Therefore the findings in this research seem highly applicable to ECD operations, where flexible layouts of the depot could likewise improve operational efficiency.

In a related context, the paper by *Maniezzo et al. (2021)* [30] study pre-marshalling strategies in block-stacking warehouses where the sequence of item retrieval is uncertain. Based upon historical data, a model is proposed that tries to reduce relocations of items by proactively reorganising them. Such an approach could be relevant for ECD operations, especially when depot utilisation is high and limited space requires different container types to be bundled together in stacking areas. That space limitations and adaptive layout strategies are connected is also shown in the research by *Alvita (2020)* [35]. This research underlines the fact that this relationship should be considered earlier in the design phase to optimise the layout and use space efficiently.

Research that is more focused on the deployment of machinery like *Yan et al. (2018)* [26], shows that handling times could be decreased when more machinery is deployed. But at the other end could also increase waiting times and operational costs. It is suggested that the optimisation of machinery should be related to yard layout, which is highly applicable to ECD operations.

2.1.3. Foundational studies for modelling and optimising ECD operations

After carefully reviewing the literature, it becomes clear that research directly focused on ECD operations is still very limited. This section will further elaborate on the key findings from the available literature. Studies that show the strongest connection to this research area are: *Hidalgo et al. (2017) [4]*, *Pascual and Smith (2020) [5]*, *Karakaya (2020) [33]*, *Karakaya et al. (2021) [34]* and *Karakaya et al. (2023) [6]*. A particular attention will be on the paper written by *Hidalgo et al. (2017)* [4], which provides a valuable and closely related methodological starting point for this research. Their simulation-based approach offers a structured way to evaluate operational policies related to ECD operations, using real-world data and statistical analysis that support decision-making.

Many aspects of their research approach are highly relevant and will be applied in this research as well. Think of the use of stochastic inputs, the use of empirical distributions representing how long different processes take based on data, as well as, scenario based testing. However, there are several important differences between their study and the focus of this research.

First, *Hidalgo et al. (2017)* [4] examine a shared depot used by multiple shipping lines, with container storage blocks designated for each individual line. This contrasts with this research, where the focus is on a single-user depot operated by one company. Storage of containers is organised per container type, condition or other specifications. This difference will affect the internal logic of container placement and retrieval, especially in situations where the yard is operating near full capacity and different container types may need to be stored together rather than separately.

Another difference is the evaluation of operational scenarios with respect to layout configurations. *Hidalgo et al. (2017)* [4] focus on a fixed yard layout, rather than investigating how different layouts influence overall performance. Their research is more focused on operational decisions, while this research explores more tactical decisions. Namely, researching how different spatial configurations can contribute to more efficient operations under varying demand levels and yard utilisation scenarios. This aligns with findings by *Gharehgozli et al. (2020)* [37], who underline the importance of innovative layout designs to improve efficiency under land and capacity constraints.

Another important distinction is that *Hidalgo et al. (2017)* [4] had access to a detailed transactional database linked to the depot layout. This research is based on historical data for which the exact configuration of the depot was not always known. However, for the most important container flows at that time the layout was known with sufficient detail to inform the modelling. As a result, this research focuses on comparing different layout and stacking strategies, rather than trying to exactly recreate past operations.

Despite these differences, several methodological components from *Hidalgo et al. (2017)* [4] remain highly relevant. The structure of their simulation experiments and statical evaluation techniques offer valuable insights that could inform the modelling approach in this study. In their conclusion, they state that the underlying methods used in their research are widely applicable. This perspective supports the notion that a simulation framework can offer insights for similar ECD facilities facing similar operational challenges. Moreover, their conclusion highlights the potential to extend their model towards the analysis of different depot layouts. This aligns closely with the core objective of this research, which is primarily focused on evaluating alternative layout configurations.

2.2. Modelling approach for ECD simulation and analysis

The reviewed literature for this section is presented in Table 2.2, where each reference is listed with corresponding search words or search technique. This approach follows the methodology described in the introduction section of this chapter.

Table 2.2: Search terms used for section 2.2

Reference	Section	Search terms	Date
Hidalgo et al. [4]	2.2	Container depot operations	since 2016
Goldsman et al. [38]	2.2	Discrete event simulation	-
Loper et al. [39]	2.2	Backwards in [38]	-
Sargent [40]	2.2.1	Backwards in [38]	-
Whitaker and Whitaker [41]	2.2	Backwards in [38]	-
Register and Register [42]	2.2.1	Backwards in [38]	-
Loper [43]	2.2	Backwards in [38]	-
Gordon and Gordon [44]	2.2.1	Backwards in [38]	-
Lowndes and Berry [45]	2.2.1	Forward in [38]	-
Veeke, Lodewijks, and Ottjes [46]	2.2.2	Delft systems approach	-
Robinson [47]	2.2.3	Conceptual modelling	2007
Robinson [48]	2.2.3	Forward in [47]	-
Robinson [49]	2.2.3	Forward in [48]	-
Drira, Pierreval, and Hajri-Gabouj [50]	2.2.4	Facility layout problem	-
C et al. [51]	2.2.4	Improvement facility layout	2016
Low and Wong [52]	2.2.4	Redesign AND facility layout	2016

To evaluate layout configurations and stacking strategies under varying capacity conditions in ECD, a suitable modelling approach is essential. The operational environment of an ECD is characterised by uncertainty, dynamic interactions between processes and resource constraints. Container flows are subject to considerable variability in arrival times, handling requirements and retrieval patterns, contributing to the overall uncertainty in the system. These conditions make analytical modelling therefore complex and often difficult to apply effectively.

One way to address this complexity is through simulation, with Discrete-Event Simulation (DES) being specifically well suited to such systems. DES models systems in which state changes happen at distinct points in time, triggered by events. Examples of such events could be, truck arrival, inspections or container movements inside the depot. Therefore, DES is well suited for modelling operational systems like logistics and inventory environments. As explained by *Goldsman and Goldsman (2015)* [38] in the book *Modeling and Simulation in the Systems Engineering Life Cycle,* by *Margaret L. Loper (2015)*, inventory systems where products are received, stored, picked and restocked are applicable for DES. ECD operations share many similarities with those inventory systems. This makes it particularly suitable for modelling logistics environments involving queues, resource allocation and stochastic process durations.

2.2.1. Simulation design and evaluation principles

The stochastic nature of container arrivals, condition determination, handling time durations and container retrieval means that simulation inputs must reflect real-world variability. As discussed in *Register (2015)* [42], Monte Carlo analysis provides a technique for exploring this uncertainties by running the simulation multiple times with randomised inputs. This technique helps evaluate the sensitivity of performance indicators such as, average gate-out or overall throughput, across different modelling scenarios.

Besides simulation, analytical methods such as queueing theory can support understanding of system dynamics. Queuing theory provides useful analytical tools to better understand the dynamics of systems with waiting lines and limited service capacity, mentioned in *Lowndess and Berry (2017)* [45] in the book *Introduction to the Use of Queueing Theory and Simulation* by *Berry, Lowndes and Trovati*. System characteristics such as, random arrival, time duration of service processes, rules of FIFO or priority-based handlings are highly relevant to this research. These principles can complement the simulation model and help interpret results.

Another important part is that the model represents actual operations. *Sargent (2015)* [40] provides a framework for verification and validation. In the case of a partially observable system, objective validation using statistical test is recommended. Statistical methods can also be applied on modelling input parameters and their randomness. Different tests help identify suitable probability distributions for variables like container arrival, retrieval, handlings times and many more. This helps in making sure that variability is added to the model what is based on data, and not on assumptions, supporting reliable outcomes.

Based on the methodological elements discussed above, a final important step is to design simulation experiments in a structured way to compare different layouts and stacking strategies. The design of experiments (DoE) method is introduced by *Gordon (2015)* [44] to plan, execute and analyse simulation runs in a systematic way. It builds on earlier concepts such as input variability, performance measurements and statical analysis. This supports the main objective of this research, namely, identifying layout configurations that maintain or improve operational performance under capacity pressure.

2.2.2. Systems thinking

Before exploring the specific components and processes within an ECD, it is critical to first clarify what the definition of a ”system” is. This concept forms the foundation for understanding the depot’s structure and interactions. The following terms and concepts are derived from *The Delft Systems Approach* by *Veeke et al (2008)* [46], and are considered highly relevant for understanding and modelling the operations of an ECD. While they are not quoted directly, these terms reflect the main ideas that define a system and are used throughout the research.

According to *Veeke et al. (2008)* in *The Delft Systems Approach* [46], a system is defined as a set of coherent elements that can be distinguished from the broader reality, referred to as ”universe”. These elements are interconnected and may also interact with other parts of that broader context. This interaction between elements of the universe and the system is called an environment. In the case of an ECD these are all elements related to the gate-in and gate-out of containers passing the boundaries of the ECD system.

Going back to the definition of a system, some elements can be grouped into ”subsystems”, where the original relationships between these elements remain unchanged. In this case, the ECD functions as an environment for the defined subsystems. Adding another layer to this, the elements defined in a subsystem can be grouped into ”entities” and ”resources”. Both are elements of the system, but the difference is that entities move inside the system, between defined subsystems, using resources. Every element has its own characteristics and these characteristics could change over time.

The so called ”state” of a system is the value of characteristics of elements at a certain moment in time. When characteristics of elements change, we speak of an ”event”. Events happen at defined moments in time, a chain of events are called ”activities”. Activities together form a process where input elements are transferred to output element with different characteristics. In the case of ECD operations, activities are related to the defined subsystems, and processes are a sequence of activities occurring in different subsystems. When studying a system over time, the behaviour of a system could be monitored. This will provide valuable insights of the system characteristics and interactions.

2.2.3. Conceptual modelling

Adding to the understanding of the system by analysing its components and relationships, the steps towards a simulation model is to start with a simplified version of the real-world context using conceptual modelling. To support this transition, two different sources provide practical guidance. The first edition of *Conceptual modelling for simulation: Definition and requirements* by *Robinson S. (2008)* [47] describes that a well-defined conceptual model is essential to make sure all stakeholders share a common understanding of the model's structure, scope and purpose. Providing also guidance on which elements to include inside the conceptual model. The second edition builds on this by presenting a framework for developing a conceptual model [48]. Which is supported by a later work of *Robinson S (2016)* [49], which helps defining the appropriate level of abstraction when modelling complex systems with practical examples. These insights help guide the correct development of a conceptual model for complex systems such as ECDs.

2.2.4. Facility layout planning

Building on the conceptual model developed through the systems thinking approach, the current layout of an ECD could be analysed and opportunities for layout improvements could be discovered. While optimisation is not the focus of this research, literature on Facility Layout Problems (FLP) helps guide layout analysis.

A comprehensive survey by *Drira et al. (2007)* [50] represents different types of FLP and presents a tree structure that can be used for narrowing down the scope of the problem. Besides this information, different layout designs are briefly discussed which could be applicable on ECDs, such as an open-field or loop layout. Another paper by *Maina et al (2018)* [51] applies Muther's Systematic Layout Planning (SLP) method to improve layouts based on activity relationships and flow analysis. Translating this to different path configurations for containers inside an ECD, an activity relationship chart could help defining new layouts. This is further underlined in the paper by *Low and Wong (2017)*, where they also implement Muther's SLP to minimise total distance travelled by machinery. Highlighting internal transport as key metric, focusing on reducing driving distances within a facility can lead to better system performance.

2.3. Conclusion and discussion on the literature review

The continued growth of global container transport increases the pressure on the logistics chain. This development has direct implications for the infrastructure and operational processes within terminals, yards and depots. As demand rises, ECDs face growing challenges related to storage space, process efficiency and equipments use. Despite their critical role in maintaining container availability, ECD operations remain underexplored in academic research. Most literature is focused on full container terminals and repositioning flows of empty containers. A few studies, such as the paper by *Hidalgo et al. (2017)* [4] and *Pascual and Smith (2020)* [5], addresses the specific operational dynamics within ECDs.

This review has shown that many principles from related logistical contexts have potential relevance for ECD operations. Concepts such as stacking strategies, (yard) layout design and the use of flexible resource allocation could similarly be applied to a depot environment. Although originally developed for container terminals or warehouse systems, these concepts offer useful perspectives for analysing and improving depot performance. Particularly when a depot is operating near its capacity. Building on these conceptual insights, a suitable method is needed to evaluate how such principles might affect ECD operations in practice. Given the stochastic and process-driven nature of depot environments, Discrete-Event Simulation is a well-suited modelling approach. DES makes it possible to asses how different layout configurations and stacking strategies affect operational performance in a realistic way based on data. The work by *Hidalgo et al. (2017)* [4], supports the use of a simulation model to test different operational policies and their impact on performance while applying a fixed depot layout. The structure of their simulation experiments and their use of statistical evaluation methods are also valuable for the modelling approach in this study. Although their research focuses on testing operational policies, their conclusion highlights the potential to extend the model toward layout analysis.

This perspective supports the idea that simulation-based analysis can generate valuable insights for ECD facilities operating in different layout and stacking scenarios. The relevance of this research lies in its ability to bridge a clear gap in the literature while also offering practical value. By applying the approach to a real-world case, the MedRepair Smirnoffweg depot, this study will not only contribute to the academic understanding of ECD operations, but also supports informed decision-making for improving depot efficiency. By developing a generic model and applying the theories discussed, this research provides valuable support for planning both existing and new depot facilities with similar operational characteristics and challenges.

3

Methodology and research framework

3.1. Research methods

Given the complexity and specific nature of the research topic, this study focused on analysing a single empty container depot to gain insights into general operational patterns. Factors such as depot layout, the variety of container movements and the varying conditions of arriving containers differ depending on demand fluctuations and truck arrival patterns. Each depot is unique, making it impractical to generalise findings without first conducting a detailed case study at one location. MedRepair Smirnoffweg was therefore an ideal case for collecting historical data on all activities occurring at this site. The analysis of this data supported the development of realistic layout scenarios, which were crucial for testing and refining the simulation model. By focusing on MedRepair Smirnoffweg, scenarios were tailored to the specific container movements and spatial challenges of this depot. Making the output both valuable and directly applicable for improving efficiency at this location, while also contributing to a broader understanding of general depot operations. In Table 3.1 below the 7 different sub-questions are mentioned with their corresponding research methods. These methods will be explained in more detail in the following paragraphs.

Sub-question	**Method(s) used**
1. What insights into empty container depot operations can be drawn from literature and real-world operational practices?	Literature Research, Expert Consultation
2. How does existing knowledge on layout and stacking strategies apply to empty container depots, and in what ways do empty container flows differ from full container flows?	Literature Research
3. What are the main operational challenges and capacity limitations in current empty container depot processes?	Data Analysis, Expert Consultation, Field Observation
4. What trends in historical data and expert insights support future operational planning for depot operations?	Data Analysis, Expert Consultation
5. Which operational scenarios should be modelled to evaluate the impact of layout and stacking strategies under varying depot conditions, including logistics strategies, demand requirements and infrastructural constraints?	Simulation Modelling, Scenario Development
6. Which modelling technique can be used to effectively evaluate the impact of different layout and stacking strategies on depot performance?	Simulation Modelling
7. What lessons can be drawn regarding the effectiveness of adaptive layout and stacking strategies under different operational scenarios?	Simulation Modelling, Simulation-Based Scenario Analysis

Table 3.1: Research sub-questions and associated methods

3.2. Research framework

Figure 3.1 outlines the structure of the research, divided into five distinct phases. This framework guided the research process and served as a roadmap throughout the project. The first phase focused on understanding the core problems and objectives. Based on a literature review, the research scope and its positioning within the sector were defined. The literature review also contributed to the exploration of suitable research methods.

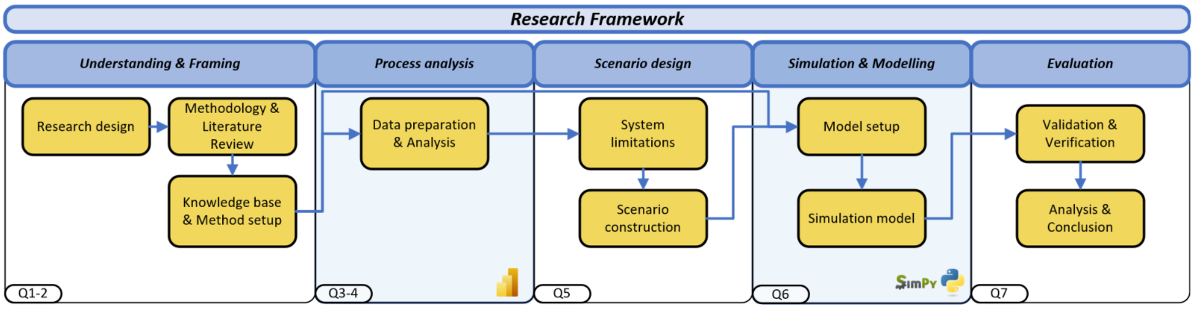


Figure 3.1: Research framework

The first research activities involved a deeper exploration of current depot operations and simulation methodology through expert consultation and literature research. These steps formed the foundation for the research and model setup, addressing sub-questions 1 and 2.

At the same time, the data analysis was conducted. Relevant data was collected, cleaned and analysed using the program Power BI. Combined with insights from expert consultations, this phase identified key operational challenges, answering sub-question 3 and 4.

Based on the previous findings, relevant operational scenarios were constructed. These scenarios include aspects such as global/regional container flow strategies (e.g. absorption vs evacuation), equipment demands (e.g. quality and specifications), import container conditions, M&R productivity limits (e.g. workforce and job types, labour hours per day etc.) and infrastructural constraints (e.g. yard capacity, gate throughput and daily moves). The development of these scenarios are carried out in collaboration with MedRepair and MSC, and were informed by findings from the literature, system and data analysis, answering sub-question 5. This reflect both practical insights and established methodological approaches in the scenarios.

Together with the knowledge base & method setup, the simulation model was constructed to answer sub-question 6. This involved the necessary steps towards building, validating and applying the simulation model. The final step was the analysis of the results of the model to draw conclusions about the performance of the depot under different strategies. This evaluation answered the last sub-question and supported the conclusion to the main research question. Below, an overview per method will be presented.

3.3. Literature research

Additionally to the literature review conducted in Chapter 2, ongoing literature research was an appropriate method for answering the first two sub-questions. These questions required a deeper theoretical understanding of layout and stacking strategies within empty container depots. They also required methodological guidance on how simulation models could be constructed, validated and verified.

The paper of *Snyder (2019)* [7] supported this approach, noting that literature research is particularly useful in interdisciplinary fields such as supply chain and operational research. It helped researchers combine different findings, identify knowledge gaps and develop theories. This all, was important for the understanding of complex systems like ECDs.

3.4. Expert consultation

Expert consultations were conducted to better understand depot operations and to support the development of realistic simulation scenarios. A distinction was made between consultations of the operational staff at MedRepair Smirnoffweg (Rotterdam) and strategic and tactical personnel within the MSC company. These consultations followed a semi-structured approach that helped to gain understanding of operational processes and tactical planning, which was also supported by the paper of *Rowley (2012)* [53].

Consultations with the operational staff of MedRepair Smirnoffweg (Rotterdam) provided insight into day-to-day workflows, bottlenecks and recurring operational issues. Consultations involving MSC experts, helped to define realistic future scenarios based on historical patterns and strategic developments. Together, these consultations provided input to accurately construct a simulation model.

3.5. Data analysis

Detailed historical data was available from the case study depot. The information received during consultations helped to find the correct data and helped to construct a targeted analysis. Using Power BI, patterns and relationships within the data were explored to better understand operational trends and validate the relevance of the scenarios.

Data analysis also included the preparation of the data for simulation, getting the data in the right format by cleaning, organising and formatting. By doing so, data preparation was key before implementing into a model.

3.6. Field observation

Field observations were carried out at the MedRepair Smirnoffweg depot to measure the duration of key operational processes. These measurements were performed once, not taking into account different utilisation situations of the depot. Therefore, this measurements did not capture how process durations and operational behaviour change under different pressure conditions.

Field studies are key in supporting model development and validation, as they provided data for complex processes within an operational system, this was also supported by the paper of *Baharmand et al. (2022)* [54]. The depot processes measured in this study were container placement and retrieval times and the driving speed of ECHs.

3.7. Simulation modelling

Based on findings gathered through literature research, expert consultations, observations and data analysis, the simulation model was developed. The model reflects the operations of the case study depot related to different layout and stacking strategies. As found in the literature review, Discrete-Event Simulation (DES) was well suited for modelling complex, sequential processes in logistics systems.

The choice of DES was further supported by the classification of model types explained by *Sargent (2015)* [55]. DES is a type of mathematical model that belongs to the category of structural models, which are suitable for systems that have defined elements, use shared resources and operate based on events. Which is indeed the case when looking into ECD operations. This type of model made it possible to represent the processes, flows and interactions within the depot in a structured and detailed way. This was essential for analysing the performance of the depot under changing levels of utilisation.

Before the simulation model could be implemented, a clear conceptual model was defined. The conceptual model is a simplified representation of the real world or system that identifies the systems main components, relationships and how they interact. Conceptual modelling involved selecting the relevant elements and structuring the logic of operations. As well as, removing unnecessary details of the system, described in *Turnitsa (2015) [56]*. This research included processes such as container gate-in and out procedures, inspections, washing, maintenance, repair, stack allocation and more. Each process was studied with its own specific conditions and durations.

As mentioned before, time does play a central role in depot operations. *Loper (2015) [57]* discusses different ways of modelling time in simulations, mentioning the choice between continuous and discrete representations. Time in DES models progresses through discrete events, as further explained in *Goldsman and Goldsman (2015)* [38]. This approach suited the system where delays or queuing had a direct effect on the system performance.

The model was informed by additional literature, needed to guide modelling assumptions, parameter selection and simplification. As well as, earlier constructed scenarios that are relevant to model. The chosen environment for running the simulation is Python, using SimPy. Section 2.2 delves deeper into the modelling approach for ECD simulation and analysis.

3.8. Scenario development

Data analysis and expert consultations contributed to the construction of scenarios. Scenarios were defined to reflect realistic operational conditions. This included determining which variables and constraints to include in the model. This also involved specifying the performance indicators used to analyse the evaluated objectives.

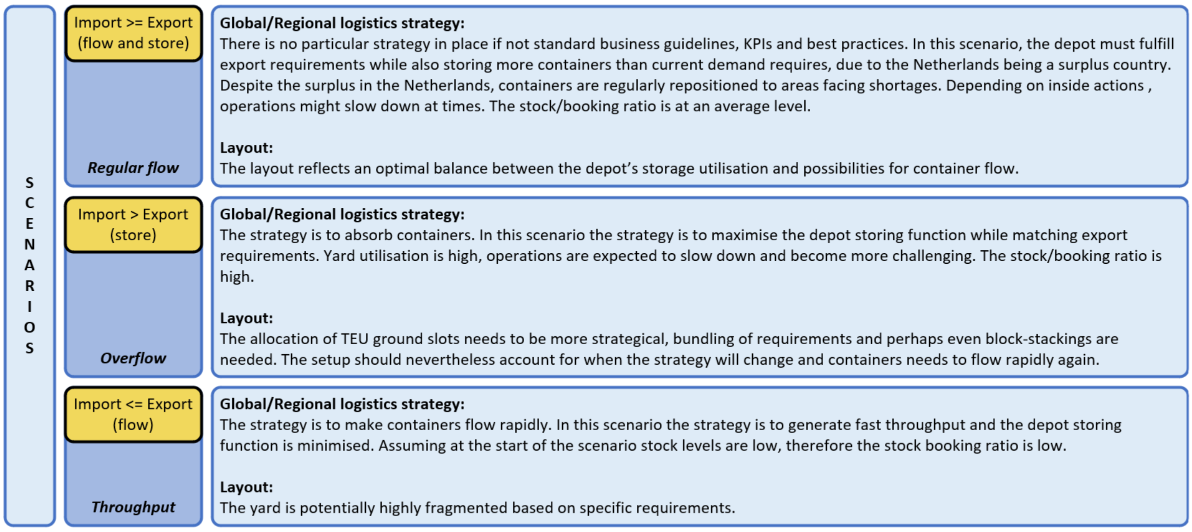


Figure 3.2: Strategic decision-making translated into three different scenarios

Figure 3.2 provide an overview of strategic scenarios that are evaluated. These scenarios serve to illustrate the direction and scope of the modelling approach. They are relevant to the operational context and were constructed and tested using the model in collaboration with MSC experts.

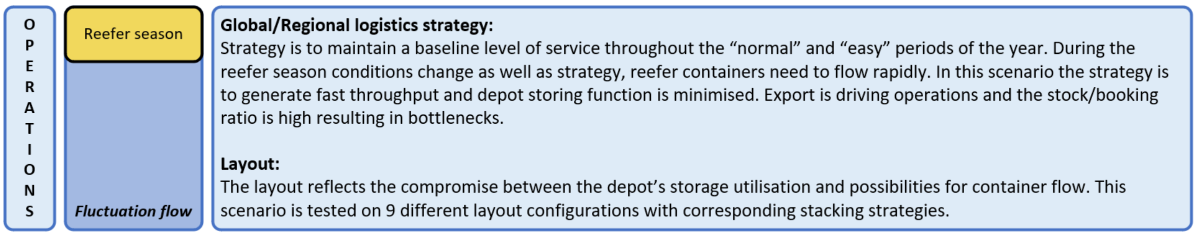


Figure 3.3: Reefer season scenario

These three strategic decision-making scenarios were tested across different layout configurations. The layouts used for testing were taken from a business-as-usual scenario, in which a simplified version of the reefer container seasons was simulated, presented in Figure 3.3. The best-performing layouts from this simulation were selected for evaluating these scenarios.

3.9. Simulation-based scenario analysis

After constructing and validating the models, different methods were used to analyse the results and assess the reliability of the models. Performance indicators are compared across the different scenarios. This was done by using comparative analysis to explore how variations in input parameters influenced outcomes, and by applying other statistical techniques to better understand model behaviour and support its validation.

3.10. Simulation framework

Building upon the research framework, a refined simulation framework is developed to analyse and improve operations in ECD operations. Unlike the research framework, which is tailored to answering the research questions, this version offers a generalised structure for breaking down similar systems, which is focused on ECD operations but could also be applied to other M&R facilities or warehousing environments in comparable operational settings.

This simulation framework, presented in Figure 3.4, serves as a practical guideline for researchers aiming to identify operational inefficiencies, test different operational, tactical and strategic scenarios, and focus on improving facilities. The core steps taken in the framework are coloured in yellow, representing a key phase in the analysis process. Specific methods or considerations are assigned to these step to support their execution, coloured in light blue. Grey boxes highlight methods and considerations that can complement to the analysis, which are considered in this research but not implemented.

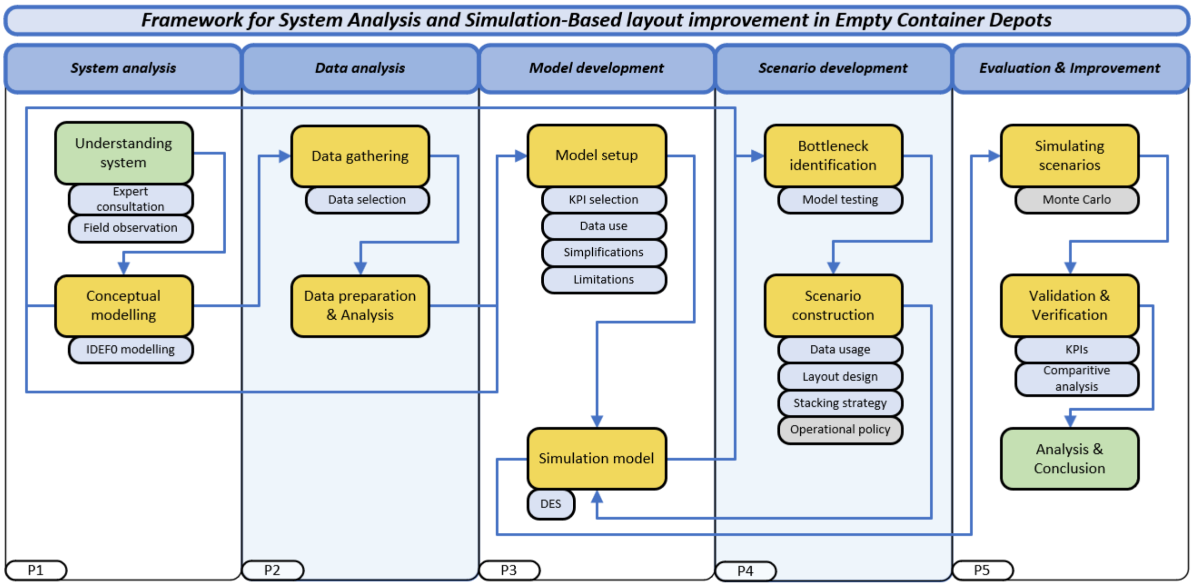


Figure 3.4: Simulation framework

4

System analysis

This chapter focuses on analysing processes within an empty container depot, with a specific focus on the operations at MedRepair Smirnoffweg. While MedRepair serves as a case study, the processes and activities examined are representative for general depot operations. By analysing this system a comprehensive overview of general depot operations can be given, which is used for further analysis in this report. The aim of this analysis is to form a basis needed for the development of a conceptual model, which will be translated into a simulation model using Python.

4.1. Empty Container Depot (ECD)

ECDs are essential nodes in the global logistics chain, yet they vary significantly in size, layout and operational complexity. Despite these differences, many ECDs share a core set of activities and processes. To better understand and improve operations across such depots, a layered breakdown of the system is presented, that captures the key components and dynamics of a typical ECD.

While the system structure is designed to be broadly applicable, it is grounded in the operational reality of a specific case: The MedRepair depot at Smirnoffweg in the port of Rotterdam. This depot is selected because of its representativeness in ECD operations. By using this location to structure, test and validate system components, this research makes sure that both practical relevance and generalisability is obtained.

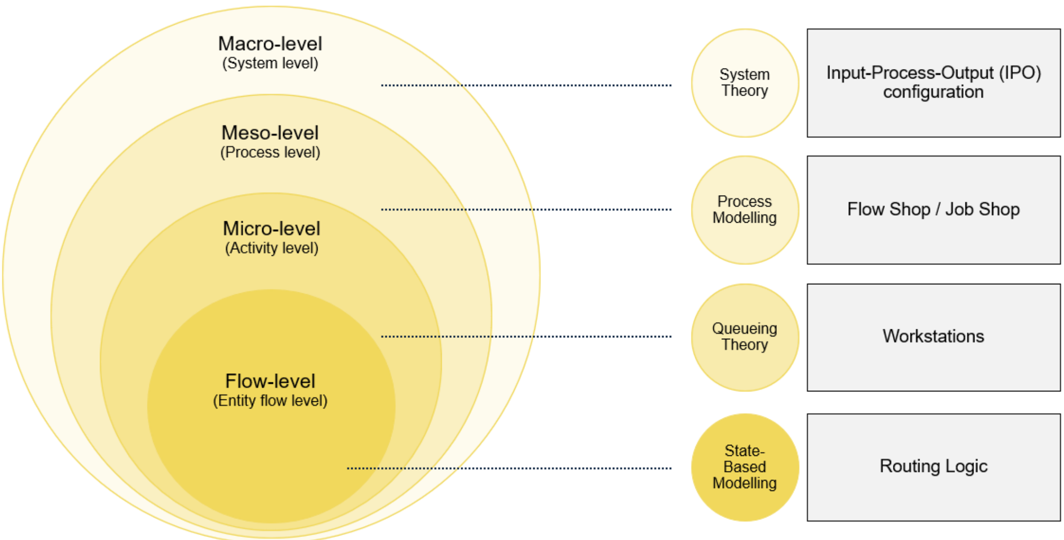


Figure 4.1: Layered breakdown of an empty container depot system

The layered breakdown of the system presented in Figure 4.1 is structured in four layers. Starting from a high-level (macro) view of the ECD system, down to the detailed behaviour of individual entities within the depot. This layered approach supports a comprehensive analysis of ECD operations. Within each level, a combination of structural configurations and analytical modelling approaches is used to describe the system. Structural elements, such as Job Shop or Flow Shop representations, help capture the sequencing of activities. While analytical components, such as queueing models, represent waiting times, service dynamics and system performance. Together, these elements define how events link to activities and how activities link to processes.

4.2. Macro-level

Starting with the lowest level of detail, defining the concept of ECD operations as a system. Based on the information of chapter 2 the ECD system is defined as a set of coherent elements that can be distinguished from the broader reality. These elements are interconnected and some of them interact with that broader reality [46].

The ECD system could be defined as a facility where containers (entities) with unknown dimensions and conditions enter the system (Input). Inside the depot multiple activities are performed (Process) before that same container moves out of the system again, with known dimensions and condition (Output). This can best be described using the IDEF0 modeling method, as explained in the book *Modeling and Analysis of Enterprise and Information Systems* by Li Q. and Chen Y. [58]. The macro-level representation of the ECD system is presented in Figure 4.2.

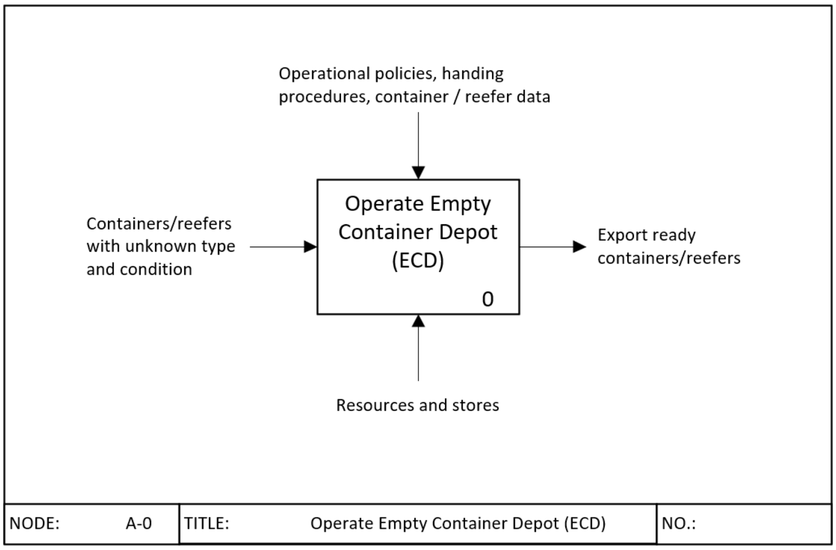


Figure 4.2: IDEF0 A-0 representation of the ECD system (lowest level of detail)

The boundaries of an ECD system are defined by the gate-in and gate-out of containers, they represent the interaction of the system with its environment.

4.3. Meso-level

The set of defined element on macro-level can be decomposed into several different subsystems at meso-level. Each subsystem consists of a unique set of elements that belongs to the set of elements of the ECD system.

The interaction between these subsystems form the basis of the overall operational flow of the depot. A sequence of interactions results in a so called process, which basically describes the sequential order of subsystem visits by a single entity. ECD operations are focused on two different entity types, dry containers and reefer containers, see section 4.4. Therefore, whole the depot operations could be split into two operational entity streams, presented in Figure 4.3.

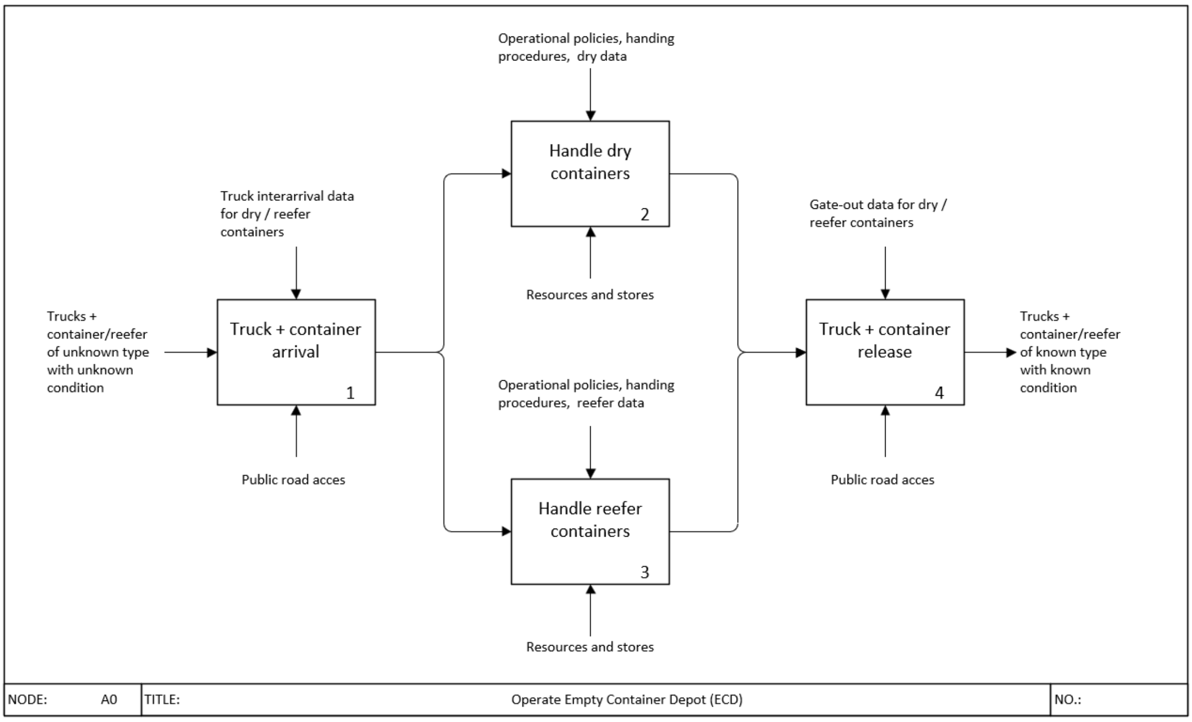


Figure 4.3: IDEF0 A0 representation of the ECD system (meso level)

For dry and reefer containers multiple activity combinations are possible that together form the system processes. In Table 4.1 all subsystems for dry and reefer containers are mentioned and numbered according to the IDEF0 modelling representation.

Table 4.1: ECD subsystems

Number	Subsystem Dry	Number	Subsystem Reefer
1	Visual Check	1	Gate-In
2	Gate-In	2	Pick Up
3	Pick Up	3	Body Check, Repair & EPTI
4	Buffer	4	PTI
5	Repair	5	Machinery Repair
6	Wash	6	Buffer
7	Export Ready	7	Wash
8	Internal Movement	8	Ready
9	To Truck	9	Settings
10	Gate-Out	10	Internal Movement
		11	To Truck
		12	Gate-Out

The subsystems described in Table 4.1 form the basis for the processes of all containers. Both types have multiple process possibilities that can best be described via a flowchart due to it complex nature. Figure 4.4 represents the interactions between different subsystems for the dry container flow according to the IDEF0 modelling method. In Figure 4.5 the interactions between the subsystems for the reefer containers are given, also according tot the IDEF0 modelling method.

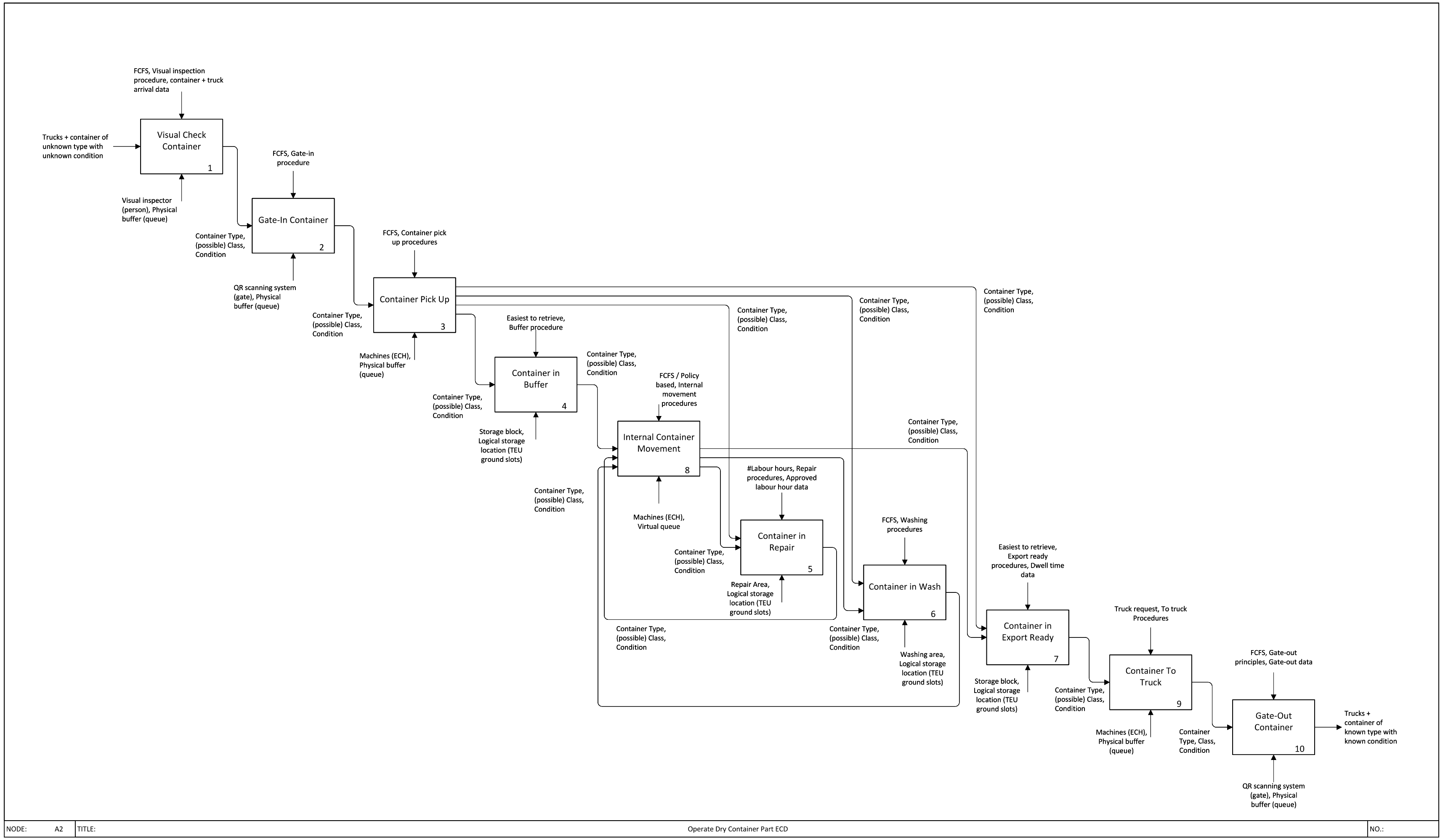


Figure 4.4: IDEF0 A2 representation of the ECD system (meso level)

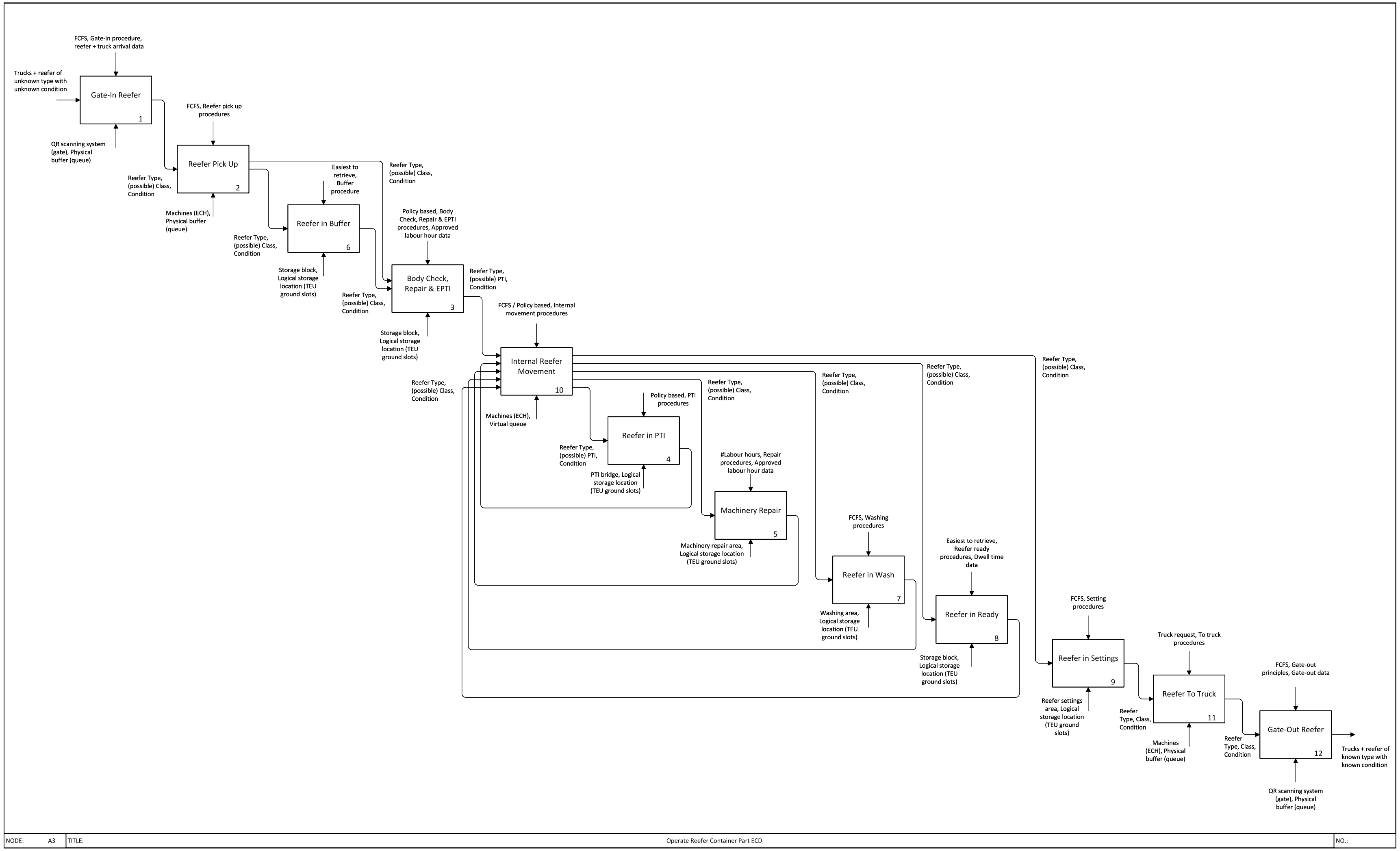


Figure 4.5: IDEF0 A3 representation of the ECD system (meso level)

4.4. Micro-level

All the subsystems have their own set of rules and most of them use inputs generated by other subsystems. These set of rules and relationships inside these subsystems will be defined on micro-level in the this subsection.

As shown in Figure 4.4 and Figure 4.5 every subsystem has an input, process and output (IPO) configuration, similar to the system itself. Each subsystem is a (work)station with its own characteristics, and uses resources and stores to handle the incoming entities.

Stores represent temporary holding areas for entities before they can be processed by a subsystem. Depending on the context, a store can take different forms: physical buffer, local storage location or virtual queue.

In these queues entities are yielded until they can be processed by the subsystems resources. Resources are active elements within the system that perform operations on entities. The type of resources could vary per subsystem but in the case of an ECD these are: gates, personnel and ECHs. Where ECHs are used for moving entities between subsystems, this is referred to as internal movement. Resources can be either dedicated to a subsystem or shared across multiple subsystems. The way resources are allocated in the system give insights into system flexibility and bottlenecks.

Within the system a clear distinction is made between two primary container flows: dry containers and reefers containers. While both types share similar physical characteristics in terms of size, their operational requirements differ. Reefer containers are equipped with integrated machinery that is responsible for temperature control inside the container, making them suitable for all kinds of cargo.

Both dry and reefer containers are available in two standard sizes: 20-foot and 40-foot container units. While reefer containers are limited to these 2 standard sizes, dry containers exist in a wider variety of configurations depending on their intended use. The system is responsible for handling both container types, each requiring specific activities before containers can be released; see also Figure 4.4 and Figure 4.5.

4.4.1. IDEF0 A2 decomposition: Dry container processes

Following the IDEF0 modelling method, the system at meso-level is further decomposed into a set of operations specific to each subsystem for dry operations. This micro-level representation provides a more detailed view of internal processes. In addition to this decomposition of each subsystem using IDEF0 diagrams, this section will also explain how control and mechanism elements are handled. Therefore, depot procedures and operational data are analysed to describe the ECD system as it functions in reality. The conducted analysis will serve as a foundational input for the conceptual modelling phase. To maintain focus and avoid repetition, this section highlights a selection of subsystems that are most relevant to the analysis. The other subsystems are discussed in Appendix B for completeness and reference.

Container in Visual Check

In Figure 4.6 the process of the visual check for dry containers is presented. In Box 1: Queue Entry, there is controlled for the truck arrival interval for dry containers.

Based on MSC data, an analysis is conducted that provided insight into the interarrival times of trucks with dry containers. No significant fluctuations in demand were observed for a full year, suggesting that the pattern of truck interarrival is similar during this analysed period. This analysis is conducted to gain insights into that pattern, which will serve as a foundational input for the conceptual modelling phase. By doing so, this analysis provides a direction for simulation modelling, specifically enabling stochastic container generation using a discrete distribution. This approach is well suited for capturing process dynamics and simulation purposes.

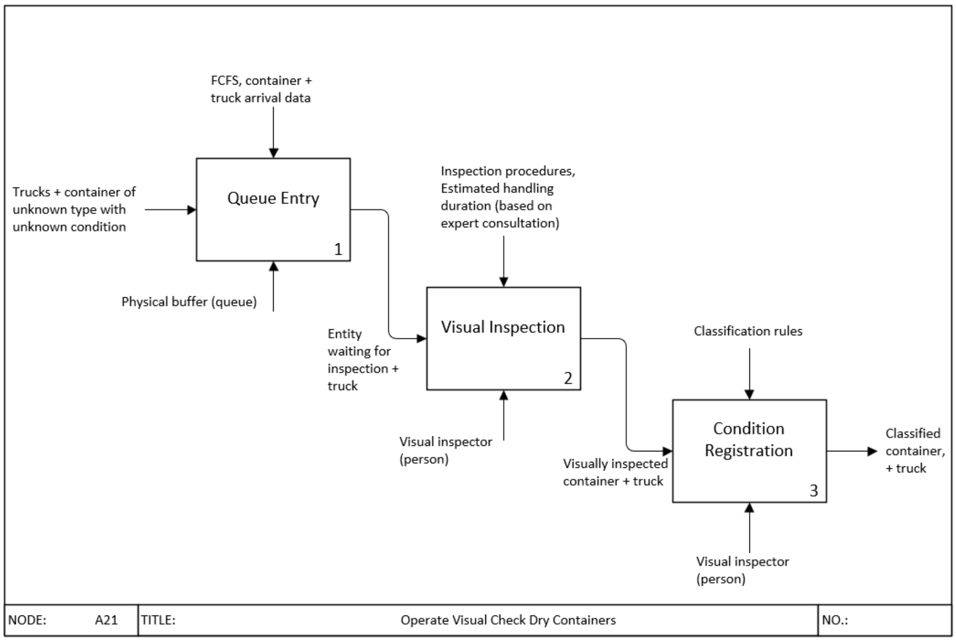


Figure 4.6: IDEF0 A21 representation of Visual Check dry container (micro-level)

Since the data is discrete and rounded to a 1 minute interval, a Chi-Square goodness-of-fit test was conducted to identify suitable probability distribution functions [59]. The first step in this analysis was the normalisation of the dataset, this to overcome inflated chi-square values and low p-values accordingly. The distribution that best fits the data according to this test is the geometric distribution. The geometric distribution is normally parametrised using the Maximum Likelihood Estimator (MLE) in the following form:

$$p = \frac{1}{\bar{x}} \tag{4.1}$$

where $p =$ Estimated probability of success (e.g., a truck arriving at a given minute)
$\bar{x} =$ Sample mean of observed interarrival times (in minutes)

The dataset used for this analysis reflect actual operational behaviour, including ad hoc decision making that influences depot performance. Due to the structured modelling approach followed in this chapter, this detailed operational variability is not fully captured. Therefore, a slightly different interpretation of the data is applied, to ensure that insight into process relationships is maintained. This is done by using an adjusted version of the MLE Equation 4.1, where δ represents an integer offset.

$$\hat{p}_{adjusted} = \frac{1}{\bar{x} + \delta} \tag{4.2}$$

Although this equation deviates from the original MLE used, it still effectively captures the overall shape and logic of the empirical distribution. The conceptual model should be designed to explore process relationships and layout dynamics, rather than replicate exact operational behaviour. Using the original MLE equation would result in a high rate of container generation, preventing meaningful insights into these relationships. This adjusted MLE equation helps with maintaining interpretable results by underestimating low interarrival time values and overestimating high interarrival time values.

In Table 4.2 the corresponding values of the Chi-Square test are presented. Indicating (almost) no significant deviation between observed interarrival frequencies and those predicted by the geometric distribution for lower adjustment parameter values. Higher values of the adjustment parameter will result in a weaker statistical fit.

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{4.3}$$

where $O_i =$ Observed frequency in interval bin i
$E_i =$ Expected frequency in interval bin i
$k =$ Number of interval bins

Table 4.2: Goodness-of-fit test outcomes, interarrival times dry containers

δ	χ^2-value	p-value	p-parameter
0	2.37	0.936	0.3110
1	6.17	0.628	0.2372
2	15.16	0.056	0.1918

The geometric distribution with δ = *2* and *p-parameter* = *0.1918* is proposed for simulation purposes, to gain best insight into process relationships and layout dynamics for the simplified representation of the real-world context. The graph of this distribution with these parameters is visualised inside Figure 4.7.

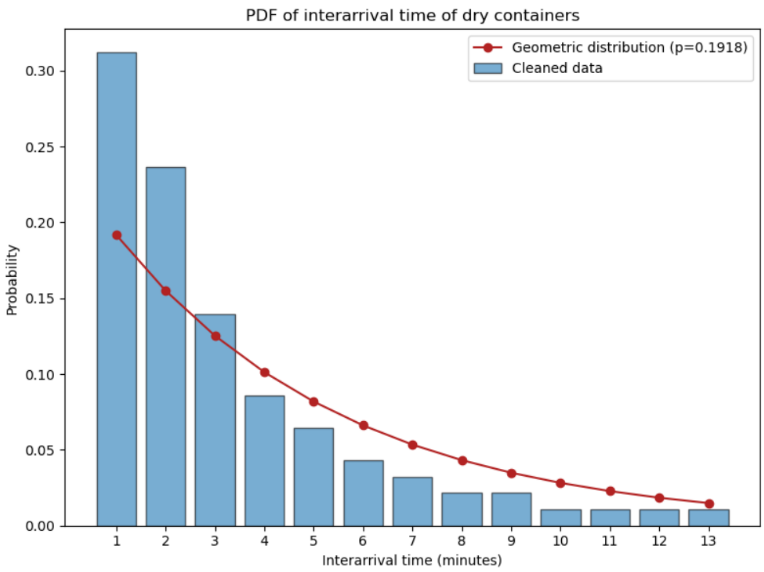


Figure 4.7: Fitted PDF to the interarrival times of trucks with dry containers

$$P(X = x) = (1 - \hat{p})^{x-1} \cdot \hat{p} \quad \text{for } x \in \{1, 2, 3, \dots\} \tag{4.4}$$

where $\hat{p} = 0.1918$

Container in Repair

In Figure 4.8 the repair process for dry containers is presented. In Box 2: Repair actions, there is controlled for the approved number of labour minutes.

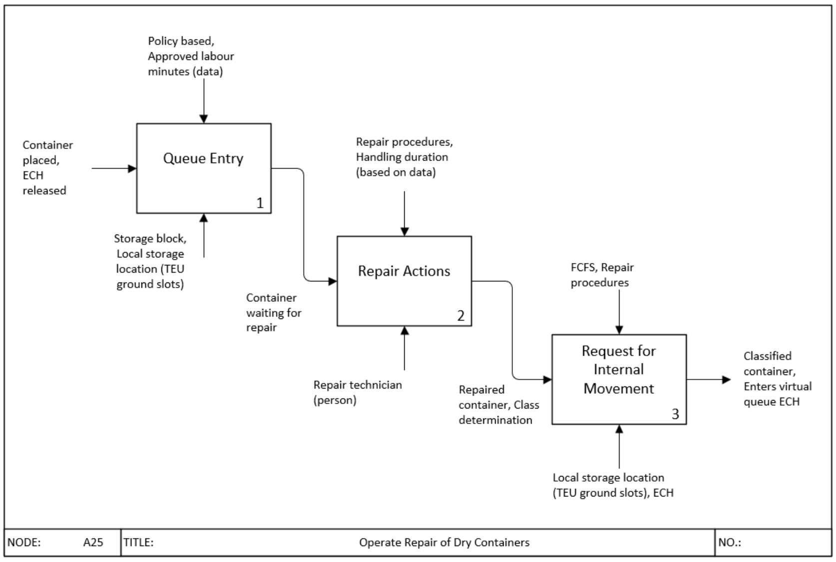
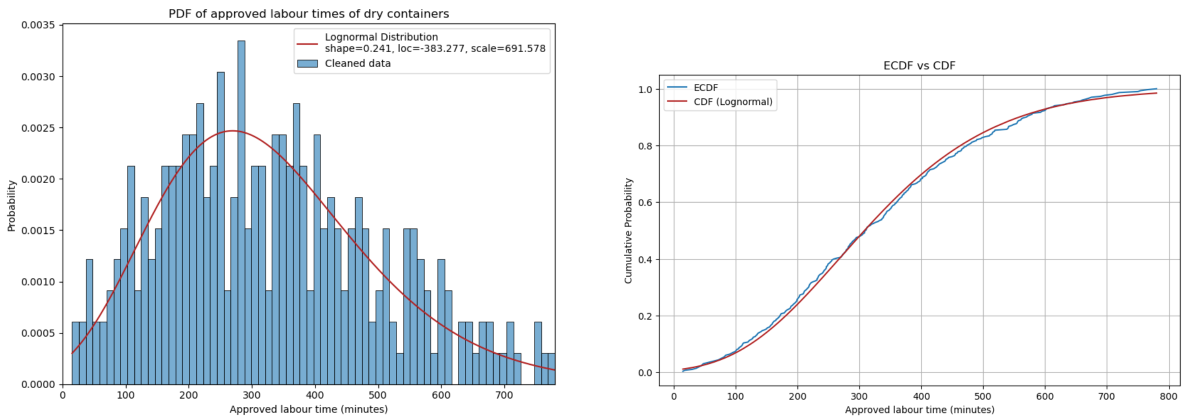


Figure 4.8: IDEF0 A25 representation of container in Repair (micro-level)

Based on MSC data, an analysis is conducted that provided insight into these operations. Taking into account the fact that the repair times of containers is continuously measured and not rounded in real life, this data is fitted using a continuous distribution. An Empirical Cumulative Distribution Function (ECDF) is constructed based on observed data of the year 2024, visualised in Figure 4.9b. This empirical distribution was then statistically compared to multiple theoretical distributions using a Kolmogorov-Smirnov (K-S) test [60]. This in order to identify the Probability Density Function (PDF) that best fits the data, visualised in Figure 4.9a. This PDF provides a simplified and generalisable form suitable for simulation. By translating the repair time observations into a continuous statistical distribution, repair times can be stochastically generated, when applying a simulation model as in this research. Both parameters mentioned in Table 4.3 suggest a good fit of the lognormal distribution to the data.



(a) PDF approved labour minutes

(b) Kolmogorov-Smirnov Test

Figure 4.9: Comparison of approved labour times data and statistical test

Table 4.3: Kolmogorov-Smirnov outcomes, approved labour times dry containers

Parameter	Value	Parameter	Value
K-S statistic	0.030	P-value	0.943

Container in Export Ready

In Figure 4.10 the dwelling process for dry containers inside the export ready storage block is presented. In Box 2: Dwelling container as Export Ready, there is controlled for the dwell time of the containers.

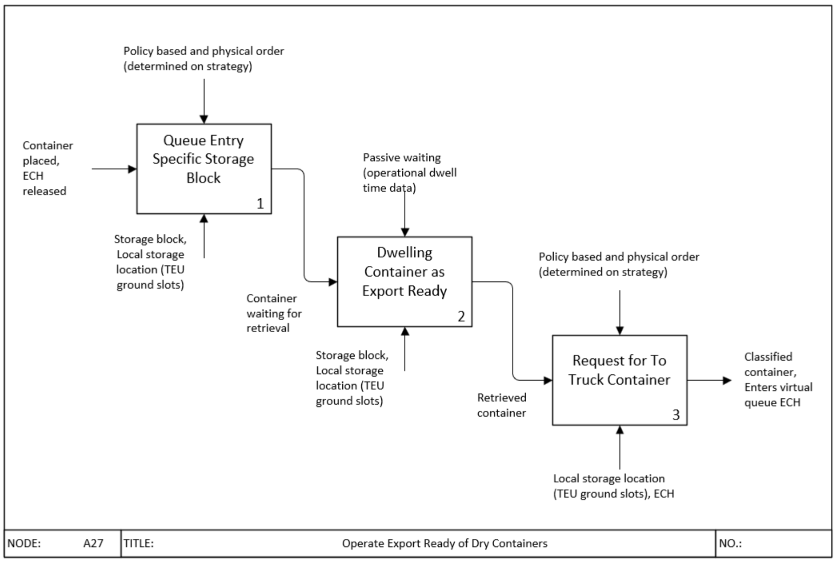


Figure 4.10: IDEF0 A27 representation of container in Export Ready (micro-level)

Dwell time data within the export ready storage block area was not directly available and was therefore derived by calculating the operational time difference between gate-in and gate-out events per container number, resulting in the total dwell time inside the depot. Later, based on path configurations all actions related to other workstations should be subtracted from this dwell time, resulting in dwell time inside the export ready storage block.

Due to the large number of data points and wide spread observations, no single distribution accurately represented the dataset. To account for this, the dataset was first cleaned and normalised, followed by a segmentation into two sections. Each section was fitted with a discrete distribution and weighted according to its relative frequency. This method improves the overall fit, helping to capture key patterns and dynamics of the real-world context. A detailed explanation of how these discrete distributions are implemented within a simulation environment is provided in chapter 5. Below a Chi-Square test is conducted for the two sections created during the analysis.

The first section, ranging from 1 to 15 minutes, represents containers that are (almost) immediately ready for export and require no additional handlings. These containers shortly visit the export ready storage block or leave the system directly. In this structured modelling approach this last step is not possible because path logic needs to be followed. Meaning that the dwell time inside the export ready storage block becomes zero. Section two, ranging from 16 to 21600 minutes, represents containers that have a longer dwell time inside the system. The Chi-Square test performed according to Equation 4.3 is presented in Table 4.4 and the corresponding discrete probability distributions are visualised in Figure 4.11 and Figure 4.12.

Table 4.4: Goodness-of-fit test outcomes, operational dwell time dry containers

Time interval (min)	χ^2-value	p-value	Fitted distribution
1-15	13.66	0.3229	Negative Binomial
16-21600	91.18	0.9999	Negative Binomial

The negative binomial distribution provides a reasonable approximation of the observed data for section one, as provided by the Chi-Square test. However, there is some deviation between the model and the observed data, meaning this is not a perfect fit.

In contrast to the outcome of section one, section two suggest a perfect fit by looking at the p-value. This is likely due to extremely low probabilities in a very large dataset. This sensitivity can lead to misleading results. Visual inspection confirms that a negative binomial distribution correctly captures the data pattern.

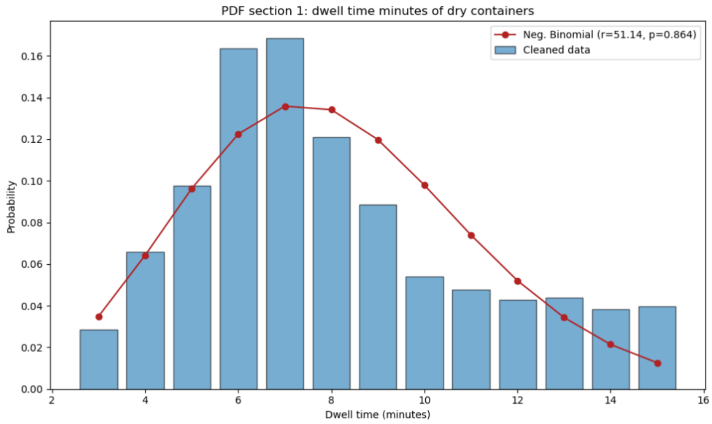


Figure 4.11: Fitted PDF section 1 operational dwell time minutes

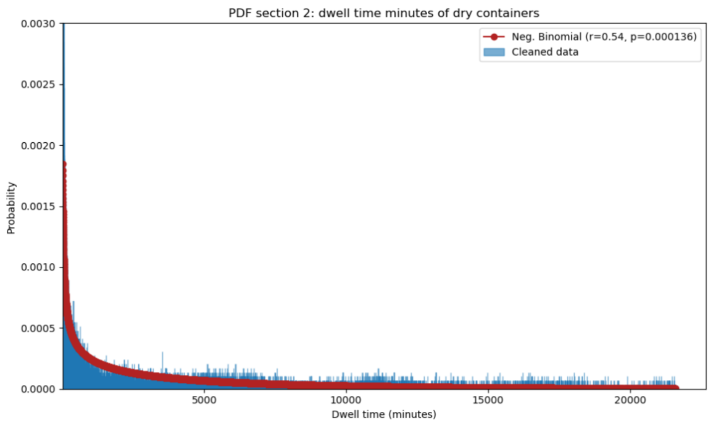


Figure 4.12: Fitted PDF section 2 operational dwell time minutes

4.4.2. IDEF0 A3 decomposition: Reefer container processes

Following the subsection 4.4.1, the system at meso-level is further decomposed into a set of operations specific to each subsystem for reefer container operations. This micro-level representation provides a more detailed view of internal processes. In addition to this decomposition of each subsystem using IDEF0 diagrams, this section will explain how control and mechanism elements are handled, similar to subsection 4.4.1. Therefore, depot procedures and operational data are analysed to describe the ECD system as it functions in reality. The conducted analysis will serve as a foundational input for the conceptual modelling phase. To maintain focus and avoid repetition, this section highlights a selection of subsystems that are most relevant to the analysis. The other subsystems are discussed in Appendix B for completeness and reference. Since most analysis follow a similar structure and have the same purpose, providing information for the conceptual modelling phase, a more detailed explanation of the analysis is described in subsection 4.4.1.

Reefer container Gate-In

In Figure 4.13 the process of reefer container gate-in is presented. In Box 1: Queue Entry, there is controlled for the truck arrival interval for reefer containers.

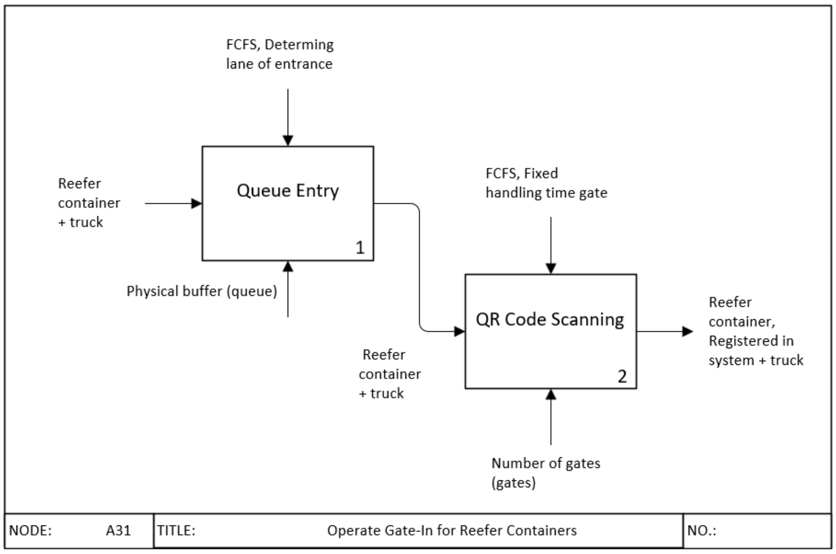


Figure 4.13: IDEF0 A31 representation of reefer container in Gate-In (micro-level)

Based on MSC data, an analysis was conducted that provided insight into the interarrival times of trucks with reefer containers. Significant fluctuations in the interarrival pattern were observed for a full year, dividing the year into three different sections.

Following the same analysis method applied to the interarrival truck times for dry containers, Equation 4.2 and Equation 4.3 are used to determine the distributions that best fit the data. As a result, a slightly different interpretation of the data is applied, to ensure that insight into process relationships is maintained. In Table 4.5 to Table 4.7, the three different sections of the year 2024 are stated, with there corresponding Chi-Square goodness-of-fit test outcomes. All sections follow the same geometric distribution.

Table 4.5: Goodness-of-fit test outcomes, section 1 January to April (normal condition)

δ	χ^2-value	p-value	p-parameter
0	3.70	0.962	0.1880
1	3.75	0.958	0.1568
2	6.99	0.800	0.1355
3	10.88	0.453	0.1194
4	14.65	0.199	0.1066
5	18.76	0.066	0.0964

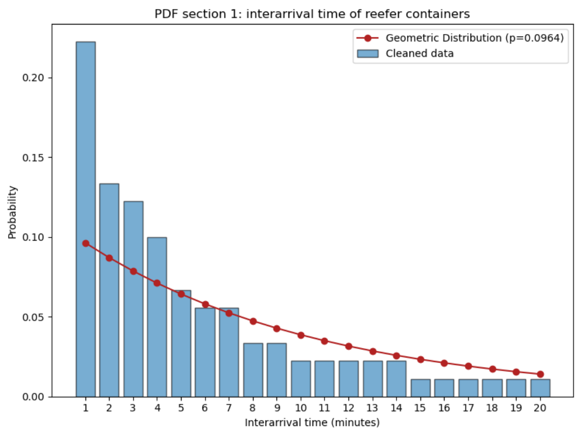


Figure 4.14: Fitted PDF section 1 to the interarrival times of trucks with reefer containers

Figure 4.14 to Figure 4.16 show the adjusted p-parameter values that should be proposed to the conceptual model, so that relationships and system dynamics can be captured. For each section, the datasets were cleaned to ensure reliability. Sections 1,2 and 3 include 85%, 80% and 89% of their total dataset respectively, based on the filtered entries. This means that the filtered data accounts for a large portion of the original data, allowing for comparison of the real-world context.

Table 4.6: Goodness-of-fit test outcomes, section 2 May to August (relaxed condition)

δ	χ^2-value	p-value	p-parameter
0	5.60	0.935	0.1175
1	4.77	0.965	0.1051
2	4.36	0.976	0.0951
3	5.56	0.937	0.0869
4	8.08	0.779	0.0799
5	9.86	0.628	0.0740
6	10.87	0.540	0.0689
7	13.83	0.243	0.0645
8	14.19	0.223	0.0606
9	16.03	0.099	0.0571
10	17.81	0.058	0.0540

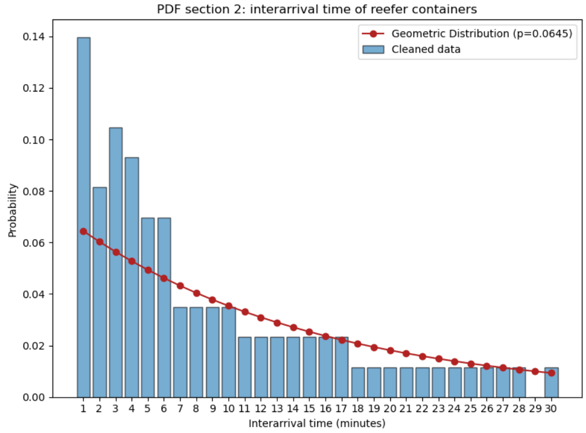


Figure 4.15: Fitted PDF section 2 to the interarrival times of trucks with reefer containers

Table 4.7: Goodness-of-fit test outcomes, section 3 September to December (stressed condition)

δ	χ^2-value	p-value	p-parameter
0	1.39	0.994	0.2575
1	3.66	0.932	0.2048
2	9.72	0.465	0.1700
3	16.40	0.089	0.1453

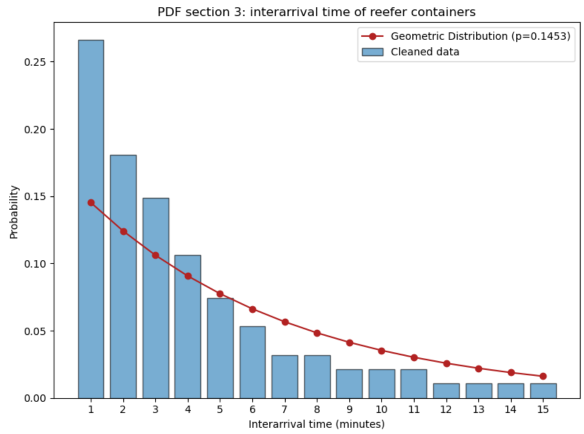


Figure 4.16: Fitted PDF section 3 to the interarrival times of trucks with reefer containers

Reefer container in Body Check, Repair & EPTI

In Figure 4.17 the repair process for reefer containers is presented. In Box 3: Repair actions, there is controlled for the approved number of labour minutes. Based on MSC data, an analysis is conducted that provided insight into these operations. Following the same approach as for dry containers, several continuous distributions are tested using a K-S test. Repair actions on reefer containers are carried out on the container body only within this designated area. Therefore, a distinction is made between containers that require only Electronic Pre-Trip Inspection (EPTI) and those that require both EPTI and Pre-Trip Inspection (PTI). Both groups have similar PDFs which are presented in Figure 4.18 and Figure 4.19.

Based on the K-S test the deviation between the fitted and the empirical distribution is small (0.030 and 0.040). Resulting in acceptable p-values accordingly, where EPTI shows a notably better fit to the observed data with respect to PTI, indicated in Table 4.8.

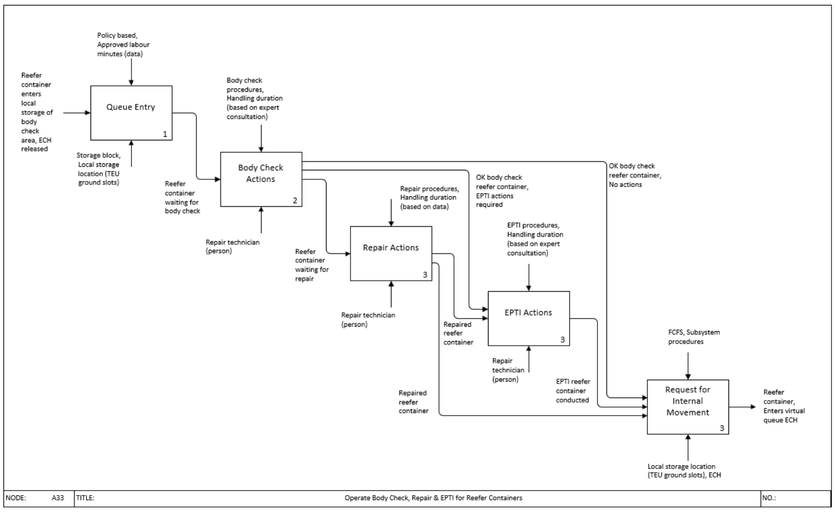
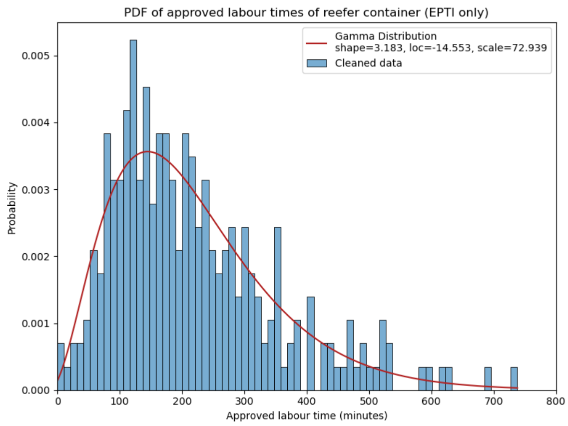
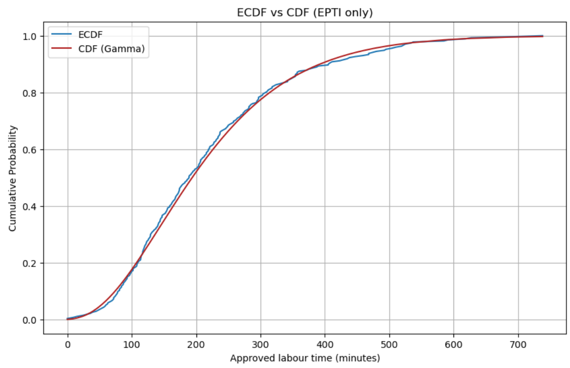


Figure 4.17: IDEF0 A33 representation of reefer container in Body Check, Repair & EPTI (micro-level)

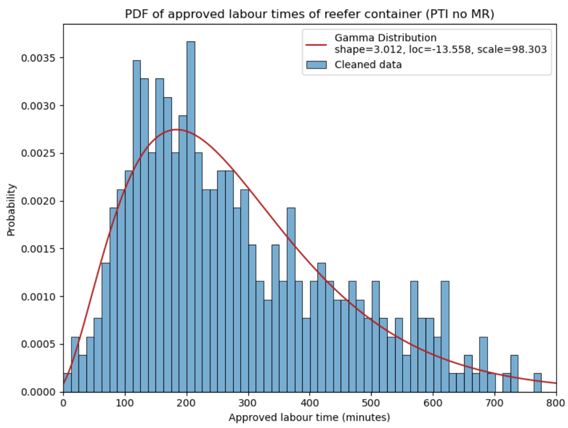


(a) PDF approved labour minutes

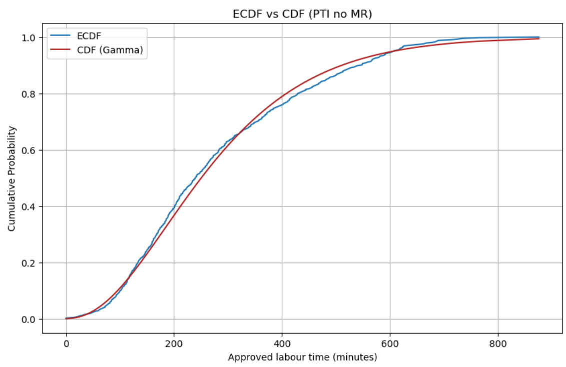


(b) Kolmogorov-Smirnov Test

Figure 4.18: Comparison of approved labour times data and statistical test (EPTI only)



(a) PDF approved labour minutes



(b) Kolmogorov-Smirnov Test

Figure 4.19: Comparison of approved labour times data and statistical test (PTI no MR)

Table 4.8: Kolmogorov-Smirnov outcomes, approved labour times reefer containers

Path	Parameter	Value	Parameter	Value
EPTI	K-S statistic	0.030	P-value	0.959
PTI no MR	K-S statistic	0.040	P-value	0.516

Reefer container in Ready

In Figure 4.20 the reefer container in ready process is presented. In Box 2: Dwelling reefer container in Ready, there is controlled for the dwelling time of the reefers.

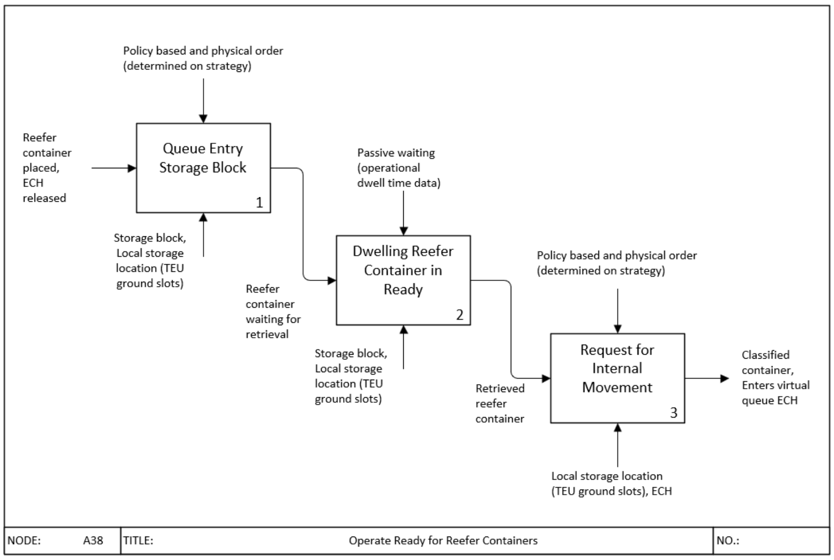


Figure 4.20: IDEF0 A38 representation of reefer container in Ready (micro-level)

Based on MSC data the time duration of operational dwelling is calculated via the gate-in and gate-out data for reefer containers. For the actual time of individual reefer containers inside this subsystem, all time durations of visited subsystems should be subtracted. No single distribution accurately represented the dataset. To account for this, the dataset was first cleaned and normalised, followed by a segmentation into two sections. Each section was fitted with a discrete distribution and weighted according to its relative frequency. Below a Chi-Square goodness-of-fit test is conducted for the two sections created during the analysis.

The first section, ranging from 1 to 2880 minutes, represents reefer containers that are (almost) immediately ready for export. Section two, ranging from 2881 to 21600 minutes, represents reefer containers that have a longer dwell time inside the system. The Chi-Square test performed according to Equation 4.3 is presented in Table 4.9 and the corresponding discrete probability distributions are visualised in Figure 4.21 and Figure 4.22.

Table 4.9: Goodness-of-fit test outcomes, operational dwell time reefer containers

Time interval (min)	χ^2-value	p-value	Fitted distribution
1-2880	25.80	0.9999	Negative Binomial
2881-21600	38.96	0.9999	Geometric

Section one and two suggest a perfect fit by looking at the p-value. This is likely due to extremely low probabilities in a very large dataset. This sensitivity can lead to misleading results. Visual inspection confirms that both distribution correctly captures the data pattern.

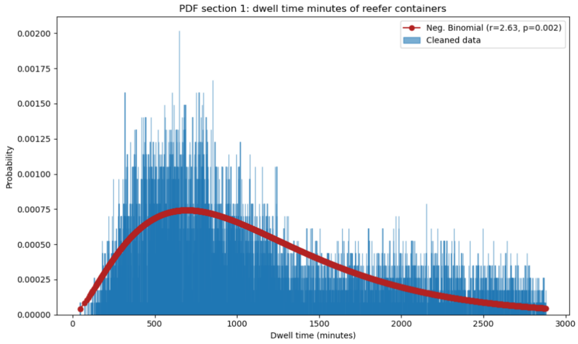


Figure 4.21: Fitted PDF section 1 operational dwell time minutes

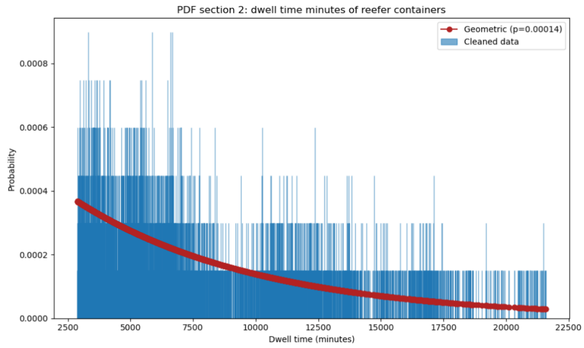


Figure 4.22: Fitted PDF section 2 operational dwell time minutes

4.5. Conclusion

This chapter focused on analysing the ECD system's (operational) characteristics and relationships. The system was broken down into four levels complemented by the use of the IDEF0 method, providing a structured overview of the components. A distinction was made between dry and reefer containers, each with their own specific relationships and processes. This layered approach offered valuable insights into subsystem interactions and helped identify operational bottlenecks through the visual inspection of the IDEF0 diagrams. All subsystems defined represent the core processes within an ECD system for both container types mentioned.

At the micro-level (highest level of detail), each subsystem and its internal processes were described in detail. This system and data analysis helped with understanding depot procedures, which further clarified how the system functions in the real-world practice. For the data analysis, both discrete and continuous data were examined to accurately capture process durations. Statistical tests, including the Kolmogorov-Smirnov and Chi-square tests, were used to determine the probability distributions that best fit the data. In some cases, these tests were adapted to better reflect the system's behaviour. This because the conceptual model is intended to explore process relationships and layout dynamics, rather than replicate exact operational behaviour. To conclude, this combined analysis serves as the foundational input for the conceptual modelling phase.

5 Model

This chapter describes the model used to simulate ECD operations. It outlines how the model was developed, based on widely applied concepts from the literature on both conceptual modelling and Discrete-Event Simulation (DES). The underlying conceptual model is introduced to clarify the system described, including key assumptions and the logic of the modelling processes, which builds upon the findings from chapter 4. Although tailored to the operations of MedRepair Smirnoffweg, the model was built in a generic and flexible way, allowing adaptation to different path configurations, layout designs, stacking strategies and operational policies. The model was created using the simulation framework presented in Figure 3.4, which defined core concepts and guided the modelling process.

5.1. Model objective

The aim of the model is to provide insight into ECD operations by testing various layout structures and stacking strategies through a flexible and easily adaptable DES simulation model. The testing of these layout structures and stacking strategies are carried out using a baseline simulation model. This baseline model is the direct translation of a conceptual model. The goal is to uncover and understand the operational relationships between subsystems, identify bottlenecks and analyse internal movement dynamics, such as congestion and flow disruption within the depot.

5.2. Model scope

To go from Phase 1: System analysis to Phase 3: Model development of the simulation framework, a structured conceptual modelling approach was followed. This process started by following the conceptual modelling framework of *S. Robinson* [48] and [49]. By doing so a five step analysis of the system was conducted, starting with the understanding of the problem situation which is thoroughly discussed in chapter 1. Followed by the understanding of the system including its parameters, discussed in chapter 4.

Final step, is the determination of the scope and the level of detail of the model, complemented by a description of assumptions and simplifications which will be presented later in this chapter. Based on the finding in chapter 4 a decision is made to focus on primary flows, container classes, types and sizes. Operational policies are assumed to be fixed and flows always follow the IDEF0 schemes presented also in chapter 4. System dynamics are based on (historical) data of the case study depot (MedRepair Smirnoffweg), as well as expert insights.

Different layout configurations and stacking strategies are evaluated against several Key Performance Indicators (KPIs) of the system, presented in section 5.4. The comparison of different settings to different scenarios will be presented in chapter 6.

5.3. Model input

For the modelling of the baseline model several inputs were used. Starting with the first determination of all subsystems included in the model. Figure 4.4 and Figure 4.5 acted as a baseline for all the processes that occur within the simulation for the dry container and reefer container part of the whole system. Supported by the different control and mechanisms for each subsystem. Taking into account relevant experimental factors that were identified based on an extensive data analysis of the case study depot.

In addition to the analysis conducted in chapter 4, further insights were gained regarding container quality and characteristics. This analysis served as input for the simulation model by supporting realistic flows within the system. By identifying the share of containers with specific qualities and characteristics, the model is able to simulate operational flows more accurately, which is an essential step to reflect system performance.

For the baseline model operational insight of the case study depot of the year 2024 is used. The numbers mentioned in Figure 5.1 to Figure 5.3 are containers that have a starting event (gate-in) beginning in year 2024 and also a final event (gate-out), which is not restricted to 2024. This implies that a full cycle for a unique ID-number is finished, the numbers are represented in Table 5.1. In addition to this, a filter was applied to both dry and reefer containers, focusing on the primary flows within the system. Therefore, these values do not accurately reflect the system's throughput of the year 2024.

- #Containers with completed cycle starting from 2024
- #Containers by TEU, Class (quality) and Type (characteristics)

Table 5.1: Number of containers with completed cycle starting from 2024

Container Type	#Containers
Dry containers	40.693
Reefer containers	19.326

Container size, class and type

Container types are divided into two categories based on size: TEU and FEU. In this report, these are referred to as 1 TEU and 2 TEU, with the latter representing a Forty-foot Equivalent Unit (FEU). For dry containers, quality was categorised into three different classes A, B and C. For reefer containers, classification "Class" reflected the type of inspection performed, not the reefer condition. All classes are summarised below:

- Class A: High-quality containers used for sensitive cargo, such as fruits
- Class B: Standard containers used for general cargo
- Class C: Lower-quality containers used for cargo with minimal quality requirements, used for scrap
- Class EPTI: A short inspection of the container's machinery
- Class PTI: A full inspection of the container's machinery
- Class MR: A failed PTI, additional full inspection and repair of the container's machinery

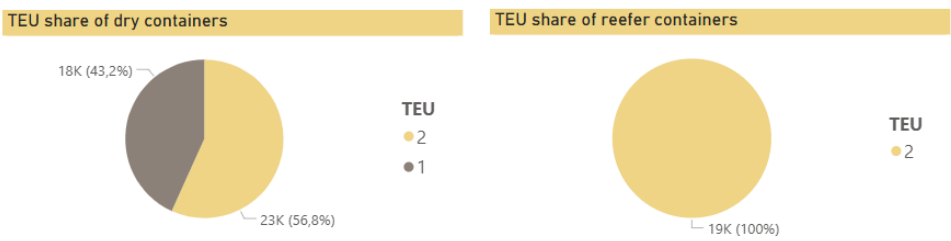


Figure 5.1: Number of containers by TEU

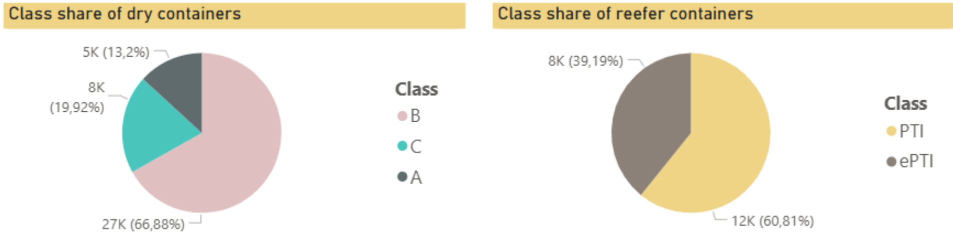


Figure 5.2: Number of containers by Class

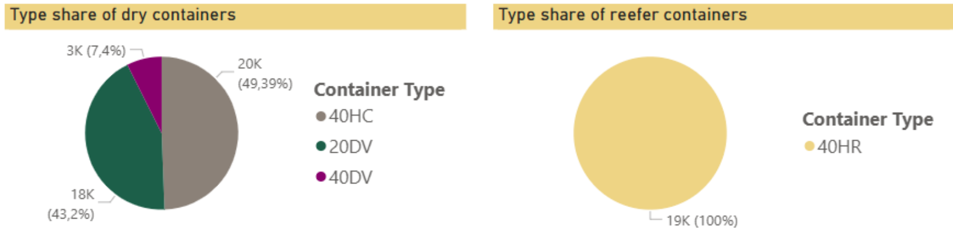


Figure 5.3: Number of containers by Type

Container path

In Figure 5.1 to Figure 5.3 the number of containers by TEU, Class and Type are given. Each container in the simulation model is assigned an ID-number, along with a set of characteristics. The generation interval for dry and reefer containers is based on the chosen PDF analysed in chapter 4. Once generated, each container is assigned a size, class and path, based on their relative frequency in the dataset. The container then follows its corresponding predefined path through the system. The relative frequency of the different paths for dry and reefer containers is presented in Table 5.2.

Table 5.2: Input path probabilities for the simulation baseline model based on data analysis

Number	Path	Count [%]	Probability [-]
1 Dry (D1)	(No actions) Export Ready	64.53	0.6453
2 Dry (D2)	Wash - Export Ready	20.45	0.2045
3 Dry (D3)	Repair - Export Ready	9.15	0.0915
4 Dry (D4)	Repair - Wash - Export Ready	5.87	0.0587
1 Reefer (R1)	PTI (other actions fixed)	55.37	0.5537
2 Reefer (R2)	EPTI (other actions fixed)	39.19	0.3919
3 Reefer (R3)	PTI + MR (other actions fixed)	5.44	0.0544

Subsystem processes

Different paths involve different combinations of subsystems visited. This means that the time a container spends inside the system depends on the specific route assigned to that container. Table 5.3 presents the time durations for each subsystem used in the baseline simulation model. For the gathering of this information, two different sources were used. Most subsystems use statistical distribution functions based on observed data, this analysis was conducted in chapter 4. Other subsystems rely on procedural knowledge gained through expert consultations of the case study depot.

Table 5.3: Input process durations per subsystem and path for the simulation model, based on data analysis and expert consultation

Number	Process	Min [min]	Max [min]	AVG [min]	Data	Procedures
A21	Normal(2, 0.5)	1.75	-	2.00	-	x
A22	Normal(0.5, 0.5)	0.25	-	0.50	-	x

Number	Process	Min [min]	Max [min]	AVG [min]	Data	Procedures
A23	Handlings + Driving	1.00	-	-	-	x
A24	Passive waiting	0	-	-	-	x
A25	Lognorm(0.240, -383, 692)	0	780	308.30	x	-
A26	Handlings + Washing	-	135	135	-	x
A27S-1	Nbinom(51.15, 0.864)	2.50	15	-	x	-
A27L-1	Nbinom(0.54, 0.000136)	17.5	21600	-	x	-
A27L-2	Nbinom(0.54, 0.000136)	155.5	21600	-	x	-
A27L-3	Nbinom(0.54, 0.000136)	343.8	21600	-	x	-
A27L-4	Nbinom(0.54, 0.000136)	480.8	21600	-	x	-
A28	Handlings + Driving	1.00	-	-	-	x
A29	Handlings + Driving	1.00	-	-	-	x
A210	Normal(0.5, 0.5)	0.25	-	0.50	-	x
A31	Normal(0.5, 0.5)	0.25	-	0.50	-	x
A32	Handlings + Driving	1.00	-	-	-	x
A33-1	Gamma(3.01, -13.56, 98.30)	0	750	-	x	x
A33-2	Gamma(3.18, -14.55, 72.94)	0	750	-	x	x
A33-3	Handlings	-	20	20	-	x
A34S	Handlings	-	15	15	-	x
A34L	Handlings	-	240	240	-	x
A35	Gamma(4.57, -110.91, 123.28)	0	1300	-	x	-
A36	Passive waiting	0	-	-	-	x
A37	Handlings + Washing	-	135	135	-	x
A38S-1	Nbinom(2.63, 0.0002)	656.93	2880	-	x	-
A38L-1	Geom(0.00014)	3536.93	21600	-	x	-
A38S-2	Nbinom(2.63, 0.0002)	336.09	2880	-	x	-
A38L-2	Geom(0.00014)	3246.09	21600	-	x	-
A38S-3	Nbinom(2.63, 0.0002)	821.06	2880	-	x	-
A38L-3	Geom(0.00014)	3701.07	21600	-	x	-
A39	Handlings	-	8	8	-	x
A310	Handlings + Driving	1.00	-	-	-	x
A311	Handlings + Driving	1.00	-	-	-	x
A312	Normal(0.5, 0.5)	0.25	-	0.50	-	x

Note: Numbers are referring to subsystems from the IDEF0 A2 and A3 figures, S: Short, L: Long, -#: Path

Subsystem capacities

These process durations per subsystem were complemented with capacities linked to each subsystem, based on expert consultation. An overview of subsystem capacities is provided in Table 5.4, where capacity types are divided into three categories.

The first is a physical buffer, which refers to the available space for trucks (with or without) containers, representing the first and last subsystems for both dry and reefer containers. The second is the local storage location, which includes designated TEU ground slots in specified areas. The third is a virtual queue, representing a request for an ECH while the container remains in a local storage location. For example, a container that has completed a repair activity requests an ECH and waits inside the repair station until it is picked up by an ECH.

Table 5.4: Input capacities for the simulation model based on layout and expert consultation

Number	Capacity type	# TEU ground slots	# Resources
A21	Physical buffer	-	1
A22	Physical buffer	-	2
A23	Physical buffer	-	1
A24	Local storage location	600	-
A25	Local storage location	126	-
A26	Local storage location	40	-
A27A	Local storage location	200	-

Number	Capacity type	# TEU ground slots	# Resources
A27B	Local storage location	964	-
A27C	Local storage location	272	-
A28	Virtual queue	-	1
A29	Virtual queue	-	1
A210	Physical buffer	-	1
A31	Physical buffer	-	1
A32	Physical buffer	-	1
A33	Local storage location	90	-
A34	Local storage location	80	-
A35	Local storage location	28	-
A36	Local storage location	576	-
A37	Local storage location	40	-
A38	Local storage location	528	-
A39	Local storage location	16	1
A310	Virtual queue	-	2
A311	Virtual queue	-	1
A312	Physical buffer	-	1

Note: Numbers are referring to subsystems from the IDEF0 A2 and A3 figures

This conceptual model is a simplified representation of the real-world system at MedRepair Smirnoffweg, focusing on the primary flows while incorporating as much operational detail as possible. As a result, certain container classes, types and paths were excluded to maintain clarity and simulation efficiency. The total storage capacity of the real-world case is equal to 4800 TEU with an operational capacity of 80%. This simplified model reduced the total capacity with approximately 8% such that the total capacity equalled 4400 TEU (excluding specials), maintaining the same operational threshold. This means that the simulation model is designed to handle up to 3520 TEU, which is the sum of TEU ground slots presented in Table 5.4.

Internal movement containers

The final input parameter focused on estimating the correct handling and driving time of the ECHs. This is presented in a matrix that follows the current driving lane setup within the depot and represent the shortest distance between the centre points of each subsystem. These distances were used to estimate travel times for container movements. This was complemented with the estimation of handling times for container pick-up and retrieval. The correct handling time values are presented in Table 4.1 and the complete distance matrix is provided in figure Table C.1 in Appendix C. Figure C.1 present the current driving lane structure of the depot.

5.4. Performance indicators

The model generated outputs that reflected the system's operational performance. To assess performance, a set of Key Performance Indicators (KPIs) was defined and is presented in Table 5.5. These outputs were essential for evaluating how well the system functioned under the original layout (baseline) and scenario-specific conditions.

These parameters provided insight into important aspects of the system, focussing on throughput, utilisation and ECH usage. Throughput indicates how efficiently the system processes containers, with higher throughput generally linked to better operational performance. ECH handling activity and driving distance are directly linked to labour and fuel costs, minimising movements while maximising handling efficiency contributes to cost reduction. This is especially important since ECD operations represent a cost for shipping lines which own there own depots. Logging subsystem occupations helps identify bottlenecks and assess whether capacities are being fully utilised. Visualising these dynamics in Power BI improves understanding of containers flows and complements the analysis conducted in chapter 4.

Table 5.5: Overview of performance indicators

Name	Description	Unit	Calculation
Throughput	Number of dry/reefer containers processed	# / day	Count of outgoing containers
Handling capacity ECH	Total number of dry/reefer containers handled by an ECH	#	Count per ECH + sum all ECHs
Driving distance ECH	Total distance covered by ECH	km	Count per ECH + sum all ECHs
Max virtual queue occupation	Number of dry/reefer containers in virtual queue ECH	#	Log simulation
Max physical buffer occupation	Number of dry/reefer containers in physical buffer subsystems	#	Log simulation
Max local storage occupation	Number of dry/reefer containers in local storage location subsystems	#	Log simulation

5.5. Assumptions & Simplifications

Throughout the system analysis and conceptual modelling process, several assumptions and simplifications were made to streamline the development of the simulation model. These decisions helped reduce complexity while maintaining the core principles and dynamics of the real-world ECD system. Starting without an initial model, the first step was to construct a robust baseline capable of testing and adapting to different layout configurations under specific operational scenarios.

Operational policies are fixed in this research, allowing for a focused analysis on how layout changes impact depot performance. The assumptions and simplifications made from a modelling perspective are summarised in Table C.8. Due to the detailed explanation of each assumption, the overview of these assumptions and simplifications is given in Appendix C.

5.6. Requirements

Table 5.6 outlines the essential requirements that guided the development of the simulation model. These included the ability to easily adjust input parameters such as process durations, distances between subsystems (reflecting layout changes) and operational policies through path configurations. Adding to this, the model is structured to support straightforward data extraction supporting the analysis and interpretation of the system.

Table 5.6: Requirements guiding the construction of the simulation model

Number	Requirements description
1	The model should accurately reflect the processes for dry and reefer containers, based on the IDEF0 diagrams numbers A2 and A3
2	The model should produce outcomes that are directly linked to KPIs to support performance analysis
3	Settings like probability distributions, fixed values and operational policies should be easy to adjust
4	The model should be easily adjustable to allow multiple simulation runs within a single execution, used for comparative testing of different scenarios and settings
5	The model must allow for easy modification of path configurations, to support the implementation and testing of different operational policies

5.7. Limitations

The constructed simulation model is a static model, meaning that all scenarios, settings, principles and path configurations are defined prior to execution. These settings remain fixed during the run, once the simulation has started. Therefore, this model does not support real-time or dynamic decision-making, which is often present in ECD operations.

The design choice of a static model was made on purpose, to remain focus on understanding the structural relationships between subsystems, rather than simulating the full complexity of dynamic operations. By doing so, the model is not capable of reallocating resources (ECHs), adjusting flows, or modifying capacities based on the operational needs.

Another important aspect of the simulation is the interarrival rate of dry and reefer containers, which was based on real-world data. Due to the static behaviour of the simplified model, the real interarrival rates were intentionally adjusted. Including the real interarrival rates would have stressed the model before meaningful insight could be drawn. Including a slightly less powerful arrival pattern following similar characteristics, helped capturing the objective of the model: understanding system relationships and identifying bottlenecks.

As a result, the model is used as a comparative tool that could analyse different layout configurations to different scenarios and settings. This to support strategic thinking and system redesign.

5.8. Implementation steps

Following the simulation framework presented in Figure 3.4, this paragraph outlines the steps taken to move from system and data analysis to the actual construction of the simulation model. It reflects one possible approach to building a model based on operational understanding and structured design. The conceptual model defined is translated into a Python model using SimPy which is a DES library in Python. The first important step was to define what to model, based on the identified entities, resources and their relationships.

Starting with the construction of setting up the simulation environment in Python. This included the setup of the whole simulation environment with its components such as, time structure, container generator and resource definition. The development started with the dry container flow of the ECD, building classes for subsystems with tailored policies. Subsystems were created one by one, to test flow logic and timing. This choice was made to verify the correct behaviour of the system. Once the dry container flow was functioning, the model was made more realistic by adding operational constraints. Such as, implementing different path configurations and probability distributions or time durations per subsystem. After finalising the dry container setup, the same structure was extended to reefer containers, using the IDEF0 A3 diagram.

This approach allowed for controlled testing and ensured the model remained focused on capturing system flows and identifying bottlenecks. This by correctly logging all relevant information used to evaluate the KPIs identified. In Figure 5.4 an overview is presented of the whole model, including its inputs and outputs.

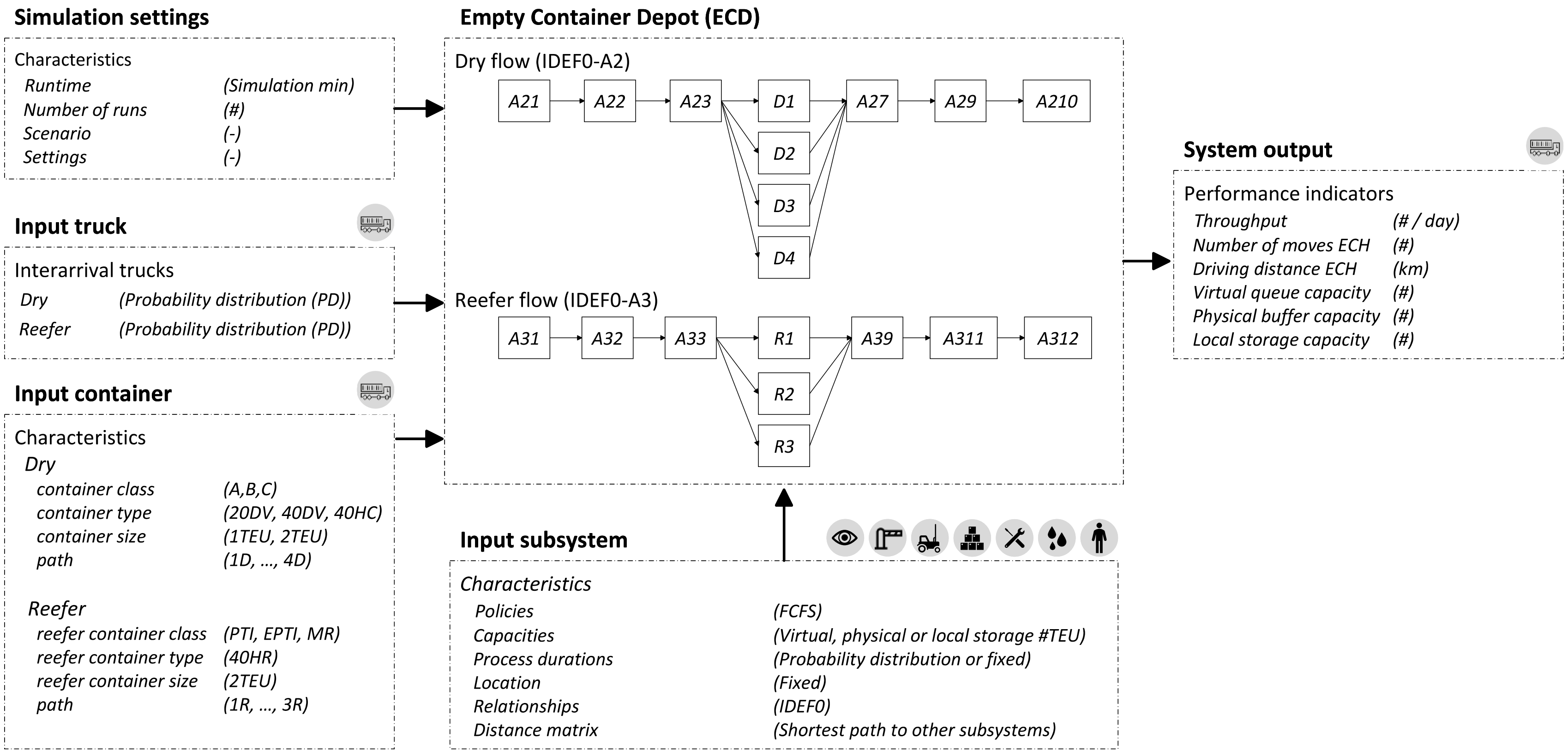


Figure 5.4: Model overview

5.9. Verification & Validation

To ensure that the simulation model accurately reflects the operational principles within an ECD, verification and validation were applied during the development process. The model was designed to support system understand and layout exploration, rather than replicating exact real-world performance. Based on findings in *S. Robinson (2016)* [49], *S. Robinson (1997)* [61], *Sargent (2015)* [40] and in *O. Balci (1994)* [62] different Validation, Verification and Testing (VV&T) techniques were used. Starting with the verification of the model comparing the conceptual model with the computerised model following the simplified version of the model development process in *Sargent (2015)* [40] and an adapted version to simulation models in *S. Robinson (1997)* [61].

Verification simulation model

The paper of *S. Robinson (1997)* [61] highlight an important step in verification of a simulation model. It is important to understand the purpose and scope of the model. Which is to provide insight into ECD operations by testing various layout structures and stacking strategies through a flexible and easily adaptable DES simulation model. The goal is to uncover and understand the operational relationships between subsystems, identify bottlenecks and analyse internal movement dynamics, such as congestion and flow disruption within the depot. This rather than creating a model that could replicate real life processes.

S. Robinson (1997) [61] mentions that the verification process needs to happen in parallel with the model constructing. During the development of the model various techniques for verification were used, also extensively discussed in *O. Balci (1994)* [62]. This paper by *O. Balci (1994)* complements different techniques that could be used in the verification process of the model. Below the list of techniques used during the construction of the simulation model, where some of these techniques will be further elaborate on in Appendix C.

- Debugging: Iteratively identifying and correcting logic errors and misconfiguration in the code
- Execution monitoring: Tracking of container movements and subsystem occupation during simulation runs
- Execution profiling: Tracking containers along specified paths, ensuring that correct logic is followed.
- Stress testing: Testing the model by influencing container generation intervals, path forcing and playing with subsystem elements and constraints. This to test robustness of the simulation, but more important for bottleneck identification

Verification involved tracking of individual containers using unique ID-numbers to monitor routing, process durations and capacity constraints. Simple debugging techniques were used that confirmed that the containers followed correct paths and respected input parameters. These input parameters were derived from system analysis, data analysis and expert consultation, ensuring correct operational logic and process durations.

Validation simulation model

Validation of the model focused on assessing whether the model behaves in line with real-world operations. This included expert review, comparison of model logic and sensitivity testing. Following the adapted simplified version of the model development process in *S. Robinson (1997)* [61] validation is there in two forms, white-box and black-box validation.

In this study, white-box validation was conducted by comparing the conceptual model, that is implemented into the Python simulation model, to the real-world operation of the depot. Key operational parameters such as container generation, path durations, repair times and travel times inside the depot were incorporated based on data. This aligns directly with the examples given for white-box validation within the paper of *S. Robinson (1997)* [61].

Black-box validation, on the other hand, evaluates the model as a whole by comparing its outputs to the the real-world under similar input conditions. Due to the static nature of the model, meaning no policy changes or redirection during runs could be executed, it was difficult to compare the performance of the model with the dynamic real-world system. Making the model useful for understanding system behaviour instead of predicting future performance under different scenario, setting, layout configurations and stacking strategies.

As suggested in *S. Robinson (1997)* [61], if not direct comparison between the real-world and model can be made, the results can be compared with the knowledge of experts to check its validity. Model outcomes are extensively reviewed and discussed with depot experts, providing a solid basis for confidence. By changing the settings in combination with debugging techniques every path, subsystem and relationship were tested and discussed. These tests and discussion sessions confirmed that constraints and operational rules defined in the simulation were correctly applied.

5.10. Conclusion model

This chapter presents the simulation model developed to represent the operations of the ECD at MedRepair Smirnoffweg. The model serves as a direct translation of a conceptual model, which is based on literature, expert consultation, system analysis and data insights. While it focuses on the specific context of the case study depot, the model is designed to be flexible. The model is capable of adapting to various layout configurations, stacking strategies, path designs and operational policies.

The primary objective of the model is to uncover and understand operational relationships between subsystems. Adding to that, the model helps identify bottlenecks and support analysis of internal movement dynamics such as congestion and flow disruptions. This is achieved by providing a wide range of input parameters, including subsystem and container specific parameters, path configurations and distances between subsystems for evaluating driving distance by ECHs. Assumptions and simplifications are applied to maintain and create a balance between model complexity and interpretability, while respecting the goal of the model, which is capturing essential dynamics of the system.

To evaluate the system performance, several indicators were defined, focusing on system throughput, occupation rates of subsystems and ECH usage. By comparing outcomes to these indicators, insights into the operational efficiency of the depot can be provided. It is important to note that the model is static in nature, relying on fixed inputs and therefore the model is unable to adapt dynamically during runtime. The primary value of the model lies in the comparative analysis of layout configurations and stacking strategies. Putting this all together, this model is a powerful tool that supports tactical and strategic decision-making and informs the rethinking of layout configurations.

6 Scenario design and simulation analysis

This chapter builds on the simulation framework defined in Figure 3.4 and focusses on Phase 4 and 5 of the framework. It outlines the construction of four different scenarios and the development of alternative layout configurations and stacking strategies. These layout designs are informed by a combination of system analysis, data analysis, model-based testing and insights from literature, presented in chapter 2 till chapter 5.

The chapter is structured in the following way. First a brief overview of the simulation objectives, followed by the formulation of scenarios and the design of the (layout) settings. This is complemented by a description of the simulation setup and analysis of simulation results. Afterwards, a discussion of the interpretation of the findings is presented, with its relationships to the set goals.

6.1. Simulation goal

The goal of these simulation experiments is to gain insight into the operational dynamics of an ECD, rather than optimise its performance. By simulating various layout configurations and stacking strategies under different seasonal characteristics, the aim is to evaluate whether alternative settings can lead to improved performance, as defined through the KPIs in section 5.4. These different settings are compared to the current layout of the case study depot of MedRepair Smirnoffweg, which will act as a baseline in every scenario. While each layout and stacking strategy remains fixed during individual simulations runs, the model allows for the development of tailored configurations that better suit specific operational conditions. This adaptive process helps identify layouts that avoid exceeding depot capacities and maintain or improve efficiency under both peak, regular and easy conditions. Simulation allows exploring system behaviour under different operational scenarios, revealing system dynamics and bottlenecks. Based on findings derived from system analysis, data analysis, model-based testing and literature, simulation helps improve understanding of the ECD system. Combining these elements will result in new layout configurations tailored to the case study conducted.

To conclude, these experiments are designed to compare the performance of different layout and stacking strategies in four different scenarios. With the goal of identifying configurations that improve ECD operations based on KPI analysis.

6.2. Scenario development

As described in section 3.8 the construction of the scenarios is informed by data analysis and expert consultations. Which is complemented with the modelling setup described in chapter 5. An important aspect of the scenarios is that they should reflect real-world operational conditions, making them relevant to test with the goal of improving ECD operations. Below a description is given for the four scenarios developed, with respect to their goals.

6.2.1. Scenario goals

The core objective is to evaluate how different layout designs and stacking strategies perform under varying seasonal characteristics of empty container logistics. By simulating both peak and regular operational periods, the model should identify configurations that help avoid exceeding depot operational capacities, maintain depot efficiency or improve efficiency. A clear distinction into two categories can be made for the four different scenarios.

Scenario 1 focused on the peak months for reefer container arrival, with its goal to test the system resilience under stress conditions. Scenario 2,3 and 4, represent regular operations, which help explore strategic decisions to improve performance. Each scenario therefore serves a unique purpose and will be explained in more detail in the following sections.

6.2.2. Scenario 1: Reefer season

This scenario is tailored to on-season operations for reefer container arrival. Based on the findings in chapter 4, little to no fluctuations in dry container arrival is observed. Making reefer container arrival here a leading specification for this scenario.

This scenario represents the peak months for depot operations, usually September to December, with fluctuating reefer container interarrival patterns. This scenario tests system resilience under stress, reflecting real-world conditions where strategic decision-making is limited. A more detailed description is given in Figure 6.1.

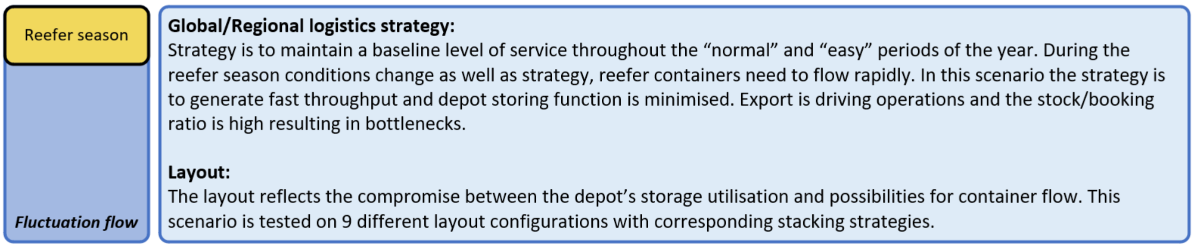


Figure 6.1: Scenario 1: Reefer season

6.2.3. Scenario 2: Normal flow

This scenario is tailored to the off-season operations for reefer container arrival. This scenario covers regular months, January to August, with stable container flows.

This scenario serves as a baseline for exploring strategic layout and stacking strategy decisions in scenarios 3 and 4. Performance is measured against the baseline model (current depot layout) to identify improvements for 3 different settings. A more detailed description of this scenario and its goal is presented in Figure 6.2.

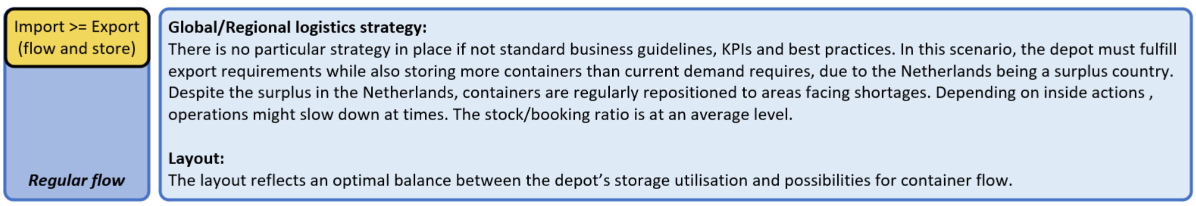


Figure 6.2: Scenario 2: Normal flow

6.2.4. Scenario 3: Overflow

This scenario is also tailored to the off-season operations for reefer container arrival. This scenario covers regular months, January to August, with stable container flows. This scenario explores strategic layout and stacking strategy decisions focussing on long-term operational efficiency. Performance is measured against the baseline model (current depot layout), other settings and scenario 2 to identify improvements. A more detailed description of this scenario and its goal is presented in Figure 6.3.

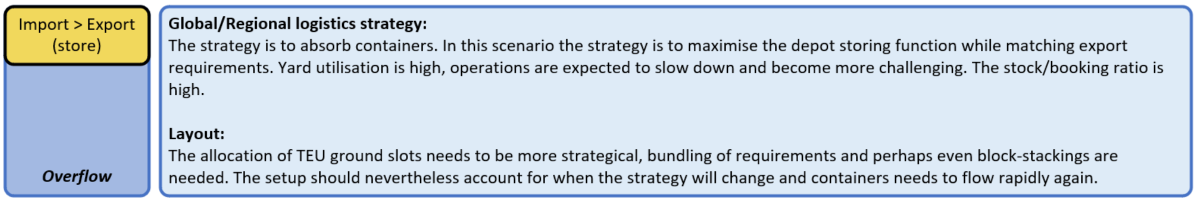


Figure 6.3: Scenario 3: Overflow

6.2.5. Scenario 4: Throughput

This scenario is also tailored to the off-season operations for reefer container arrival. This scenario covers regular months, January to August, with stable container flows. This scenario explores strategic layout and stacking strategy decisions focussing on long-term operational efficiency. Performance is measured against the baseline model (current depot layout), other settings and scenario 2 to identify improvements. A more detailed description of this scenario and its goal is presented in Figure 6.4.

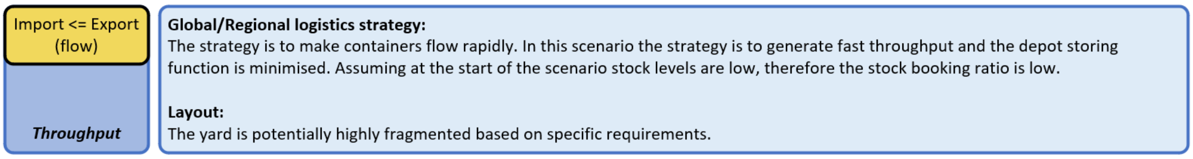


Figure 6.4: Scenario 4: Throughput

6.3. Layout development

This section introduces the creation of eight layout settings, developed based on insights from system analysis, data analysis, model testing and literature. These designs are the result of combining findings from phases 1 to 3 of the simulation framework, providing realistic, tailored and data-driven configurations.

6.3.1. Setting goals

The goal of layout development is to design performance oriented settings tailored to ECD operations. These settings focus only on spatial configuration and subsystem capacities, keeping all other simulation parameters constant. By doing so, a clear comparison of layout and stacking strategies can be made against the baseline model. Where the aim is to design new configurations that improve performance across the four scenarios described.

Settings are focused on two main aspects, the spatial layout of subsystems and container stacking decisions. The simulation assigns ECHs to specific flows, making them responsible for (reefer) container pick-up, internal movement and gate-out activities. Most settings aim to reduce the internal movement distances of ECHs, as they account for the majority of moves within the depot.

6.3.2. Setting design approach

Following the simulation framework in Figure 3.4, layout setting development is part of the scenario construction and builds on findings from phases 1 to 3. Using the techniques mentioned in section 5.9 to test the model described in chapter 5, provided a thorough analysis of the system discovered in phases 1,2 and 3 of the simulation framework.

Important findings include upstream bottlenecks such as the shared washing area (A26) and reefer ready (A310) subsystems, caused by a combination of process durations and limited capacities. Simulating different dry and reefer container generation rates revealed how bottlenecks shifted through the system for both the dry and reefer container part. This was constantly observed by checking the occupation rates of all subsystems over time.

These findings from system analysis, data analysis and model testing form a substantial part of the basis for the constructing of settings. This foundation is further complemented by methods and insights discussed in the literature in chapter 2.

The layout development approach in this research closely aligns with the methodology described in the paper by *Maina et al. (2018)* [51]. This paper describes the use of Muther's SLP to (existing) facility layout, using flow analysis and an Activity Relationship Chart (ARC) to guide decisions, which are both used for layout development in this research. Since subsystem placement is not strictly constrained, dry and reefer container flows drive layout decisions, aiming to reduce distance travelled between subsystems by ECHs. These relationships between the different subsystems for IDEF0 A2 and A3 are described in Figure 6.5 for the case study depot.

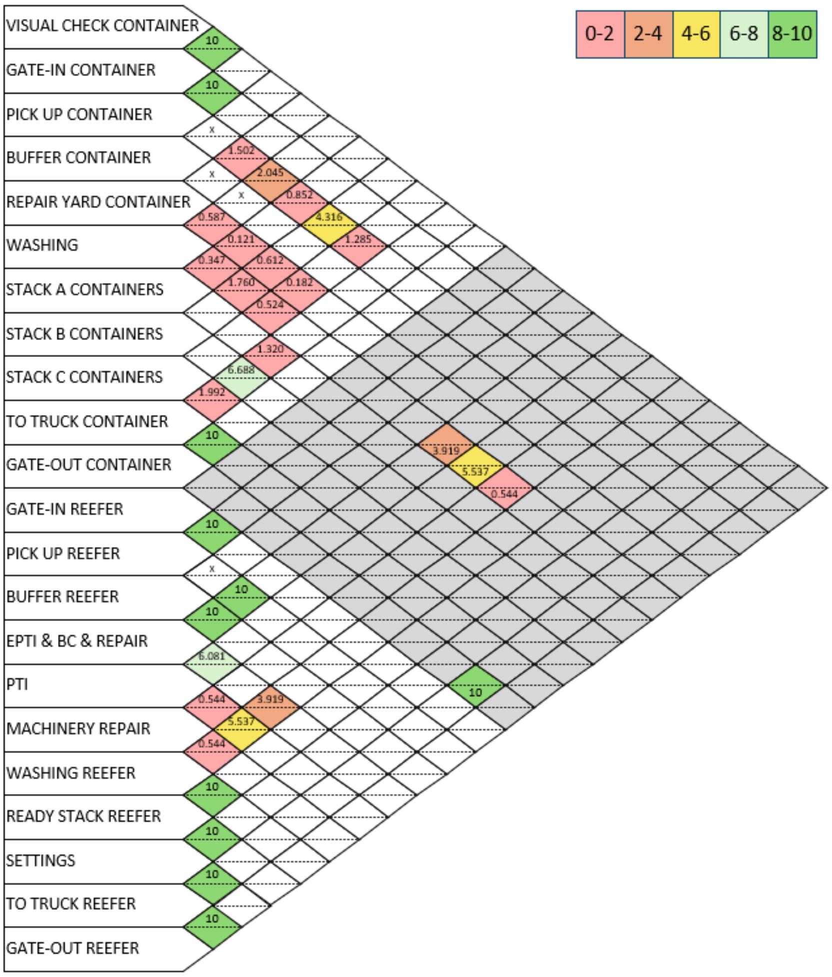


Figure 6.5: Activity Relationship Chart, focused on container flow case study

Maina et al. (2018) [51] use the Pairwise Exchange Method (PEM) in combination with a distance matrix based on rectilinear centroid-to-centroid distances. This aligns closely with the way the distance between subsystems is calculated, following existing infrastructure. While their objective is to minimise material handling costs, this research focuses on flow efficiency, specifically reducing distance travelled by ECHs which is one of the KPIs defined. This approach is further supported by *Low and Wong (2017)* [52], who also apply SLP to redesign an existing layout with the goal to reduce distance travelled using simulation.

In contrast to *Maina et al. (2018)* [51], this research does not use Multi-Criteria Decision Making (MCDM) as evaluation technique. Instead this research uses selected elements of the SLP framework used in *Maina et al. (2018)* [51], to use as input for simulation-based evaluation. The improvements demonstrated in *Maina et al. (2018)* [51] supports the expectation that performance improvements can be obtained through this layout development approach used in this research.

6.4. Simulation setup & Analysis

Following up on section 6.2 and section 6.3, this section outlines the simulation setup used to evaluate settings to scenarios. For every scenario-specific setting, the simulation environment and input data are described. This structured approach is useful for the comparison and analysis of the model outcomes.

6.4.1. Scenario 1: Reefer season setup

A brief introduction into the setup for scenario 1 is presented. All settings follow the same characteristics as described in Figure 5.1, Figure 5.2, Figure 5.3, Table 5.2, Table 5.3 and Table 5.4. These characteristics cover most of the, in Figure 5.4 described, input parameters. In Table 6.1 the simulation settings are described, Table 6.2 includes truck interarrival rates for dry and reefer containers. Simulation minutes only take into account the first 5 days of every week (working days), with corresponding opening and closing hours of the depot. The average of 25 simulation run outcomes will be compared, this to gather insights into relationships and system behaviour.

Table 6.1: Scenario 1: Simulation settings

Characteristics	Value	Unit
Runtime	230.400	Simulation minutes
Number of runs	25	-
Measurement interval	780	Simulation minutes
Depot open	780	Operating minutes
Depot closed	660	Non-operating minutes
Driving speed ECH	10	km / h
Occupation all subsystems at start	0	#TEU used

Table 6.2: Scenario 1: Interarrival containers

Container type	Probability distribution	Interval [min]	# Operational days
Dry	Geom(p=0.1918)	0 < 201.600	140
Dry	Geom(p=0.0001)	≥ 201.600	20
Reefer	Geom(p=0.0964)	0 < 57.600	40
Reefer	Geom(p=0.0645)	57.600 < 72.000	10
Reefer	Geom(p=0.1453)	72.000 < 100.800	20
Reefer	Geom(p=0.0645)	100.800 < 115.200	10
Reefer	Geom(p=0.0964)	115.200 < 201.600	60
Reefer	Geom(p=0.0001)	≥ 201.600	20

This scenario is tested for nine different layout configurations and stacking strategies including the baseline setting. Which represent the current layout of the case study depot. Below a description of the development of each setting is presented following the process described in subsection 6.3.2.

Setting Baseline

In Figure 6.6 the baseline setting for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. This layout acts as a baseline for the setting comparison. Table 6.3 includes references to other tables, which provide the actual input values for this setting.

Table 6.3: Scenario 1: Baseline settings

Characteristics	Input
Capacities	Table 5.4
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.1

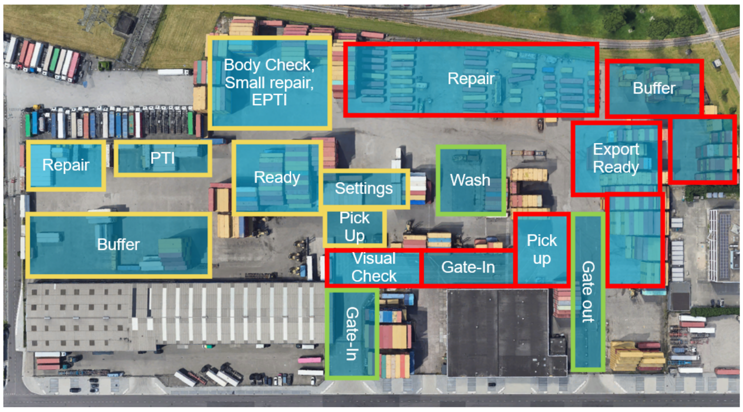


Figure 6.6: Schematic overview of baseline layout ECD

Setting 1

In Figure 6.7 setting 1 for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.4 includes references to other tables, which provide the actual input values for this setting. As described in subsection 6.3.2 settings are informed by findings form the system analysis, data analysis and model testing. Complemented by an analysis of the ARC in Figure 6.5, where path probabilities for successive subsystems are described. Based on the ARC chart analysis, in combination with insight from other analysis steps, setting 1 is constructed.

By analysing the current baseline setting in relation to the ARC, the placement of subsystems can be reconsidered. It is important to respect flows with high occurrence (presented in green), as these subsystems are likely best positioned close to each other to minimise ECH driving distances. Another key factor is the ratio between dry and reefer containers, as shown in Table 5.1. Nearly 30.000 containers (dry and reefer combined) pass through subsystems *A26* and *A37*, which corresponds with the shared washing area for this case study depot, following subsystem codes in Figure 4.4 and Figure 4.5. From this total, 64% are reefer containers and only 34% are dry containers.

Prioritising the path for reefers by relocating this station closer to successive reefer subsystems can further reduce the ECH travel distance for ECHs responsible for internal movements. By interchanging this station with subsystems *A38* and *A39* a new layout is created, keeping the distance between *A26/A37* to *A39* unchanged. This setting will only look into this layout change, keeping stacking strategies similar as in the baseline setting.

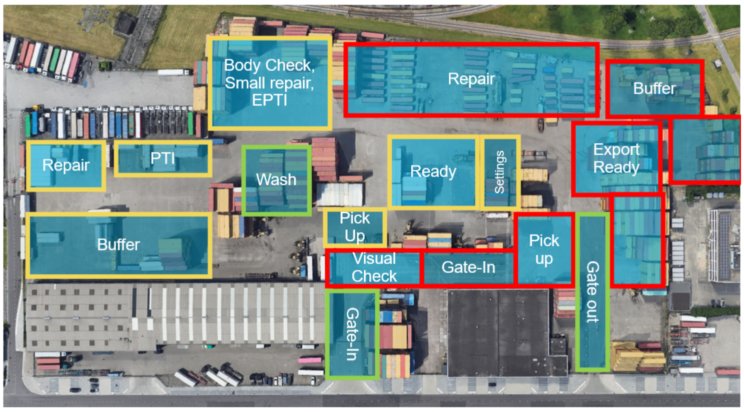


Figure 6.7: Schematic overview of setting 1 layout ECD

Table 6.4: Scenario 1: Setting 1

Characteristics	Input
Capacities	Table 5.4
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.2

Setting 2 OD

In Figure 6.8 setting 2 OD for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.5 includes references to other tables, which provide the actual input values for this setting. Insights from chapter 4 and Figure 6.5, together with results form model-testing, inform the construction of a new layout configuration.

A clear bottleneck is detected in subsystem *A33*, which corresponds with the body check and EPTI area for reefer containers. This subsystem, characterised by limited capacity, long process durations and 100% of the flow passing through it, will result in a fast accumulation of containers inside this area. This in combination with high reefer interarrival rates could cause problems to the system.

When *A33* has reached its capacity, reefer containers will be redirected to the buffer zone. When the buffer capacity is reached, trucks will have to wait until the capacity becomes available, resulting in trucks standing outside on the public road, which is highly undesirable.

For other subsystems such as *A25*, corresponding to the repair yard for dry containers, initial set capacity is never reached. By shifting capacity from *A25* to *A33*, a new layout and stacking strategy can be provided, that is more tailored to current depot operations. By interchanging the TEU ground slots between these subsystems, the centres are placed closer to the pick up areas for both container types. Resulting in less driven distance for ECHs related to these activities.

This setting number 2 is separated into two different settings, the "Only Distance (OD)" and "Combined (C)" settings. The OD setting is less realistic, as it only relocates the centres of the subsystems without adjusting their capacities. This setting is included to compare the effects of a layout change alone versus a combined change in both layout and stacking decisions.

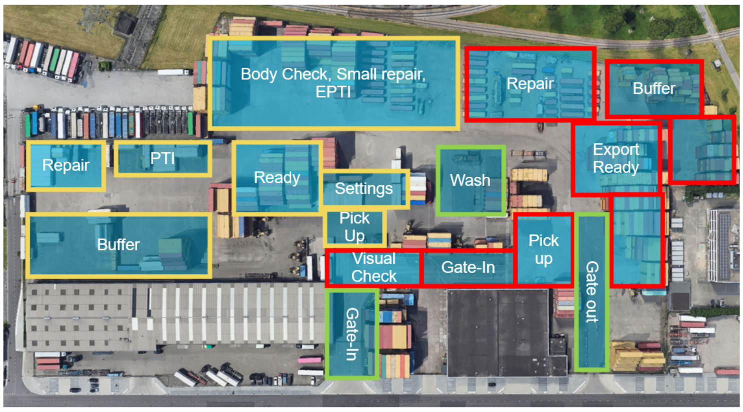


Figure 6.8: Schematic overview of setting 2 layout ECD

Table 6.5: Scenario 1: Setting 2 OD

Characteristics	Input
Capacities OD	Table 5.4
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.3

Setting 2 C

In Figure 6.8 setting 2 C for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.6 includes references to other tables, which provide the actual input values for this setting. The setting construction follows the same approach as described for Setting 2 OD.

Only difference is the correct adaptation of the number of TEU ground slots assigned to each subsystem, which is defined in Table 6.7. With this new configuration, two main improvements are expected. First, bottleneck dynamics can be better managed, as more capacity is assigned to subsystem *A33*. Second, by relocating the centre of the repair yard (*A25*) closer to its successive subsystems for dry containers, the driving distance for ECHs responsible for pick-up and internal movements should be reduced.

Table 6.6: Scenario 1: Setting 2 C

Characteristics	Input
Capacities C	Table 6.7
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.3

Table 6.7: Input capacities for setting 2 based on layout and expert consultation

Number	Capacity type	# TEU ground slots	# Resources
A25	Local storage location	72	-
A33	Local storage location	144	-

Setting 3

In Figure 6.9 setting 3 for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.8 includes references to other tables, which provide the actual input values for this setting. As described in subsection 6.3.2 settings are informed by findings form the system analysis, data analysis and model testing. Complemented by an analysis of the ARC in Figure 6.5, where path probabilities for successive subsystems are described.

Focussing on this flow presented in the ARC, interchanging subsystems *A33* and *A36* could lead to a reduction in internal movement distances. By not changing distance with respect to each other, but also to previous subsystem *A32*, flow might be optimised. Bringing subsystem *A33* and *A34* closer together, but at the cost of increasing distance between *A33* and *A37*. This setting is highly focused on the reefer section of the system, keeping the configuration for dry containers fixed.

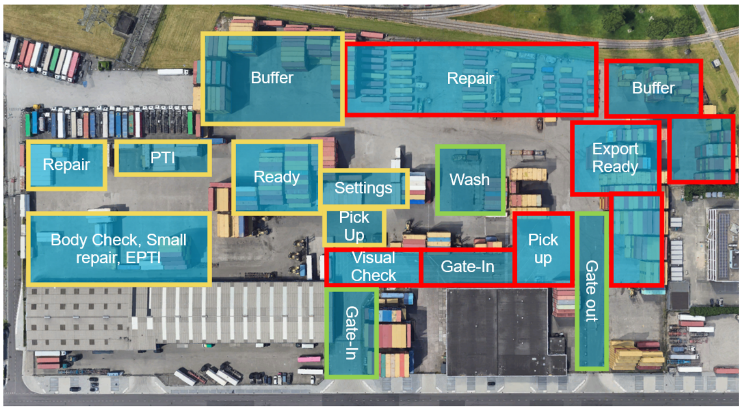


Figure 6.9: Schematic overview of setting 3 layout ECD

Table 6.8: Scenario 1: Setting 3

Characteristics	Input
Capacities	Table 5.4
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.4

Setting 4 OD

In Figure 6.9 setting 4 OD for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.9 includes references to other tables, which provide the actual input values for this setting. This setting combines the approaches used in setting 1, 2 and 3. It first interchanges subsystems *A33* and *A36*, as well as *A26/A37* and *A38, A39*. Afterwards, the sizes of both *A25* and *A36* are adjusted. This setting number 4 is also separated into two different settings, the "Only Distance (OD)" and "Combined (C)" settings. Following the same logic used as in setting number 2. This combined approach tests if integrating these changes will improve performance, focused on bottleneck dynamics and ECH driving distances.

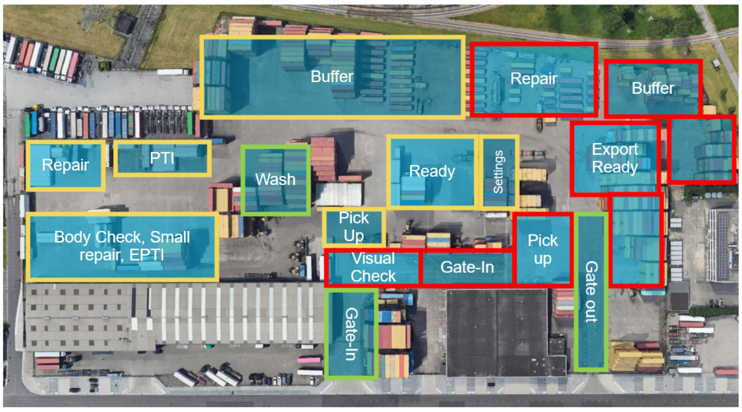


Figure 6.10: Schematic overview of setting 4 layout ECD

Table 6.9: Scenario 1: Setting 4 OD

Characteristics	Input
Capacities OD	Table 5.4
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.5

Setting 4 C

In Figure 6.10 setting 4 C for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.11 includes references to other tables, which provide the actual input values for this setting. The setting construction of this setting follows the same approach as described for Setting 4 OD. Only difference is the correct adaptation of the number of TEU ground slots assigned to each subsystem, which is defined in Table 6.7. With this new configuration, the expectation is that bottleneck dynamics can be better handled.

Table 6.10: Input capacities for setting 4 based on layout and expert consultation

Number	Capacity type	# TEU ground slots	# Resources
A25	Local storage location	72	-
A36	Local storage location	774	-

Table 6.11: Scenario 1: Setting 4 C

Characteristics	Input
Capacities C	Table 6.10
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.5

Setting 5

In Figure 6.11 setting 5 for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.12 includes references to other tables, which provide the actual input values for this setting. As described in subsection 6.3.2 settings are informed by findings form the system analysis, data analysis and model testing. Complemented by an analysis of the ARC in Figure 6.5, where path probabilities for successive subsystems are described. By rethinking the current system, which is constrained by its current shape and perimeter configuration, a complete new layout setup can be designed. This conceptual redesign excludes consideration of the financial investment required to implement such structural changes. This setting will adjust the current shape and perimeter configuration, while maintaining the same surface area.

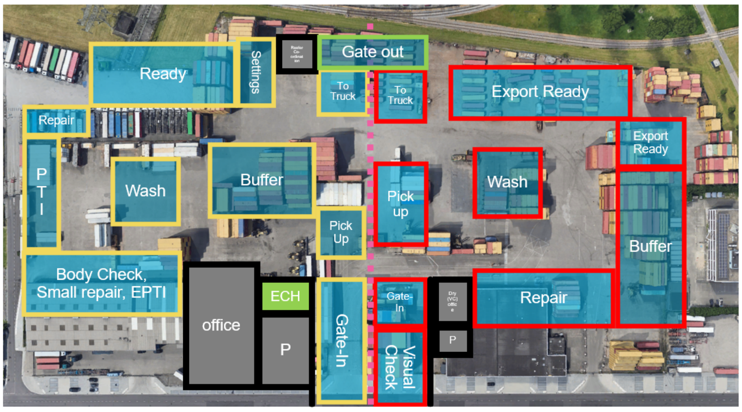


Figure 6.11: Schematic overview of setting 5 layout ECD

Following the logic described above, a new system can be developed, that focuses on two main goals. First, reducing internal driving distances of ECHs responsible for the internal movements of both dry and reefer containers. Second, provide a strategy that is better in controlling the bottleneck dynamics within the system. Key adaptations to the system are presented below:

- Shape and perimeter are assumed to be rectangular, as presented in Figure 6.11. Adjusting the current irregular shape to a more regular shape, as discussed in *Drira et al. (2007)* [50].
- Gate-in and gate-out operations for both container streams remain separated. However, trucks will enter from one side of the facility and exit from the opposite side. Since containers are picked up and placed from the side, trucks can follow a straight path through the depot, simplifying the process and ensuring clarity for drivers.
- Layout has been adapted from a traditional open-field configuration to a hybrid design that combines elements of both loop and open-field layouts, based on layouts discussed in *Drira et al.*

(2007) [50]. Driving distances are calculated using the layout configuration described in Figure C.2.

- Based on model testing, the combined washing are for *A26* and *A37* in the baseline layout creates a significant bottleneck. Therefore, this section has been split, providing separate washing facilities for both dry and reefer containers streams. Positioning *A26* and *A37* centrally aligns with flow analysis outcomes presented in the ARC.
- Distances between other subsystems are minimised based on successive flow analysis presented in the ARC. Adding to this, the flow for reefer containers is expected to be clockwise, following the path logic in Figure 4.5. For dry containers this would be the opposite, moving container mostly counter clockwise, following the path logic in Figure 4.4. This adjustment is expected to reduce the driving distances within the facility, especially on the reefer side.
- Other supporting elements, such as office, parking areas, coordination centres and warehousing are also incorporated in the layout design. These components maintain similar dimensions, but they are not further elaborated upon in this setting.

Table 6.12: Scenario 1: Setting 5

Characteristics	Input
Capacities	Table 6.13
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.6

Table 6.13: Input capacities for setting 5 based on layout and expert consultation

Number	Capacity type	# TEU ground slots	# Resources
A26 + A37	Local storage location	40 + 40	-

Setting 6

In Figure 6.12 setting 6 for this scenario 1 is presented, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Table 6.14 includes references to other tables, which provide the actual input values for this setting. The setting construction of this setting follows the same approach as described for setting 5, but complements this setting by an improved version of setting 5 which is derived by model-testing.

Key differences are in the placement of the dry repair yard, buffer spaces and placement of the supporting elements. Running setting 5 reveals a clear bottleneck in upstream flows for reefer containers. Therefore, a different stacking strategy is implemented by stacking 7 levels high in stead of 6 high, which is normally the maximum stacking height used. This is done only for subsystem *A39*, which is the ready stack for reefer containers. Other adaptations to the capacity are discussed in Table 6.15.

Expected is that this improved strategy is better in controlling bottlenecks dynamics for this specific scenario. With respect to driving distances of ECHs there is not a significant difference expected.

Table 6.14: Scenario 1: Setting 6

Characteristics	Input
Capacities	Table 6.15
Process durations	Table 5.3
Location	Fixed
Distance matrix	Table C.7

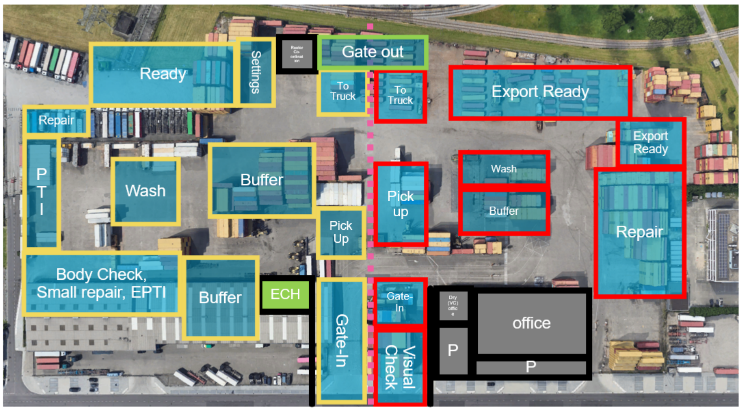


Figure 6.12: Schematic overview of setting 6 layout ECD

Table 6.15: Input capacities for setting 6 based on layout and expert consultation

Number	Capacity type	# TEU ground slots	# Resources
A24	Local storage location	200	-
A26	Local storage location	20	-
A36	Local storage location	976	-
A37	Local storage location	40	-
A38	Local storage location	728	-

6.4.2. Scenario 1: Reefer season analysis

This scenario is evaluated using the KPIs defined in Table 5.5, following the same structure as presented in this table. The KPIs are grouped into three main categories: throughput, ECH usage and subsystem occupation rates. This section begins with a brief summary of the key findings for scenario 1, highlighting the main conclusions. In addition to the main conclusions, a more detailed explanation of the results is provided to offer further insights.

Overview of scenario 1 results

To provide a clear understanding of the system dynamics, it is important to evaluate the KPIs together. This combined view helps explain the scenario outcomes more effectively. Starting with the analysis of the throughput for the nine different settings defined.

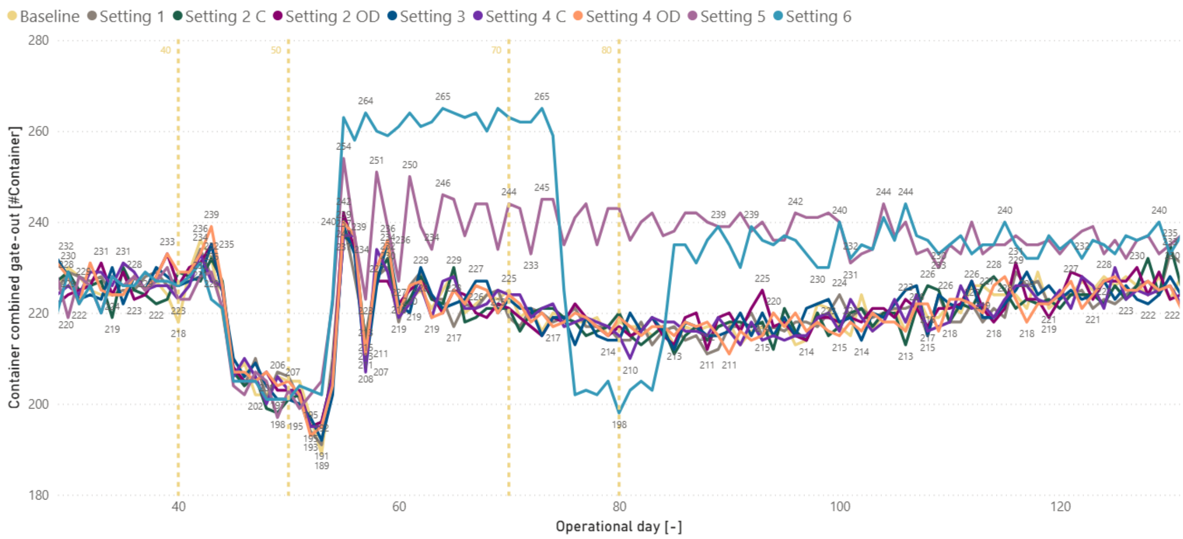


Figure 6.13: Scenario 1: Average dry and reefer container gate-out per operational day

As shown in Figure 6.13, settings B to 4 follow the same throughput pattern. The same holds for the occupation rates and bottleneck dynamics for these settings. Although ECH usage (number of moves and driven distance) across settings is different, this is not directly reflected in the throughput. Movements of containers within the depot account for a small percentage of the total dwell time of containers inside the depot, therefore this is not directly visible in the throughput. Meaning that process durations within subsystems highly influences throughput of similar settings, as they account for a large share of the total dwell time inside the system.

For settings 5 and 6 the throughput pattern, bottleneck dynamics and ECH usage are different. Besides the process durations within subsystems, throughput is influenced by bottleneck occurrence. Settings 5 and 6 are better in handling and preventing bottlenecks for this scenario. Therefore the varying generation rates of reefer containers are better reflected in the different periods, this pattern is clearly visible in Figure 6.13.

Adding to this analysis, the next KPI category is focused on the usage of ECHs. Following the approach in subsection 6.3.1, the settings focus on the reduction of driving distances for ECHs responsible for the internal movement of (reefer) containers. As shown in Table 6.16 and Table 6.17, the total number of moves and distance covered by ECH responsible for these processes, is lowered for most settings.

Table 6.16: Scenario 1: Comparison of number of moves by an ECH to the baseline setting

		C PU		C IM		C TT		R PU		R IM1		R IM2		R TT
Total SB		21,070		11,622		20,868		11,377		25,240		18,963		11,376
△ S1	+	29	+	39	-	7	+	21	+	386	-	272	+	21
△ S2 OD	+	4	-	47	+	1	+	12	-	23	+	7	+	12
△ S2 C	-	48	-	62	-	49	-	4	-	344	-	147	-	4
△ S3	+	2	+	19	+	9	-	8	-	22	-	12	-	8
△ S4 OD	+	1	+	3	-	34	+	41	+	467	-	369	+	41
△ S4 C	+	50	+	21	+	3	+	35	+	536	-	164	+	36
△ S5	+	12	-	2.898	+	183	+	37	+	2.089	-	2.372	+	37
△ S6	+	29	-	2.769	+	202	+	73	+	2.323	-	4.063	+	73

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.17: Scenario 1: Comparison of distance travelled by an ECH to the baseline setting [in m]

		C PU		C IM		C TT		R PU		R IM1		R IM2		R TT
Total SB		3,261,237		2,971,552		1,683,047		3,301,807		7,116,044		5,576,460		796,392
△ S1	+	319,554	+	1,617,804	-	1,303	+	6,748	-	1,127,505	-	1,295,956	+	2,508,934
△ S2 OD	-	288,634	-	189,557	+	955	-	617,288	-	20,265	-	43,586	+	815
△ S2 C	-	292,375	-	188,735	-	4,035	-	731,239	-	127,353	-	88,548	-	246
△ S3	-	195	+	389	+	529	-	13,400	-	11,056	-	6,402	-	563
△ S4 OD	+	20,005	+	1,445,374	-	3,490	+	961,416	-	889,767	-	949,149	+	2,514,746
△ S4 C	+	28,380	+	1,451,306	+	339	+	916,169	-	872,477	-	916,741	+	2,513,064
△ S5	+	1,399,663	-	907,125	+	1,536,788	-	348,464	-	3,182,915	-	3,181,934	+	230,953
△ S6	+	1,558,943	-	947,208	+	1,540,460	-	71,273	-	3,010,059	-	3,497,694	+	234,175

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Settings 1 to 4 have similar characteristics, with same bottleneck occurrence, but slightly different ECH use. This is related to the differences in driving distance between subsystems. Values do not deviate much because similar container flows occur for settings B to 4.

Settings 5 and 6 follow a totally different layout setup where bottleneck dynamics are better handled and driving distances are lowered, especially for the reefer part. This combination improves the flow of containers inside the system, which is reflected by throughput under different interarrival rates of containers. For this flow less containers are redirected to buffer areas, which results in less moves made by ECH responsible for internal movements. To conclude, both settings 5 and 6, result in fewer total moves, reduced internal movement driving distances and improved throughput under varying container interarrival rates.

To complement the analysis of throughput and ECH movements, subsystem occupation rates are examined to provide insights into spatial utilisation and bottleneck formation within the depot. Visual inspection of subsystem occupation rates helps identify bottlenecks. By iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks by changing the layout structures and stacking strategies.

Comparison of settings 1 to 4 show that although ECH usage is different occupation rates and bottleneck dynamics remain similar. This is also reflected in the throughput pattern for these settings. Following the approach described above, rethinking the system and its layout configuration could change these patterns. Settings 5 and 6 show different occupation rates and bottleneck dynamics under the same simulation conditions. This results in different ECH usages and throughput values. A more detailed explanation and visualisation of the occupation of subsystems is presented in 6.4.2: Occupation rate analysis.

Throughput analysis

Understanding throughput behaviour of the system requires first an understanding of what influences the throughput. In Figure 6.13 the throughput is analysed after a 30 operational days warm-up time, which is supported by the determination of the warm-up time defined in section D.1. Starting with zero containers inside the system would not reflect real throughput of the system. By visually inspecting the throughput values after 30 days the throughput stabilises, as generation rates of dry and reefer containers remain stable. Dividing this visual representation into 4 different segments, conclusions can be drawn on the throughput of different settings compared to the baseline settings. Insights are complemented by visually inspecting occupation rates for both dry and reefer container subsystems presented in 6.4.2: ECH travelled distance analysis.

- **Operational day interval 40-50**: Truck arrival shift from a normal situation to an easy situation, resulting in less reefer containers entering the system between days 40 and 50 of the simulation. For this period of 2 operational weeks, a drop in throughput is visible. Every setting follows the same pattern. To complement this analysis a visual inspection is needed for every setting for the occupation rates for both dry and reefer subsystems. By analysing the occupation rates of all settings, the conclusion can be drawn that under these interarrival rates of trucks, no bottlenecks occur. Influencing factors are process durations, handling times and distance travelled by ECH.
- **Operational day interval 50-70**: Truck arrival shift from an easy situation to a stressed situation, resulting in more reefer containers entering the system between days 50 and 70. For this period of 4 operational weeks, an increase in throughput is visible. Every setting, which is related to the current layouts and driving lanes, follows the same pattern. Scenarios 5 and 6 show improved throughput in this period. At some point the throughput stabilises and even decreases. When visually inspection the occupations of subsystems, the system is completely full at this point. Throughput relies on process durations, subsystem capacity and ECH availability and driving distances.
- **Operational day interval 70-80**: Truck arrival shift back from a stressed situation to an easy situation, resulting in less reefer containers entering the system between days 70 and 80. Setting B to 5 all keep following the same pattern, this is related to containers that where still waiting outside the system to enter. So this decreased truck interarrival rate does not immediately result in pressure relieve. The drop in throughput for setting 6 requires additional visual inspection of the occupation rates of subsystems. As discovered, no clear bottlenecks occurred in this system, meaning the system was not completely full yet. Therefore it follows the pattern related to the interarrival rates.
- **Operational day interval 80-130** Truck arrival shift back from an easy situation to a normal situation. For setting B to 4, this results in a slight increase in throughput to the level obtained before day 40. The point where the gradient of the line is equal to 0, is the moment when a balance is reached for the request for reefer internal movement by ECHs. ECHs that are assigned to the internal movement processes, supply containers to successive subsystems based on FCFS policy. A move that directly contributes to the throughput of the system is the movement of container between the ready stack for reefers and settings area. If there are many other internal movement requests, when the system is facing high occupation rates, the share of movements from ready reefer to settings is less. Meaning that less reefers are provided to the settings area. This is visualised through a shifting gradient. Settings 5 and 6 remain stable, this is highly related to the fact that no bottlenecks where detected at the reefer operation side. Linking this back to the internal

movement requests from reefer containers standing in the buffer area, ECH remains assigned to other tasks, which directly contribute to the throughput value.

ECH number of moves analysis

Table 6.16 represent simulation outcomes for the 8 different settings compared to the baseline setting. The number of moves presented reflects the total number of moves executed by a single ECH during the simulation runtime for this scenario. To fairly compare amount of moves with performance it should be linked to the total distance travelled of the different ECHs, which is done in 6.4.2: ECH travelled distance analysis.

Below, a brief explanation is provided for each movement type to facilitate a better understanding of the presented values. Insights are complemented by visually inspecting occupation rates for both dry and reefer container subsystems presented in 6.4.2: Occupation rate analysis.

- **Internal movement**: Most settings focus on reducing the distances travelled for internal movements. As shown in the column for *ECH IM C* in Table 6.16, for some settings the number of moves in total is reduced. This is related to the performance of the setting. For settings 1 to 4 the layout and performance of the depot is similar, meaning same characteristics and moves are requested. For scenario 5 and 6 no direct bottlenecks occur. Resulting in less request from containers standing in buffer zones. This will result in less moves made by the ECH related to internal movement of dry containers. For reefer containers a similar pattern is shown in Table 6.16, where the combined total of moves is often lower. For *ECH1 IM R*, the amount of moves is sometimes higher. This is related to the policy of the simulation model. Because the distances between stations are often less, more moves can be made in the same time period. This implies that *ECH1 IM R* is more often available for a movement when a container requests a move. This results in a shift to more moves covered by *ECH1 IM R* and a decrease of moves covered by *ECH2 IM R*.
- **Pick up and gate-out movements**: Although layout settings primarily focus on reducing the internal movements, pick-up and to-truck movements are still influenced by spatial configurations of subsystems. In settings B to 4, the distances between the pick-up and gate-out areas with respect to consecutive subsystems remain consistent, resulting in only minor variations in movement counts. Overall system dynamics, such as throughput and occupation rates, remain comparable and lead to similar movement patterns. In contrast, settings 5 and 6 introduce entirely different layouts that significantly change the system's behaviour. By removing bottlenecks, these layouts allow for faster processing and reduce truck queueing times in the pick-up area. Although the overall truck arrival patterns remains similar, the timing of container handling shifts. As a result, the total number of moves during the simulation is not directly comparable to the baseline. To draw meaningful conclusions, these number of moves should be interpreted alongside other KPIs, such as throughput and occupation rates.
- **Total moves**: Table 6.18 and Table 6.19 present to combined total number of ECH moves per setting. These totals are strongly influenced by internal movements of both dry and reefer containers, which account for the largest share of variation in move counts.

Table 6.18: Scenario 1 (part 1): Differences in moves across settings (S1, S2 OD, S2 C, S3), compared to the baseline setting

Metric	SB	S1	S2 OD	S2 C	S3
$\sum$ Moves [#]	120,515	120,733	120,481	119,857	120,496
$\sum$ difference [#]	-	+ 218	– 34	– 658	– 19

Table 6.19: Scenario 1 (part 2): Differences in moves across settings (S4 OD, S4 C, S5, S6), compared to the baseline setting

Metric	SB	S4 OD	S4 C	S5	S6
$\sum$ Moves [#]	120,515	120,666	121,032	117,604	116,383
$\sum$ difference [#]	-	+ 151	+ 517	– 2,912	– 4,133

Notes: Values are aggregated across all ECHs.

ECH travelled distance analysis

Table 6.17 represent simulation outcomes for the 8 different settings compared to the baseline setting. The distance travelled reflects the total distance travelled by a single ECH during the simulation runtime for this scenario. To fairly compare distance travelled with performance it should be linked to the amount of moves of different ECHs, which is done in 6.4.2: ECH number of moves analysis.

Below, a brief explanation is provided for each movement type to facilitate a better understanding of the presented values. Insights are complemented by visually inspecting occupation rates for both dry and reefer container subsystems presented in 6.4.2: Occupation rate analysis.

- **Internal movement**: Following the same reasoning as presented in the settings, the choice is made to primarily focus on reducing internal movement for both dry and reefer containers. By decreasing distance between successive subsystems the distance travelled by ECHs related to internal movements should be reduced. This in combination with the reasoning behind the number of moves would provide valuable insight if these setting result in less distance travelled. As shown, performance indicator throughput is not directly influenced by this layout configurations for settings 1 to 4. The travel times of ECHs with containers are a small percentage of the total dwell time of containers inside the system. Although internal movement distances are lowered, this is not reflected in the throughput for settings that follow similar system dynamics, highlighting that process durations within subsystems strongly influence model outcomes.
- **Pick-up and gate-out movements**: Although layout settings primarily focus on reducing the internal movements, pick-up and to-truck movements are still influenced by spatial configurations of subsystems. In settings B to 4, the distances between the pick-up and gate-out areas with respect to consecutive subsystems remain consistent, resulting in only minor variations in distances covered per move. But when added to multiple moves during a full simulation, these numbers can become significant. To correctly compare the distance travelled it should be linked to the number of moves, throughput and occupation rates of the subsystems. In contrast, settings 5 and 6 introduce entirely different layouts that significantly change the system's behaviour. By removing bottlenecks, these layouts allow for faster processing and reduce truck queueing times in the pick-up area. To draw meaningful conclusions, the total distance travelled should be interpreted alongside other KPIs, such as throughput and occupation rates.
- **Total distance travelled**: Changing layout configuration could help reduce the total distances travelled for different settings. While not contributing to the improvement of throughput for settings 1 to 4, a reduction in driven distance can still offer operational benefits. Shorter travel distances can lead to lower operating costs for ECHs, particularly in terms of labour hours, fuel use and equipment depreciation. It is important to note that this research does not provide a detailed financial analysis of these potential cost savings. Settings 5 and 6 present further improvements in both throughput and reduced travel distances. By rethinking the system its structure and prioritising flow both performance indicators can be improved. This is complemented by the occupation rates of subsystems for these settings. As shown, the occupation rates of subsystems are controlled which result in maintaining operational efficiency. Table 6.20 and Table 6.21 present to combined total distance travelled of ECH per setting. These totals are strongly influenced by internal movements of both dry and reefer containers, which account for the largest share of variation in distance travelled.

Table 6.20: Scenario 1 (part 1): Differences in distance across settings (S1, S2 OD, S2 C, S3), compared to the baseline setting

Metric	SB	S1	S2 OD	S2 C	S3
$\sum$ distance [m]	24,706,540	26,734,817	23,548,980	23,274,009	24,675,842
$\sum$ difference [m]	-	+ 2,028,276	– 1,157,560	– 1,432,531	– 30,698

Table 6.21: Scenario 1 (part 2): Differences in distance across settings (S4 OD, S4 C, S5, S6), compared to the baseline setting

Metric	SB	S4 OD	S4 C	S5	S6
$\sum$ distance [m]	24,706,540	27,805,675	27,826,580	20,253,505	20,513,883

Metric	SB	S4 OD	S4 C	S5	S6
$\sum$ difference [m]	-	+ 3,099,135	+ 3,120,040	– 4,453,035	– 4,192,657

Notes: S = Setting, OD = Only Distance, C = Combined. Values are aggregated across all ECHs.

Occupation rate analysis

Figure 6.14 and Figure 6.15 represent simulation outcomes for the baseline setting representing the number of TEU occupied throughout the simulation. For clarity some subsystems are excluded from the graph, most following a straight line around the value of zero.

By visually inspecting occupation rates for both dry and reefer container subsystems, insights are gained into bottleneck dynamics inside the system. If aligned with other KPIs a comprehensive review can be provided for the different settings. Eighteen different visualisations are compared highlighting 3 different settings here in this section. The other figures are represented in Appendix D.

By following the logic presented in this scenario and other analyses, insights can be gained in the occupation rates of the different subsystems. Dividing the graph into four different segments with respect to simulation minutes. Taking into account the analyses of ECH KPIs and throughput, settings 5 and 6 are presented here as comparison of the baseline, as they show significantly different container flows.

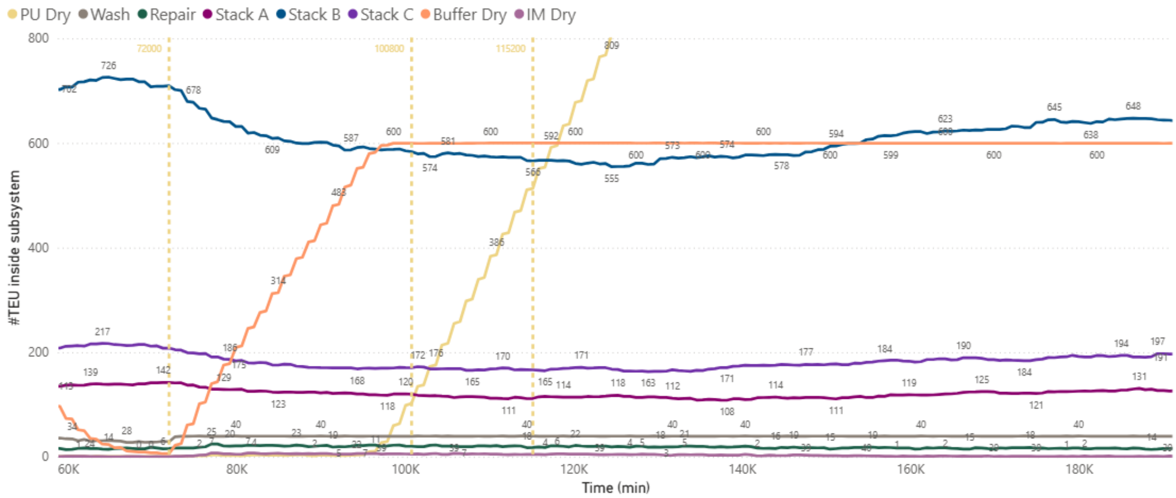


Figure 6.14: Scenario 1: Occupation subsystems (dry) setting baseline

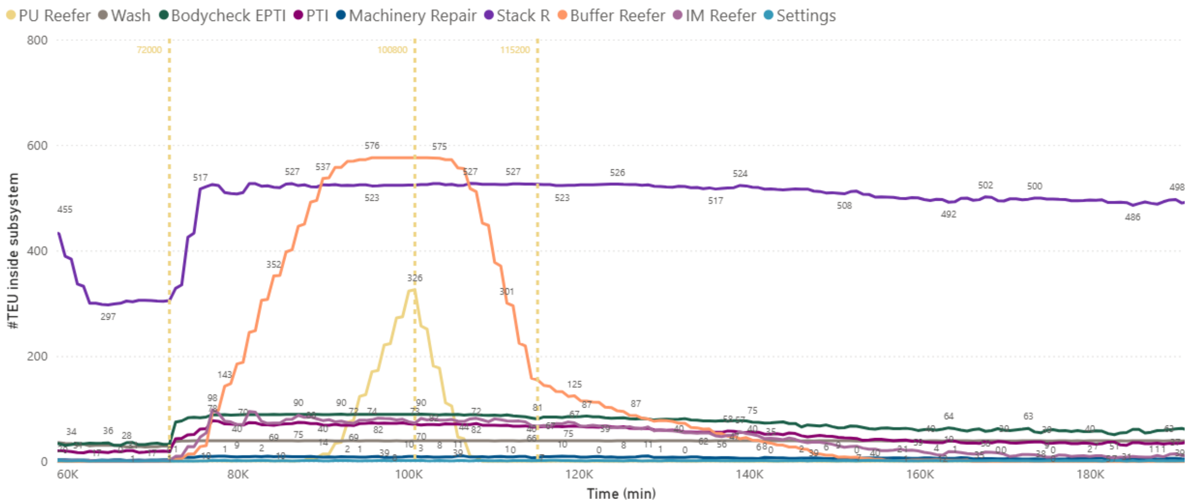


Figure 6.15: Scenario 1: Occupation subsystems (reefer) setting baseline

- **Simulation minute interval 57.600-72.000**: Truck arrival shift from a normal situation to an easy situation, resulting in less reefer containers entering the system between minutes 57.600 and 72.000. For this period of 2 operational weeks, a slight decrease in occupation of subsystems is visible, especially in the ready stack for reefer containers, all settings follow a similar pattern. By analysing the occupation rates of all settings, the conclusion can be drawn that under these interarrival rates of trucks, no bottlenecks occur. Capacities are not reached in this situation leading to normal operations.
- **Simulation minute interval 72.000-100.800**: Truck arrival shift from an easy situation to a stressed situation, resulting in more reefer containers entering the system between minutes 72.000 and 100.800. For this period of 4 operational weeks, an increase in occupation rates is clearly visible for the baseline setting. As individual subsystems begin to full, they eventually reach their capacity limits. When this happens, dependent processes are forced to wait, creating a bottleneck that moves through the system. As shown in the figures, the bottleneck reaches the pick-up subsystems for both dry and reefer containers. Translating this into the real world problem, this situation presents a complete occupied depot where no trucks with containers can enter. Trucks have to wait because direct placement of containers in subsystems is not possible. This bottleneck is overcome in setting 5 on the dry side, because of the introduction of a separate wash area for dry containers. The bottleneck still reaches the pick-up area for the reefer operations side, as the yellow line shows an increase in occupation rate of this area. In this situation both the reefer ready area and reefer buffer area are completely full. Following setting 6, both bottlenecks for dry and reefer operations are overcome, which is a result of the increased capacity in the reefer ready area. By increasing capacity in this area the effects of this increased reefer interarrival rate are mitigated.
- **Simulation minute interval 100.800-115.200**: Truck arrival shift back from a stressed situation to an easy situation, resulting in less reefer containers entering the system between minutes 100.800 and 115.200. The lower interarrival rate of reefer containers in combination with the predefined policies and process durations, the baseline settings shows a recovery in the reefer operations section. The dry system remains full due to a continued inflow of containers that were waiting for pick-up. Setting 5 shows a similar pattern for reefer container operations and is able to recover faster. Analysing both bottleneck dynamics, both bottlenecks move inwards again with the same speed, but with a different starting point. Taking the maximum values for trucks waiting outside of the depot for reefer containers (yellow line). For setting 6 there were no bottlenecks after 100.800 minutes, so an immediate drop of occupation rates in reefer operations is visible. Adapting immediately to the changes in interarrival conditions without delays.

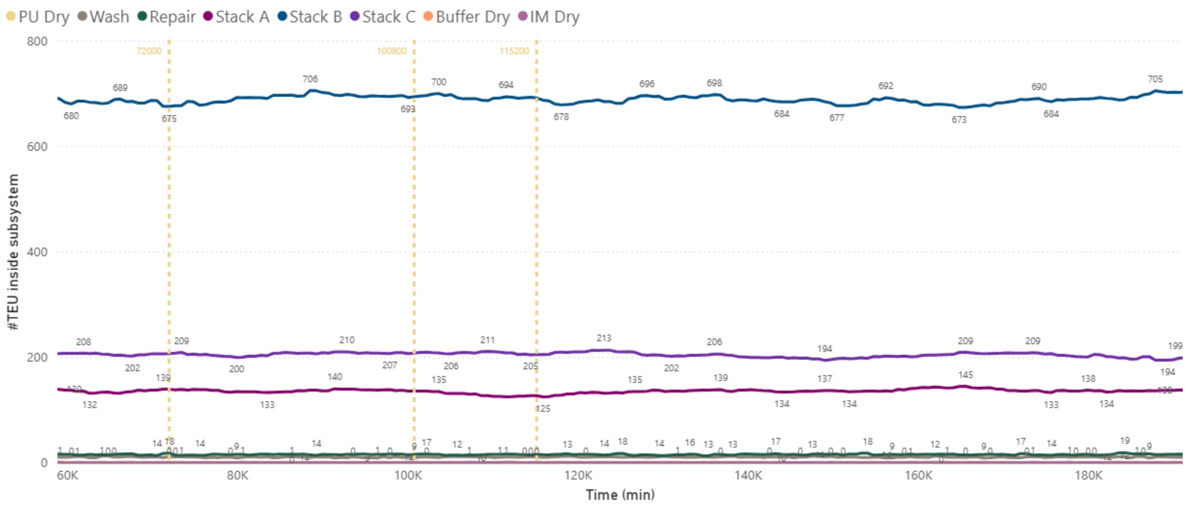


Figure 6.16: Scenario 1: Occupation subsystems (dry) setting 5

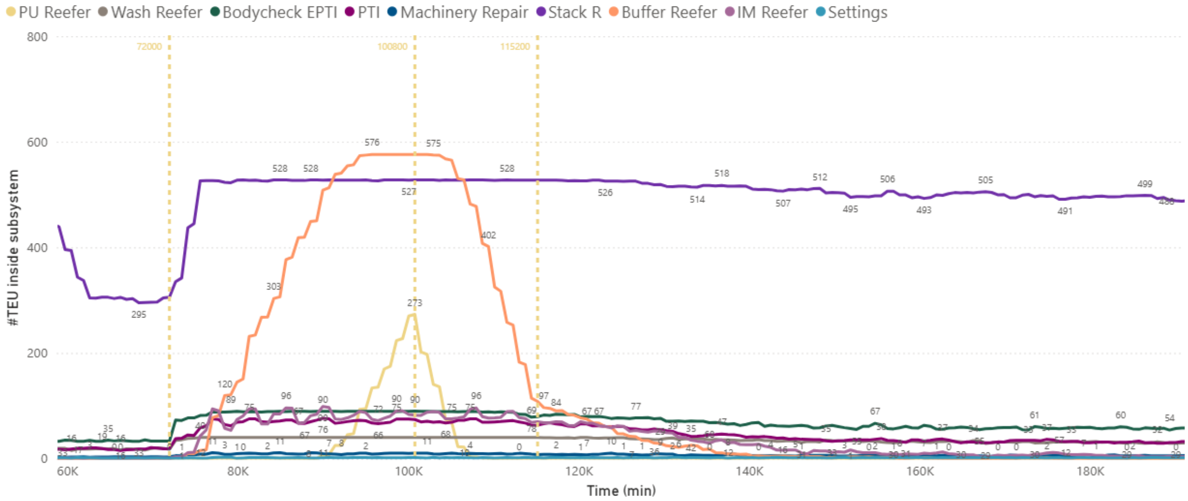


Figure 6.17: Scenario 1: Occupation subsystems (reefer) setting 5

- **Simulation minute interval 115.200 - 187.200** Truck arrival shift back from an easy situation to a normal situation. For the baseline setting a recovery for the reefer operations is visible, subsystems are emptied especially focused on reefer ready stack, buffer and upstream subsystems. The moment in time that the system fully recovered from the stress period is linked to the gradient of the throughput visualised in Figure 6.13. After approximately 90 operational days a certain configuration is reached of the assignment of moves for the ECHs response for the internal movement. This is the moment in time where moves from the ready stack reefer to the settings area has reached a certain ratio, contributing to gaining throughput by supplying the settings area with reefer containers. There are still some containers inside the buffer stations but the ratio of movement request for internal movement shifted. In the occupied situation there are many request for movements not directly contributing to the throughput. Because of the FCFS policy of the ECHs, this result in longer waiting time for reefer containers inside the ready stack, creating a bottleneck in the setting supply. For setting 5 this moment is reached at a similar time for reefer containers. But as there were no bottlenecks on the dry operation side, throughput remains high. Setting 6 shows that during the whole simulation the interarrival pattern of both dry and reefer containers is followed. There are no bottlenecks in the system and throughput relies on containers entering the system.

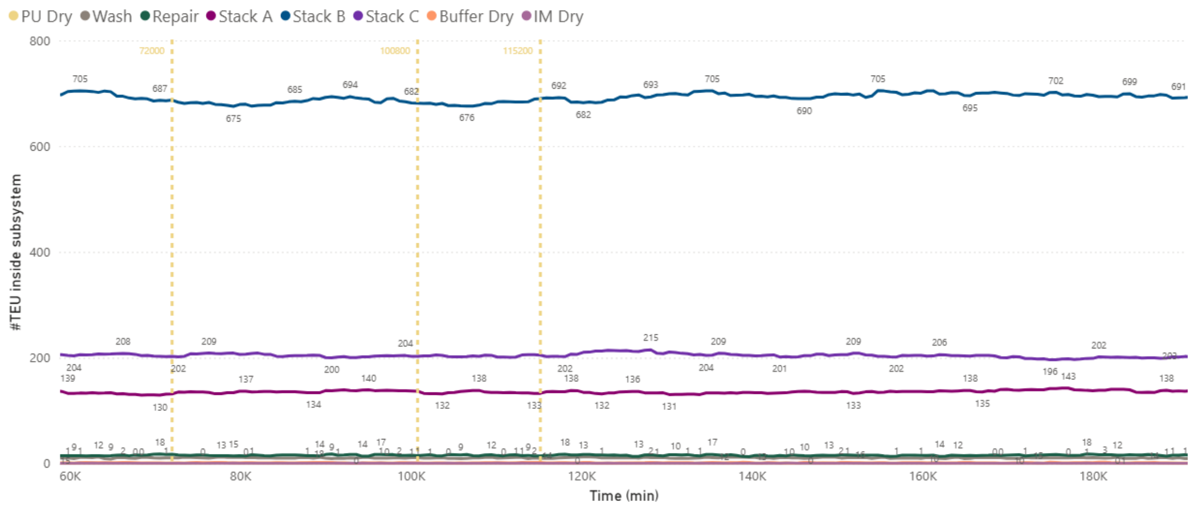


Figure 6.18: Scenario 1: Occupation subsystems (dry) setting 6

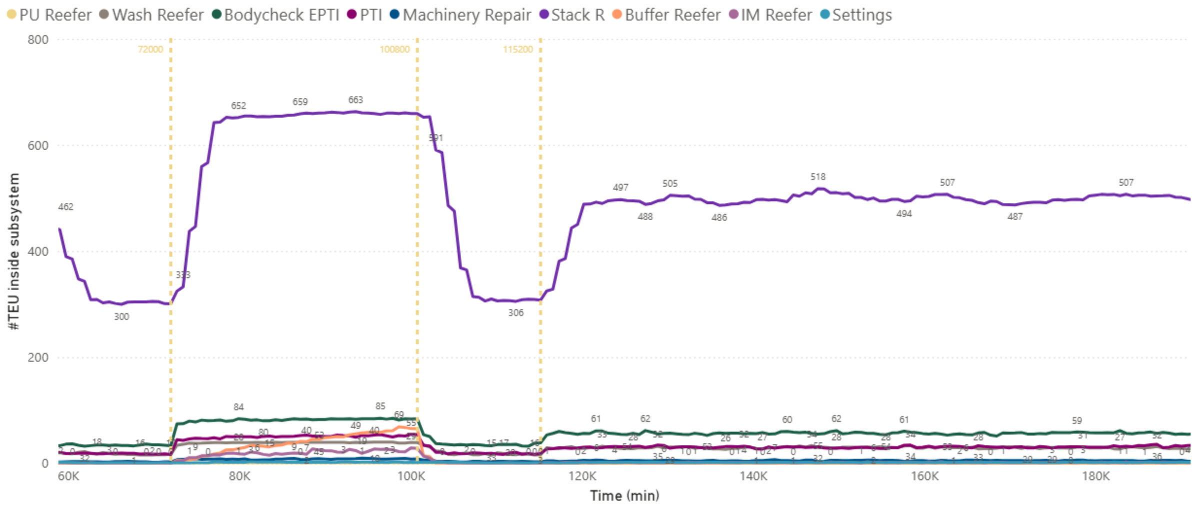


Figure 6.19: Scenario 1: Occupation subsystems (reefer) setting 6

By iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks by changing the layout structures and stacking strategies. This in combination with comparing other KPIs helps understand system dynamics, improve throughput and reduce operational usage of ECHs.

6.4.3. Scenario 2: Normal flow setup

A brief introduction into the setup for scenario 2 is presented. All settings follow the same characteristics as described in Figure 5.1, Figure 5.2, Figure 5.3 Table 5.2, Table 5.3 and Table 5.4. These characteristics cover most of the, in Figure 5.4 described, input parameters.

In Table 6.22 the simulation settings are further described, complemented by Table 6.23 which includes truck interarrival rates for dry and reefer containers. Simulation minutes only take into account the first 5 days of every week (working days), with corresponding opening and closing hours of the depot.

Table 6.22: Scenario 2: Simulation settings

Characteristics	Value	Unit
Runtime	115.200	Simulation minutes
Number of runs	25	-
Measurement interval	780	Simulation minutes
Depot open	780	Operating minutes
Depot closed	660	Non-operating minutes
Driving speed ECH	10	km / h
Occupation all subsystems at start	0	#TEU used

Table 6.23: Scenario 2: Interarrival containers

Container type	Probability distribution	Interval [min]	# Operational days
Dry	Geom(p=0.1918)	0 < 86.400	60
Dry	Geom(p=0.0001)	≥ 86.400	20
Reefer	Geom(p=0.0964)	0 < 86.400	60
Reefer	Geom(p=0.0001)	≥ 86.400	20

Settings

For this scenario, four different settings are simulated. These settings correspond to the baseline setting and settings number 2C, 5 and 6. For the setting characteristics is referred to subsection 6.4.1, this to prevent unnecessary repetition.

6.4.4. Scenario 2: Normal flow analysis

The comparison of results follows a similar approach as described in subsection 6.4.2: Scenario 1: Reefer season analysis. In Figure 6.20 and Table 6.24 to Table 6.27 the results of the simulation are presented. Insights are complemented by visually inspecting occupation rates for only dry container subsystems presented in Appendix D.

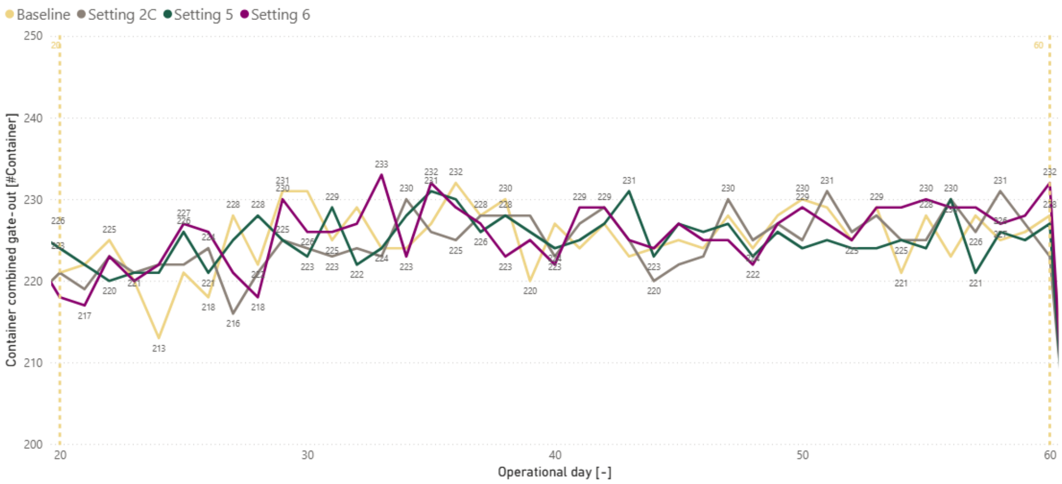


Figure 6.20: Scenario 2: Average dry and reefer container gate-out per operational day

In Figure 6.20 the throughput is analysed after a 20 operational days warm-up time, which is supported by the determination of the warm-up time defined in section D.1. This scenario serves as a baseline for exploring strategic layout and stacking strategy decisions for dry container operations in scenarios 3 and 4. The results presented in this section closely align with the findings from subsection 6.4.2: Scenario 1: Reefer seasons analysis. Although the conclusions are similar due to the stable container flow at the start of the simulation, this scenario is included to highlight that even under normal operating conditions, differences among settings exist. Presenting this analysis contributes to a more complete understanding of the system's behaviour. Below the results are briefly discussed here to set the baseline for scenarios 3 and 4.

- **Throughput**: The throughput of all four settings follow a similar pattern, as shown in Figure 6.20. Process duration account for the largest share of the total container dwell time inside the system. Therefore, less driving distance or a reduction in moves for ECHs, is not directly visible in the throughput of the ECD system.

Table 6.24: Scenario 2: Comparison of number of moves by an ECH to the baseline setting

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	9,045	4,763	9,009	4,594	10,230	6,591	4,594
△ S2 C	- 12	- 40	- 11	- 25	- 48	- 55	- 25
△ S5	- 37	- 1,037	- 33	- 4	+ 1,157	- 1,166	- 4
△ S6	- 21	- 955	- 17	- 11	+ 1,144	- 1,167	- 11

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.25: Scenario 2: Differences in moves across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
$\sum$ Moves [#]	48,826	48,610	47,703	47,788
$\sum$ difference [#]	–	– 216	– 1,123	– 1,038

Notes: Values are aggregated across all ECHs.

Table 6.26: Scenario 2: Comparison of distance travelled by an ECH to the baseline setting [in m]

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	1.397.720	1.222.670	725.591	1.148.823	2.864.519	1.964.477	321.629
△ S2 C	– 123.261	– 81.536	+ 470	– 326.450	– 34.404	– 61.527	– 1.781
△ S5	+ 594.779	– 339.750	+ 646.889	+ 182.163	– 1.171.925	– 1.199.605	+ 91.570
△ S6	+ 663.008	– 352.167	+ 648.609	+ 180.139	– 1.171.710	– 1.201.177	+ 90.943

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.27: Scenario 2: Differences in distance across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
$\sum$ distance [m]	9.645.430	9.016.942	8.449.550	8.503.075
$\sum$ difference [m]	–	– 628.488	– 1.195.880	– 1.142.355

Notes: S = Setting, C = Combined. Values are aggregated across all ECHs.

- **ECH moves and distance**: This analysis builds on the analysis conducted in subsection 6.4.2. Table 6.24 to Table 6.27 show that the total number of ECH moves and driving distances vary across settings due to layout and stacking strategy differences. While these differences are not directly reflected in the throughput, the stabilisation of occupation rates within subsystems do settle around different values, not exceeding the operational capacity. Different settings show different yard utilisation configurations, which help better understand the system under these interarrival conditions. Under these circumstances the throughput remains similar and occupation rates stay within operational limits. However, ECH usage differs across settings, showing that even when KPIs appear stable, layout and stacking strategies can still improve operational efficiency by better managing equipment use. Overall, the total driving distance and number of moves is reduced in all settings compared to the baseline setting. Resulting in less time needed for ECH operations resulting in similar throughput values.

- **Occupation rates**: In Figure 6.21, the occupation for dry container subsystems is visualised for the baseline setting, presenting a constant occupation rate throughout the simulation for all subsystems. In Appendix D the occupation of other relevant dry systems are presented. Because of unchanged interarrival patterns for both dry and reefer containers the graph is almost horizontal. No bottlenecks occur in this situation and operations run without any inefficiencies.

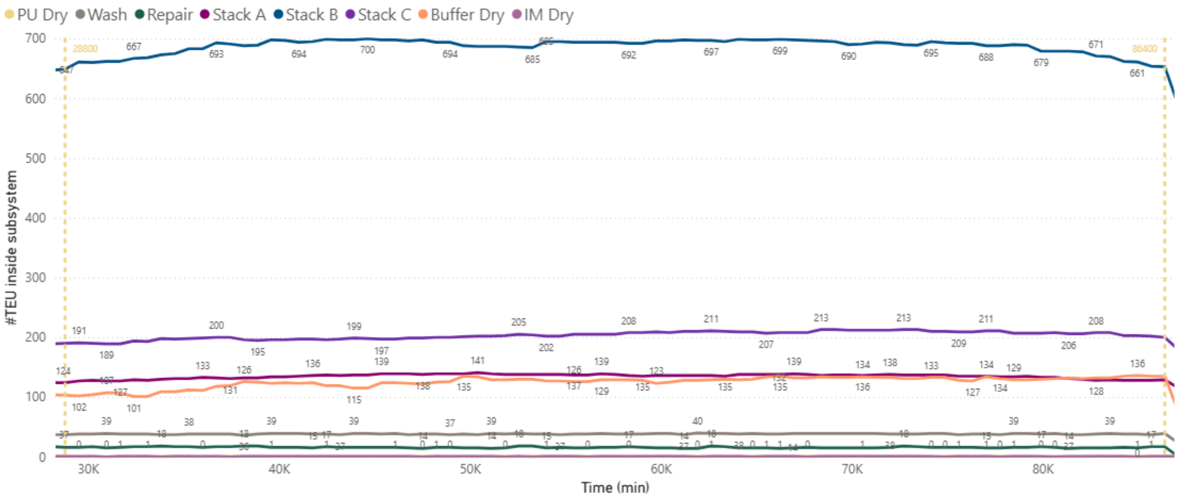


Figure 6.21: Scenario 2: Occupation subsystems (dry) setting baseline

6.4.5. Scenario 3: Overflow setup

A brief introduction into the setup for scenario 3 is presented. These characteristics are based on the input parameters described in Figure 5.4. Some settings follow the same characteristics as described in Figure 5.1, Figure 5.2, Figure 5.3 and Table 5.2. Some input parameters are different than described in Table 5.3 and Table 5.4. The simulation settings are similar to the characteristics presented in Table 6.22 and Table 6.23.

The strategy implemented in this scenario is to maximise the depot storing function while matching export requirements. The storage of containers is focused on the dry operations side rather than for the reefer operations side, because reefer containers need to flow rapidly. To simulate this scenario, the dwell time inside export ready stacks for dry containers is lengthened. This lengthening of dwell time will result in a lower throughput of dry containers. The adjusted input parameters for the corresponding process are presented in Table 6.28. Where the minimum dwell time inside subsystem *A27* is set to a minimum of 5 operational days. To meet export requirements, dwell times for immediately available containers are not affected.

Table 6.28: Scenario 3: Adjusted input for process durations

Number	Process	Min [min]	Max [min]	AVG [min]	Data	Procedures
A27S-1	Nbinom(51.15, 0.864)	2.50	15	-	x	-
A27L-1	Nbinom(0.54, 0.000136)	3917.5	21600	-	x	-
A27L-2	Nbinom(0.54, 0.000136)	4055.5	21600	-	x	-
A27L-3	Nbinom(0.54, 0.000136)	4243.8	21600	-	x	-
A27L-4	Nbinom(0.54, 0.000136)	4380.8	21600	-	x	-

Settings

For this scenario, four different settings are simulated. These settings correspond to the baseline setting and settings number 2C, 5 and 6. For the setting characteristics is referred to subsection 6.4.1, this to prevent unnecessary repetition.

6.4.6. Scenario 3: Overflow analysis

The comparison of results follows a similar approach as described in subsection 6.4.2: Scenario 1: Reefer season analysis. In Figure 6.22 and Table 6.29 to Table 6.32 the results of the simulation are presented. Insights are complemented by visually inspecting occupation rates for only dry container subsystems.

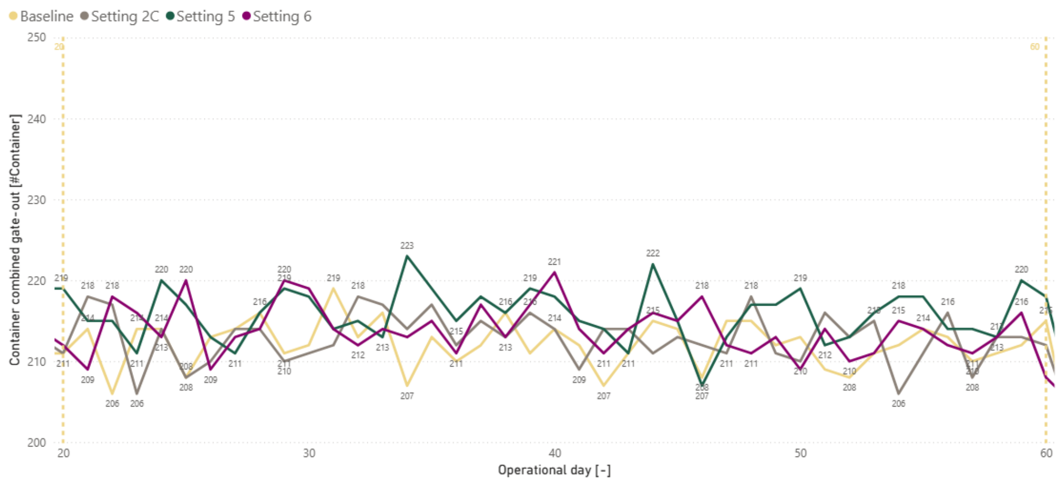


Figure 6.22: Scenario 3: Average dry and reefer container gate-out per operational day

In Figure 6.22 the throughput is analysed after a 20 operational days warm-up time, which is supported by the determination of the warm-up time defined in section D.1. Some of the results closely align with the findings from subsection 6.4.2: Scenario 1: Reefer seasons analysis, and are therefore not mentioned here. The focus will be on the behaviour of different settings to this strategic decision of storing containers within the depot for a longer period. Presenting this analysis contributes to a more complete understanding of the system's behaviour. Below the comparison of the settings is presented in relationship with the KPIs defined.

- **Throughput**: The throughput of all four settings follow a similar pattern, as shown in Figure 6.22. Process durations account for the largest share of the total container dwell time inside the system. Therefore, less driving distance or a reduction in moves for ECHs, is not directly visible in the throughput of the ECD system. Comparing outcomes to scenario 2, on average the throughput is lowered because of the longer dwell times inside the export ready stacks for dry containers.

Table 6.29: Scenario 3: Comparison of number of moves by an ECH to the baseline setting

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	9,035	5,035	8,948	4,568	10,169	6,654	4,568
△ S2 C	- 21	- 23	- 16	+ 28	- 23	+ 81	+ 28
△ S5	- 0	- 370	+ 23	- 5	+ 1,174	- 1,280	- 5
△ S6	- 18	- 261	- 17	- 4	+ 1,173	- 1,289	- 4

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.30: Scenario 3: Differences in moves across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
$\sum$ Moves [#]	48,978	49,031	48,514	48,557
$\sum$ difference [#]	–	+ 53	– 463	– 421

Notes: Values are aggregated across all ECHs.

Table 6.31: Scenario 3: Comparison of distance travelled by an ECH to the baseline setting [in m]

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	1.398.369	1.280.640	721.383	1.160.274	2.821.247	2.008.721	319.809
△ S2 C	– 125.733	– 77.427	– 922	– 321.186	– 17.467	– 29.339	+ 1.977
△ S5	+ 692.603	– 356.676	+ 650.742	+ 162.928	– 1.133.730	– 1.252.062	+ 90.978
△ S6	+ 622.739	– 342.943	+ 644.818	+ 163.064	– 1.134.547	– 1.253.951	+ 91.078

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.32: Scenario 3: Differences in distance across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
$\sum$ distance [m]	9.710.444	9.140.347	8.565.226	8.500.702
$\sum$ difference [m]	–	– 570.097	– 1.145.218	– 1.209.742

Notes: S = Setting, C = Combined. Values are aggregated across all ECHs.

- **ECH moves and distance**: This analysis builds on the analysis conducted in subsection 6.4.4. Table 6.29 to Table 6.32 show that the total number of ECH moves and driving distances vary across settings due to layout and stacking strategy differences. Different settings show different yard utilisation configurations, which help better understand the system under these strategic decisions. Under these circumstances throughput remains stable, but occupation rates exceed operational limits at different points in time. These dynamics are influenced by the layout and stacking decision made within settings, which will be elaborated on more thoroughly. To fairly compare the number of moves and distance travelled, results should be linked to the occupation of the dry subsystems.

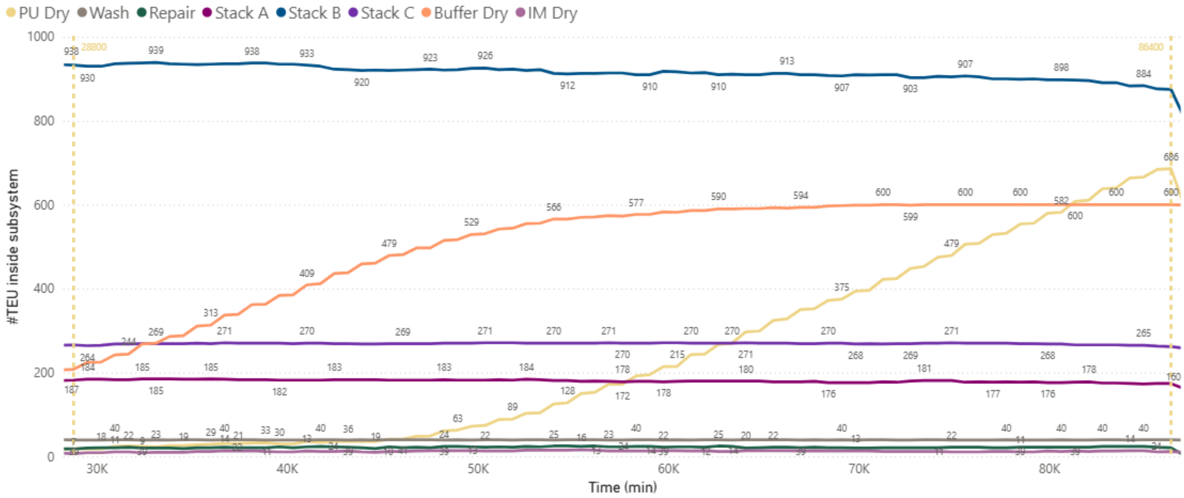


Figure 6.23: Scenario 3: Occupation subsystems (dry) setting baseline

- **Occupation rates: setting baseline**: In Figure 6.23 the occupation of the relevant dry systems is presented. Following the logic of the strategic decision, export ready subsystems start filling with containers. When capacity is reached containers are not redirected, so this result in trucks with containers waiting outside of the depot. In the meantime, the washing area is fully occupied, resulting in the redirection of containers to the buffer area. At some point in time this capacity of the buffer is also reached. In real life this scenario would not happen, because operational on the spot decision making would overcome this problem. But following this logic, the dynamics of the bottleneck within the system is presented. Comparing this baseline setting with the other three settings presented in Figure 6.24 to Figure 6.26, provide insight into different bottleneck dynamics.
- **Occupation rates: setting 2C**: Where setting 2C follows a similar pattern compared to the baseline setting, the increase of the occupation in subsystem PU dry starts later. Meaning that this setting can provide this strategy for slightly longer time before the bottleneck moves outwards of the system. Important to note is that the differences are very minimal, so from a strategic point of view both settings show similar behaviour.

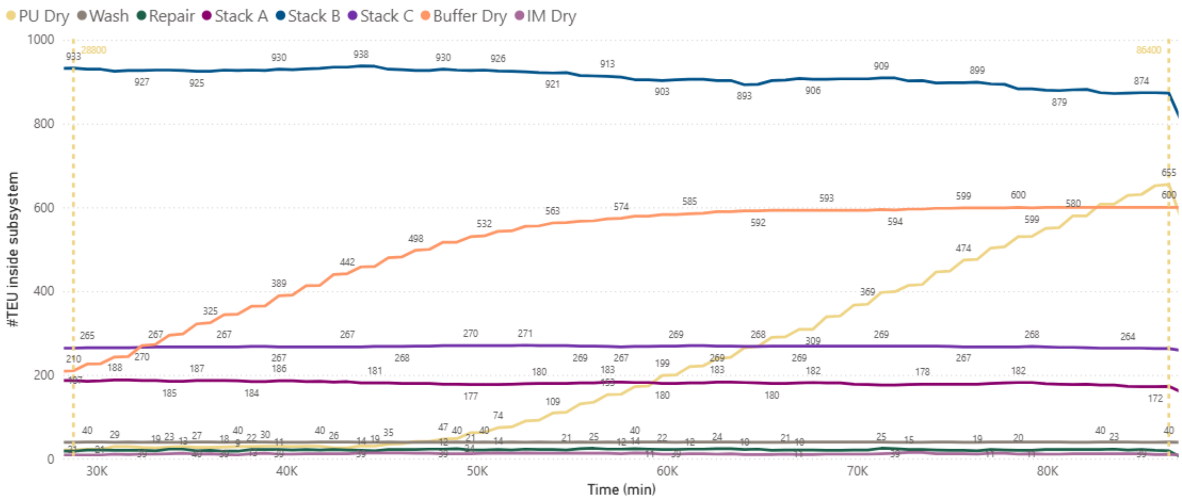


Figure 6.24: Scenario 3: Occupation subsystems (dry) setting 2C

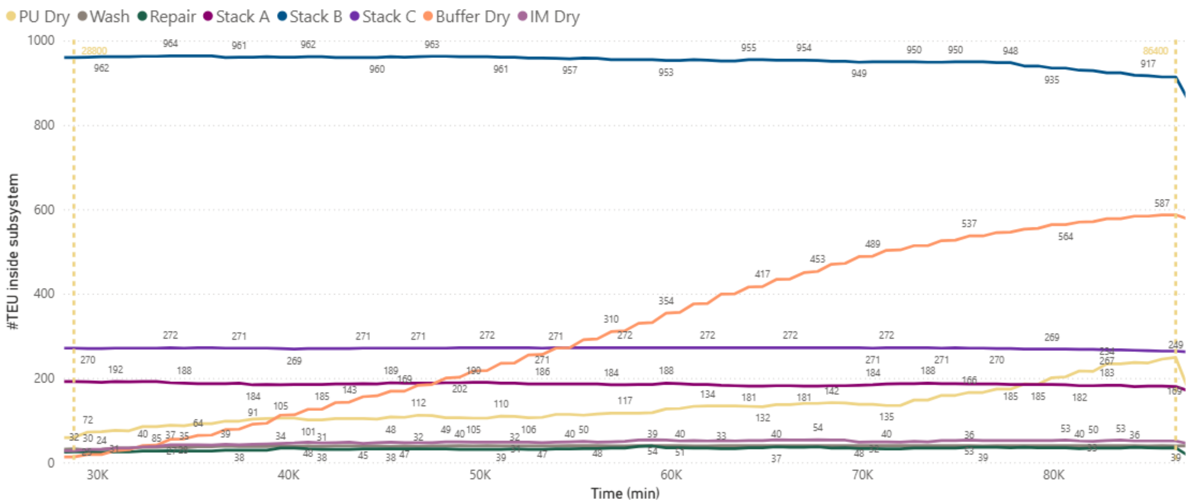


Figure 6.25: Scenario 3: Occupation subsystems (dry) setting 5

- **Occupation rates: setting 5**: Setting 5 deviates from this pattern described in setting baseline and 2C. Due to increased driving distance for ECH pick-up for dry containers, process durations are longer. Resulting in a bottleneck for the pick-up for dry containers early in this scenario. Important to notice here is that the bottleneck slowly moves outwards of the system, compared to settings B and 2C. Analysing the setup of this setting, could help identify what causes this bottleneck. Setting 5 input shows that the designated washing area for dry help relief the system, resulting in a lower arrival rate of containers entering the buffer area. Towards the end of the simulation, buffer capacity is nearly reached. This suggest that the increase in trucks waiting outside the depot is primarily driven by containers that are immediately ready for export but cannot enter the stacks.
- **Occupation rates: setting 6**: Comparing this to setting 6, where the buffer area capacity is lower, results in slightly different bottleneck behaviour. As capacity is reached for the buffer zone, both export ready and those containers that need a wash have to wait. Increasing the speed of the bottleneck moving outward of the system.

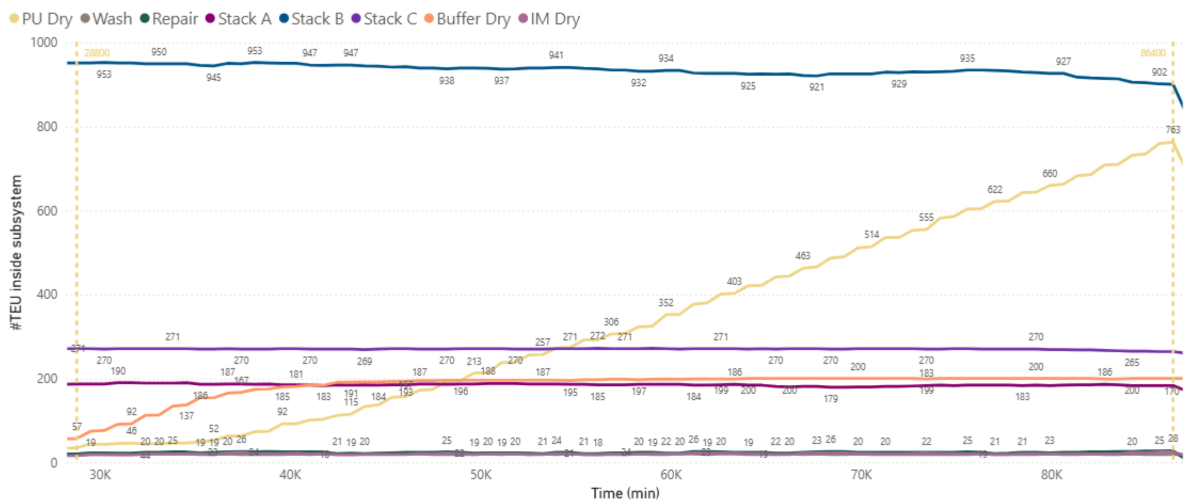


Figure 6.26: Scenario 3: Occupation subsystems (dry) setting 6

6.4.7. Scenario 4: Throughput setup

A brief introduction into the setup for scenario 4 is presented. These characteristics are based on the input parameters described in Figure 5.4. Some settings follow the same characteristics as described in Figure 5.1, Figure 5.2, Figure 5.3 and Table 5.2. Some input parameters are different than described in Table 5.3 and Table 5.4. The simulation settings are similar to the characteristics presented in Table 6.22 and Table 6.23.

The strategy implement in this scenario is to make containers flow rapidly. The strategy is to generate fast throughput and the depot storing function is minimised. The way throughput is affected is by reducing the dwell time inside export ready stacks for dry containers. The reefer operations side is not affected, as reefer containers need to flow rapidly throughout the full year. The adjusted input parameters for the corresponding process are presented in Table 6.33. Where the maximum dwell time inside subsystem *A27* is set to a maximum of four operational days.

Table 6.33: Scenario 4: Adjusted input for process durations

Number	Process	Min [min]	Max [min]	AVG [min]	Data	Procedures
A27S-1	Nbinom(51.15, 0.864)	2.50	15	-	x	-
A27L-1	Nbinom(0.54, 0.000136)	17.5	3120	-	x	-
A27L-2	Nbinom(0.54, 0.000136)	155.5	3120	-	x	-
A27L-3	Nbinom(0.54, 0.000136)	343.8	3120	-	x	-
A27L-4	Nbinom(0.54, 0.000136)	480.8	3120	-	x	-

Settings

For this scenario, four different settings are simulated. These settings correspond to the baseline setting and settings number 2C, 5 and 6. For the the setting characteristics is referred to subsection 6.4.1, this to prevent unnecessary repetition.

6.4.8. Scenario 4: Throughput analysis

The comparison of results follows a similar approach as described in subsection 6.4.2. In Figure 6.27 and Table 6.34 to Table 6.37 the results of the simulation are presented. Insights are complemented by visually inspecting occupation rates for only dry container subsystems presented in Appendix D.

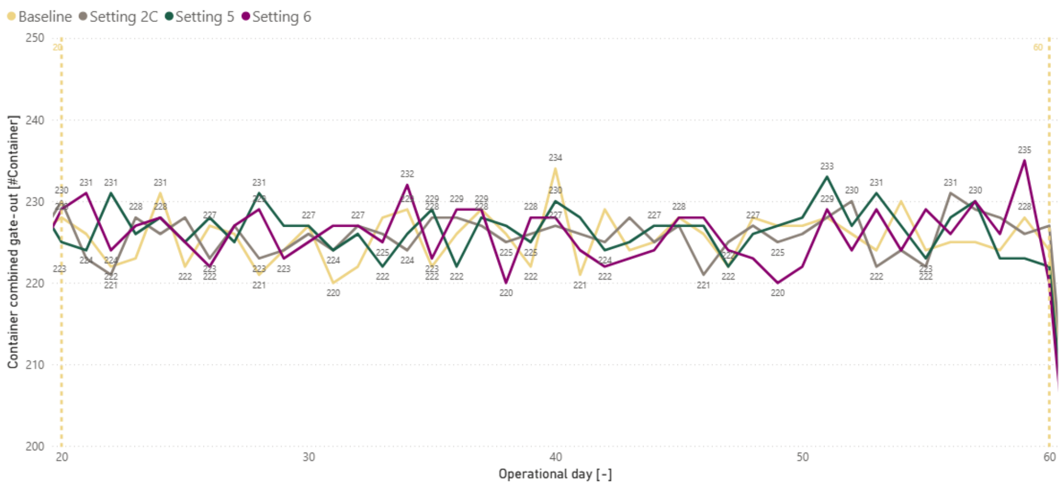


Figure 6.27: Scenario 4: Average dry and reefer container gate-out per operational day

In Figure 6.27 the throughput is analysed after a 20 operational days warm-up time, which is supported by the determination of the warm-up time defined in section D.1. Some of the results closely align with the findings from subsection 6.4.2: Scenario 1: Reefer seasons analysis, and are therefore not mentioned here. The focus will be on the behaviour of different settings to this strategic decision of improving container flow. Presenting this analysis contributes to a more complete understanding of the system's behaviour. Below the comparison of the settings is presented in relationship with the KPIs defined.

- **Throughput**: The throughput of all four settings follow a similar pattern, as shown in Figure 6.27. Process durations are the same, and contribute to a large share of container dwell time inside the system. Therefore, less driving distance or a reduction in moves for ECHs is not directly visible in the throughput of the ECD system. The throughput values are similar compared to the normal situation, stating that if the process durations are lowered the system performance does not increase related to the gate out of containers. This suggest that ECH handling capacity restricts a further improved of the throughput. This in relation to the number of gate-out requests per day, as figures in Appendix D show stabilised export ready occupation rates.

Table 6.34: Scenario 4: Comparison of number of moves by an ECH to the baseline setting

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	9,040	4,684	9,040	4,546	10,174	6,481	4,545
△ S2 C	- 19	- 26	- 19	+ 26	+ 26	+ 63	+ 26
△ S5	- 22	- 958	- 22	+ 26	+ 1,160	- 1,083	+ 25
△ S6	- 30	- 895	- 30	+ 31	+ 1,189	- 1,092	+ 31

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.35: Scenario 4: Differences in moves across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
∑ Moves [#]	48,510	48,585	47,636	47,716
∑ difference [#]	–	+ 76	– 873	– 794

Notes: Values are aggregated across all ECHs.

Table 6.36: Scenario 4: Comparison of distance travelled by an ECH to the baseline setting [in m]

	C PU	C IM	C TT	R PU	R IM1	R IM2	R TT
Total SB	1.394.669	1.203.134	729.711	1.136.407	2.856.615	1.928.602	318.211
△ S2 C	– 126.402	– 78.689	– 2.934	– 313.638	– 19.334	– 22.499	+ 1.792
△ S5	+ 600.555	– 322.032	+ 649.825	+ 189.034	– 1.168.730	– 1.167.703	+ 93.268
△ S6	+ 662.406	– 335.553	+ 647.285	+ 190.724	– 1.167.004	– 1.170.224	+ 93.808

Notes: △ = Difference to baseline, SB: Setting Baseline, C: Container, R: Reefer, PU: Pick-Up, IM: Internal movement, TT: To Truck

Table 6.37: Scenario 4: Differences in distance across settings (S2 C, S5, S6), compared to the baseline setting

Metric	SB	S2 C	S5	S6
∑ distance [m]	9.567.349	9.005.644	8.441.565	8.488.789
∑ difference [m]	–	– 561.705	– 1.125.784	– 1.078.560

Notes: S = Setting, C = Combined. Values are aggregated across all ECHs.

- **ECH moves and distance**: This analysis builds on the analysis conducted in subsection 6.4.4. Table 6.34 to Table 6.37 show that the total number of ECH moves and driving distances vary across settings due to layout and stacking strategy differences. Different settings show different yard utilisation configurations, which help better understand the system under these strategic decisions. Under these circumstances throughput and occupation of dry subsystems remains stable per setting. These dynamics are influenced by the layout and stacking decision made within settings, which will be elaborated on more thoroughly. To fairly compare the number of moves and distance travelled, results should be linked to the occupation of the dry subsystems
- **Occupation rates**: In Appendix D the occupation of the relevant dry systems are presented. The system is focused on low dwell time of dry containers, therefore occupations rates are way lower compared to the normal and overflow situation. For the baseline and 2C setting, dry buffer capacity is used. For setting 5 and 6, no buffer space is used for the temporarily storage of containers.

6.5. Conclusion

The goal of these simulation experiments was to gain insight into the operational dynamics of an ECD, rather than optimising its performance. By simulating various layout configurations and stacking strategies under different seasonal characteristics, the aim was to evaluate whether alternative settings could lead to improved performance, as measured by KPIs, compared to the current situation and layout of the case study depot.

To achieve this, four different scenarios were developed. Scenario 1 focused on the peak months for the arrival of reefer containers, testing the resilience of the system under stress conditions. Scenario 2,3 and 4 represented regular operations, providing a basis for exploring strategic decisions to improve performance. Each scenario served a unique purpose, with the core objective being to evaluate how different layout configurations and/or stacking strategies perform under varying characteristics within empty container logistics.

Based on research findings, eight different settings were constructed and tested to the four different scenarios. The aim of these tests was to identify new configurations that could improve performance in these scenarios. Several important findings emerged for each scenario and related settings. Due to the depth and complexity of some insights, the analysis and discussion are provided in section 6.4.

The general conclusion is that by iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks, improve ECH usage and maintain or improve throughput of the system. These improvements are achieved through targeted changes in settings. This demonstrates that by following the simulation framework and conducting the described steps as intended, ECD operations can be improved and system dynamics can be better understood.

6.6. Discussion

By iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks, improve ECH usage and maintain or improve throughput of the system. The simulations, tailored to fixed input parameters, provide the intended insight into ECD operations. While the model incorporates multiple assumptions and simplifications, the model captures the system behaviour sufficiently for comparative analysis. This aligns with the research goal, providing a baseline understanding of system dynamics and creating a simulation framework that can obtain operational improvements through iterative simulation modelling.

However, this chapter focuses on a few selected scenarios and settings, where only small changes are made one at a time. This choice was made to maintain visibility into system dynamics, making it easier to see how specific changes affect the outcomes. In the real-world, many factors such as policies or ECH usage can change simultaneously, which makes it difficult to identify what is actually influencing results when multiple input parameters are changed at once. Still, several key questions remain after this analysis. Is layout the most influential factor to system performance, or do other factors drive throughput, bottleneck occurrence or other related parameters? While the results show that layout can indeed improve selected KPIs, adopting a broader perspective on depot operations might be beneficial for an additional deeper understanding of how various factors interacts. Reconsideration of some assumptions and simplifications is therefore justified, because the results suggest that other parameters also contribute to further improvements. Adding to this, not only improvements need to be further researched, also financial considerations should be taken into account in further analysis of the layout configurations and stacking strategy choices. For a more detailed discussion on these recommendations, a reference is made to the discussion presented in chapter 7.

Interpreting layout configurations

Based on the simulation outcomes, the best performing layout for the reefer season is setting number 6, which is an iteratively created improvement of the baseline setting. It needs to be addressed that this layout and configuration is completely different and unrealistic to adjust to, because of the currently fixed perimeter configurations. Therefore shifting to this layout is not possible for this current location. It could be possible when new facilities are analysed. Respecting the same volumes, processes, relationships and similar factors. Setting number 6 would then be a better configuration evaluated to the defined KPIs. For the reefer season a more realistic strategy exists in small adjustments to the current operations.

Setting number 2C, where an improvement in KPIs for ECH usage is visible. This could be adjusted directly, from a practical perspective, but still requires a financial analysis.

Adding to this insight, it is important to note that when following the framework and iteratively comparing model outcomes to the KPIs, performance could be improved. Setting 6 demonstrates the best performance in terms of container flow, occupation rates and ECH usage during the reefer season. However, when strategic priorities shift toward maximising the storage function of the depot, setting 5 becomes more suitable. Overall, setting 6 remains optimal for throughput efficiency. It is important to note that these settings diverge significantly from the current configuration. Setting 2C presents a practical improvement for both reefer and off-season, as it improves performance across the KPIs, making it a quick-win solution.

A renewed interpretation of the results adds to the analysis above, as it introduces an alternative perspective on operational decision-making. The visualisation of container flows provides stakeholders with a clear view of system dynamics and occupations rates. During the reefer season, operational focus should shift towards reefer handling by structurally dividing the depot into two separates streams. This approach addresses the bottleneck caused by the washing area if both used for dry and reefer containers. A recommended strategy is to allocate additional space for reefers and redirect dry containers during this period if possible. Redirection could involve assigning dry containers to alternative terminal or depots, particularly when M&R actions are not required or expected based on available data and forecasts. This would reduce the operational pressure on the dry container operation side.

Alternatively, and in line with the previous approach, process durations within the depot can be improved. For example, favouring blow-out procedures over full washing if possible, this allows for increased container flow. Another complementary strategy is to reduce the number of minor repairs conducted within the EPTI subsystems. Service should only be provided when containers fail to meet essential quality standards. This would shorten container dwell times, relieve pressure on this subsystem and improve flow to other operational areas. This strategic consideration raises the question if the depot should consistently deliver fully refurbished containers intended for long-term use, or prioritise flow efficiency while still meeting safety and quality standards for gate-out? This line of reasoning support early engagement with targeted solutions to overcome bottlenecks within the ECD.

Although the proposed layout and stacking configurations offer improvements, they are based on a simplified system. Real-time decision-making and operational flexibility, such as dynamic ECH assignment, mitigate inefficiencies in practice. Dynamic behaviour has not yet been addressed in this research. This is due to the initial focus on providing a foundational understanding of system relationships, which is essential before incorporating more complex elements into the analysis.

Operational implications and strategic planning

The report is useful for both logistics agents from shipping companies and depot personnel by improving mutual understanding of depot system dynamics. The framework demonstrates how individual decisions can influence overall system performance, offering a foundation for tactical planning and operational improvement. As the model is applied, a series of questions arise. What are the flows within the depot and which paths do containers follow? How long do processes take to complete and where do bottlenecks emerge? In what areas does the depot fall short and where should efforts be directed to improve efficiency? The model not only informs these questions but also helps to answer them through its structure, simulation results and settings. These findings offer awareness for both parties operational needs and constraints, promoting improved communication, proactive planning and more effective collaboration.

From a logistics perspective, this research emphasises the importance of informing depots in advance about expected short- and long-term flows. This enables the depot to adjust their layout and stacking strategies and resource allocation. Especially when multiple scenario sequences are considered. How should consecutive layouts interact; and how can transitions between layout be managed over time? While these aspects are not directly addressed in this study they present valuable directions for future research and operational reflection. Building on this, the framework also offers practical guidance for logistics agents by indicating how long certain strategies can be sustained before bottleneck emerge. This supports timely interventions to relieve pressure on specific subsystems, particularly when combined with emerging data-driven solutions such as dashboards and long-horizon forecasting tools. Understanding system dynamics support tactical decision-making for logistics agents. Combined with the model, it becomes possible to simulate forecasts and scenarios, which supports dynamic management of storage occupation. Shifting from reactive planning for depot operations to more proactive management of operations.

In summary, the framework equips decision-makers with a strategic tool to anticipate operational challenges, evaluate layout performance under varying conditions and align logistics and depot strategies for more resilient and efficient outcomes.

7

Conclusion and discussion

7.1. Conclusion

This research addressed the question of how adaptive layout and stacking strategies can improve operations in empty container depots. The provide an answer to this question, several different sub-questions were created that helped break down this broader question into specific components. For every question a concise answer is provided. Together these answers provide a structured and solid foundation for answering the main research question.

Sub-question 1*: What insights into empty container depot operations can be drawn from literature and real-world operational practices?*

Literature on Empty Container Depots (ECDs) is limited, specifically focused on layout design and stacking strategies which make expert consultation essential for operational insights. ECD systems are in practice complex systems with separated container flows for both dry and reefer container types. While ECDs share similarities with warehousing, M&R facilities and container terminals they differ in multiple aspects. Many aspects of this system are stochastic, starting with container arrival up until process durations and potential container gate-outs based on export requirements. Other aspects such as, weight, machinery usage, absence of unique ID retrieval make depot operations differ from previously mentioned systems. Therefore combining insights from both the limited literature and real-world practices is critical for understanding empty container depot systems.

Sub-question 2*: How does existing knowledge on layout and stacking strategies apply to empty container depots, and in what ways do empty container flows differ from full container flows?*

Literature findings on layout and stacking strategies offer valuable guidance for empty ECDs, but here are important distinctions compared to the handling of full containers. Full containers are managed differently due to their weight, cargo or specific handling requirements. Empty containers are lighter, less unique and often handled without considering a unique identification number.

In ECDs containers arrive mostly in unknown conditions and leave after inspection, with or without additional activities conducted upon the container. Depending on paths and activities, the layout and configuration of the yard is determined. This influences the design choice of storage blocks, driving lanes widths and stacking heights. Handling equipments such as empty container handlers, which are able to pick containers from the side, and sometimes two at a time, further shape these design parameters.

The relevant literature reaches beyond the container logistics, insights from facility layout planning and M&R facilities, provide practical guidance on layout development. Methods such as Systematic and Facility Layout Planning and Activity Relationship Charts are particularly relevant to ECD operations. While some of the general layout and stacking principles apply and contribute to design choices, the unique characteristics of ECD operations require tailored strategies.

***Sub-question 3**: What are the main operational challenges and capacity limitations in current empty container depot processes?*

The main operational challenges in current empty container depot operations include the stochastic arrival pattern of both dry and reefer containers. In periods of low interarrival times, the system is stressed and bottlenecks occur. This is a result from fixed process durations and the availability of handling capacity of equipment such as ECHs. Long process durations in combination with inefficient layout configurations contribute to bottleneck development within the system. When systems are stressed for longer periods of time, systems capacities can be pushed beyond the operational capacity with results in more inefficient operations.

Adding to this, ECD needs to accommodate for a diverse range of operational activities. Where dividing this activities into separated blocks is a common approach these choices are limited by spatial constraints of the facility. Insights from system analysis reveal that capacities of subsystems, process durations and internal movement of container using ECHs collectively restrict overall depot performance. Other factors that further affect depot performance, which are beyond the scope of this research, are also critical to investigate. Due to the focus on a simplified system, these parameters were not included in the analysis. These findings are discussed in the discussion chapter, where recommendations for future research and improvements is provided.

***Sub-question 4**: What trends in historical data and expert insights support future operational planning for depot operations?*

Analysis of MSC data of the year 2024 from the case study depot MedRepair Smirnoffweg revealed distinct seasonal patterns in reefer container arrival and demand fluctuations. Referred to as the reefer season, this season creates operational pressure, limiting flexibility for tactical changes due to high activity and tight ECH usage. On the other end, the period outside of this season, offers greater opportunities for strategic planning and improvements in depot layout and stacking strategies.

During this period, depot procedures can focus on global/regional logistics, either by absorbing containers for storage or facilitating more containers to the container logistics system. The simulation model developed in this research was designed to explore these process relationships and system dynamics for a full year. Combining the knowledge gained through system and data analysis and expert consultations, future operational planning within depots can become more adaptive. Making sure that the depot remains efficient and responsive to changing demands or strategies throughout the year.

***Sub-question 5**: Which operational scenarios should be modelled to evaluate the impact of layout and stacking strategies under varying depot conditions, including logistics strategies, demand requirements and infrastructural constraints?*

Based on data analysis and expert consultation, two distinct periods in the year are important to ECD operations. First the reefer season, when the interarrival rates of reefer containers become more critical. Second, the off-reefer season, where both dry and reefer container flows are stable and predictable. This second period in time is divided into three different strategical decision scenarios. These four different scenarios together capture the main operational variations needed for modelling ECD operations.

During the reefer season it is important to focus more on layout design and stacking strategies. During the off-season, strategic decision-making regarding process durations combined with layout and stacking becomes more relevant. Both periods should be tested under different settings to evaluate the effects of logistics strategies. All settings are informed by literature, system analysis and data analysis.

***Sub-question 6**: Which modelling technique can be used to effectively evaluate the impact of different layout and stacking strategies on depot performance?*

To address the complexity of evaluating different layout and stacking strategies in ECDs, simulation-based modelling is highly efficient. Where among the available techniques, Discrete-Event Simulation (DES) is particularly well-suited. DES models systems in which state changes happen at distinct points in time, triggered by events. Examples of such events could be, truck arrival, inspections or container movements inside the depot.

Given the stochastic and process-driven nature of depot environments, Discrete-Event Simulation is a well-suited modelling approach. DES makes it possible to asses how different layout configurations and stacking strategies affect operational performance in a realistic way based on data. When combined with correct KPI selection a proper comparison of settings to scenarios can be made.

***Sub-question 7**: What lessons can be drawn regarding the effectiveness of adaptive layout and stacking strategies under different operational scenarios?*

Following the analysis and KPI comparison of the scenarios and settings the conclusion can be drawn that, different layouts perform better under different conditions, highlighting the relevance of adaptive layouts. Taking as an example setting 6, which outperforms other setting in terms of occupation rates, throughput, ECH management and bottleneck control related to scenario 1.

In scenario 2,3 and 4 there is no clear winner in terms of throughput, but improvements are more focused and visible in reduced driving distances and bottleneck control. Setting 5 performs best when considering scenario 2 to 4, especially because of separated washing areas, enough buffer space for dry containers and reduced driving distances for internal movements.

Other settings which are more restricted to current operational layout also show improved performance based on the KPIs selected in this research. Therefore, adaptive layout and stacking strategies could improve performance on its own by keeping other parameters constant.

***Main research question**: How can adaptive layout configurations and stacking strategies contribute to the improvement of operations within an empty container depot, considering global/regional logistics strategies, demand requirements and infrastructural constraints?*

Adaptive layout configurations and stacking strategies help depots respond better to seasonal demand fluctuations and varying truck interarrival patterns. By testing different designs in realistic scenarios, improvements can be made in equipment use, driving distances and bottleneck control within the system. This together supports more flexible operations that will result in improved overall performance.

Based on the findings in this research, shipping companies that own their own depots are advised to apply the framework to proactively manage layout transitions and stacking strategies in alignment with forecasted flows. This enables more resilient operations and improves the coordination between logistics agents and depot personnel. section 7.2 expands on this recommendation by providing a more detailed explanation of the relevance for shipping companies and depot owners.

7.2. Discussion

Container volumes are expected to grow in the coming years, this will result in increased pressure on depots. Depot will need to handle more containers within limited space, while also adapting to market conditions to remain operationally efficient. This research explored how layout design and stacking strategies affect depot performance under high yard utilisation and changing market conditions.

The created simulation framework was useful in gaining understanding into system dynamics and bottleneck behaviour. Applied to a simplified system, this framework helped improve operations by tailoring decisions to realistic operational scenarios. However, the analysis also showed that layout and stacking are not the only factors that drive performance. To improve operations further, assumptions and simplifications made during the research should be reconsidered to better reflect the real-world decision-making, not only the system dynamics. Adopting a broader perspective on depot operations could lead to additional effective solutions.

If considered and studied, ECD systems are likely to become better in handling container volumes in the future. Making ECD systems interesting facilities that could serves an additional purpose beside providing M&R activities and storage. These facilities could help relief terminals or other facilities from handling empty containers by taking on a more active role in container delivery and pick-up. Strategic planning of ECDs allows carries to use them as alternative access points, reducing pressure on terminals, which supports more flexible operations. This could strengthen terminal operations, especially in disrupted scenarios as shown in the past. When focused on future container volumes this makes an ECD an interesting facility to further investigate. Below some recommendations are provided for future research.

Future research recommendations

While the results show that layout can indeed improve selected KPIs, adopting a broader perspective on depot operations might be beneficial for an additional deeper understanding of how various factors interacts. A more detailed discussion on further improvements is stated below, starting with the first recommendation which is more of a validation of choices.

This is related to the investments required for shifting to different layout configurations and/or strategies. Analysis of the different settings show that setting 5 and 6 consistently improve operations, but these improvements come with significant investments. Therefore proposed is, that in future research, a comprehensive cost-benefit analysis should be conducted. This analysis should consider investments in machinery, infrastructure (electricity points and washing facilities), labour hours, fuel and ECH depreciation. This analysis complements to this research by providing insight into a fair financial comparison between settings.

Another recommendation to future research should be related to the division of ECH responsibility to different areas. Taken as a core assumption in this research is that ECHs are responsible for a selected area. Based on the results, driving distance and number of moves, proves that this ECH usage is unrealistic. In real operations these values should be more or less similar, with deviates from the findings in this research using that fixed policy. Future research therefore should focus on dynamic ECH assignment, aiming for a more balanced distribution of driving distances. This could improve bottleneck control even further.

Adding to that, dynamic behaviour could be extended towards the operational policies for ECHs. Processes are now FCFS, which is unrealistic in real life. If ECH handlers could self-assign tasks, task management and selection will be better handled. Incorporating this into the existing model could further improve depot operations. To conclude, developing a more dynamic model for ECH usage and internal logistics is a promising direction for future work.

Final directions might include researching slot systems for truck arrival. Shown in the analysis this is a key factor to the performance of the depot. If controlled for truck arrival, operations within the depot can be more structured. Or incorporation of different gate-in and gate-out possibilities, think of barge connections, where multiple containers can gate-in or gate-out in a short period of time.

Strategic recommendations for key stakeholders

As highlighted in section 6.6, the simulation outcomes emphasise the importance of a collaborative strategy between empty container depots and shipping lines. When both parties have a shared understanding of system dynamics, targeted improvements can be implemented. From a logistics perspective, the developed model serves as a decision-support tool for simulating operational strategies and forecasting future demand scenarios. This facilitates stakeholders with a tool that help evaluate the impact of layout changes, resource allocation and scheduling adjustments before implementation. Collaboration becomes more critical given the increasing reliance on data-driven solutions, including predictive flow forecasting and accurate stock management. These new insights help aligning the strategies of logistics agents and managers more effectively. It is recommended to schedule bi-weekly coordination meetings, where several aspects are important to discuss. These meetings should include a review of current performance indicators, followed by an evaluation of the effectiveness of recent adjustments. Followed by a discussion on market developments and volume changes, which informs the planning for the upcoming weeks.

Adding to the benefits of collaboration, it is equally important to understand how this framework and model translates into the day-to-day operations at the depot level. How can these model insights support depot operators in improving their processes while maintaining service quality. Depots function primarily to execute the logistics strategies set by shipping companies, and their ability to do so efficiently has direct cost implications. Their core responsibility is to provide the correct container at the right time while respecting the quality standards. By doings so, operational costs are generated. The ideal scenario is to maintain service quality while minimising these costs. The model helps depot operators identify where adjustments can be made, offering insight into process efficiency and strategic alignment. It supports a broader view of operations, focussing on reflection on current practices. This would help guide improvements taking into account data-driven forecasts or shipping line strategies.

Bibliography

[1] United Nations Conference on Trade and Development (UNCTAD). *Review of Maritime Transport 2024*. Tech. rep. Geneva, Oct. 2024, pp. 1–38. URL: https://unctad.org/topic/transport-and-trade-logistics/review-of-maritime-transport.

[2] Eurostat. *Globalisation patterns in EU trade and investment*. Tech. rep. Luxembourg: Publications Office of the European Union, Oct. 2017, pp. 1–220. DOI: 10.2785/65836. URL: https://ec.europa.eu/eurostat/en/web/products-statistical-books/-/ks-06-17-380.

[3] Olcay Polat and Hans-Otto Günther|. "The impact of seasonal demand fluctuations on service network design of container feeder lines". In: *Journal of Transportation and Logistics* 1.1 (Apr. 2016), pp. 39–58. ISSN: 2459-1718. DOI: 10.22532/JTL.237886. URL: https://dergipark.org.tr/en/pub/jtl/issue/22136/237886.

[4] Felipe Hidalgo et al. "Empty container stacking operations: Case study of an empty container depot in valparaiso chile". In: *Proceedings - Winter Simulation Conference* (June 2017), pp. 3114–3125. ISSN: 08917736. DOI: 10.1109/WSC.2017.8248031.

[5] Jimena Pascual and Alice E. Smith. "Using Simulation to Improve Container Depot Operations". In: (2020), pp. 487–513. ISSN: 2509-6435. DOI: 10.1007/978-3-030-11866-2{_}21. URL: https://link.springer.com/chapter/10.1007/978-3-030-11866-2_21.

[6] Erhan Karakaya et al. "Design of empty container depot layouts using data and analytics". In: *Flexible Services and Manufacturing Journal* 35.1 (Mar. 2023), pp. 196–240. ISSN: 19366590. DOI: 10.1007/S10696-022-09452-Z/FIGURES/18. URL: https://link.springer.com/article/10.1007/s10696-022-09452-z.

[7] Hannah Snyder. "Literature review as a research methodology: An overview and guidelines". In: *Journal of Business Research* 104 (Nov. 2019), pp. 333–339. ISSN: 0148-2963. DOI: 10.1016/J.JBUSRES.2019.07.039.

[8] Bert Van Wee and David Banister. "How to Write a Literature Review Paper?" In: *Transport Reviews* 36.2 (Mar. 2016), pp. 278–288. ISSN: 14645327. DOI: 10.1080/01441647.2015.1065456. URL: https://www.tandfonline.com/action/journalInformation?journalCode=ttrv20.

[9] Héctor J. Carlo, Iris F.A. Vis, and Kees Jan Roodbergen. "Storage yard operations in container terminals: Literature overview, trends, and research directions". In: *European Journal of Operational Research* 235.2 (June 2014), pp. 412–430. ISSN: 0377-2217. DOI: 10.1016/J.EJOR.2013.10.054.

[10] Christian Bierwirth and Frank Meisel. "A survey of berth allocation and quay crane scheduling problems in container terminals". In: *European Journal of Operational Research* 202.3 (May 2010), pp. 615–627. ISSN: 0377-2217. DOI: 10.1016/J.EJOR.2009.05.031.

[11] Kap Hwan Kim, Young Man Park, and Mi Ju Jin. "An optimal layout of container yards". In: *OR Spectrum* 30.4 (Oct. 2008), pp. 675–695. ISSN: 01716468. DOI: 10.1007/S00291-007-0111-6/METRICS. URL: https://link.springer.com/article/10.1007/s00291-007-0111-6.

[12] Kap Hwan Kim and Ki Young Kim. "Routing straddle carriers for the loading operation of containers using a beam search algorithm". In: *Computers & Industrial Engineering* 36.1 (Jan. 1999), pp. 109–136. ISSN: 0360-8352. DOI: 10.1016/S0360-8352(99)00005-4.

[13] Jaeho Kang et al. "Deriving stacking strategies for export containers with uncertain weight information". In: *Journal of Intelligent Manufacturing 2006 17:4* 17.4 (Aug. 2006), pp. 399–410. ISSN: 1572-8145. DOI: 10.1007/S10845-005-0013-X. URL: https://link.springer.com/article/10.1007/s10845-005-0013-x.

[14] Yusin Lee and Nai Yun Hsu. "An optimization model for the container pre-marshalling problem". In: *Computers & Operations Research* 34.11 (Nov. 2007), pp. 3295–3313. ISSN: 0305-0548. DOI: 10.1016/J.COR.2005.12.006.

[15] Taejin Park et al. “Dynamic adjustment of container stacking policy in an automated container terminal”. In: *International Journal of Production Economics* 133.1 (Sept. 2011), pp. 385–392. ISSN: 0925-5273. DOI: 10.1016/J.IJPE.2010.03.024.

[16] Lu Chen and Zhiqiang Lu. “The storage location assignment problem for outbound containers in a maritime terminal”. In: *International Journal of Production Economics* 135.1 (Jan. 2012), pp. 73–80. ISSN: 0925-5273. DOI: 10.1016/J.IJPE.2010.09.019.

[17] Jörg Wiese, Leena Suhl, and Natalia Kliewer. “Planning Container Terminal Layouts Considering Equipment Types and Storage Block Design”. In: *Operations Research/ Computer Science Interfaces Series* 49.1 (2011), pp. 219–245. ISSN: 1387666X. DOI: 10.1007/978-1-4419-8408-1{_}12. URL: https://link.springer.com/chapter/10.1007/978-1-4419-8408-1_12.

[18] Michael Ranau. “Planning Approach for Dimensioning of Automated Traffic Areas at Seaport Container Terminals”. In: *Operations Research/ Computer Science Interfaces Series* 49.1 (2011), pp. 179–193. ISSN: 1387666X. DOI: 10.1007/978-1-4419-8408-1{_}10. URL: https://link.springer.com/chapter/10.1007/978-1-4419-8408-1_10.

[19] Byung Kwon Lee and Kap Hwan Kim. “Optimizing the yard layout in container terminals”. In: *OR Spectrum* 35.2 (Mar. 2013), pp. 363–398. ISSN: 14366304. DOI: 10.1007/S00291-012-0298-Z/METRICS. URL: https://link.springer.com/article/10.1007/s00291-012-0298-z.

[20] Nils Kemme. “Effects of storage block layout and automated yard crane systems on the performance of seaport container terminals”. In: *OR Spectrum* 34.3 (July 2012), pp. 563–591. ISSN: 01716468. DOI: 10.1007/S00291-011-0242-7/METRICS. URL: https://link.springer.com/article/10.1007/s00291-011-0242-7.

[21] Jörg Wiese, Leena Suhl, and Natalia Kliewer. “An analytical model for designing yard layouts of a straddle carrier based container terminal”. In: *Flexible Services and Manufacturing Journal* 25.4 (Dec. 2013), pp. 466–502. ISSN: 19366582. DOI: 10.1007/S10696-011-9132-1/FIGURES/27. URL: https://link.springer.com/article/10.1007/s10696-011-9132-1.

[22] Mustafa Egemen Taner, Osman Kulak, and Mehmet Ulaş Koyuncuo□lu. “Layout analysis affecting strategic decisions in artificial container terminals”. In: *Computers & Industrial Engineering* 75.1 (Sept. 2014), pp. 1–12. ISSN: 0360-8352. DOI: 10.1016/J.CIE.2014.05.025.

[23] Dominik Kress, Sebastian Meiswinkel, and Erwin Pesch. “Straddle carrier routing at seaport container terminals in the presence of short term quay crane buffer areas”. In: *European Journal of Operational Research* 279.3 (Dec. 2019), pp. 732–750. ISSN: 0377-2217. DOI: 10.1016/J.EJOR.2019.06.028. URL: https://www.sciencedirect.com/science/article/pii/S037722171930520X?casa_token=DokhoX8yM9AAAAAA:Zxv5OGPSLVGKPuXrSfH49vM3VucskwD-WaaSfi80Xy94ZH8saMeZPL45E2Xk_vjwOMZyzCPX3_8.

[24] Hamdi Dkhil, Adnan Yassine, and Habib Chabchoub. “Multi-objective optimization of the integrated problem of location assignment and straddle carrier scheduling in maritime container terminal at import”. In: *Journal of the Operational Research Society* 69.2 (Feb. 2018), pp. 247–269. ISSN: 14769360. DOI: 10.1057/S41274-017-0184-9. URL: https://scholar.google.com/scholar_url?url=https://www.tandfonline.com/doi/pdf/10.1057/s41274-017-0184-9%3Fcasa_token%3Dgpl8C225DTwAAAAA:rPm5Fblay4FVJ8G-y-2CUsIdUl-kVvBPkfA-uHx7H5jVPkZL9fn53byr4kejQrbd_0EuYuVIhnsw8g&hl=nl&sa=T&oi=ucasa&ct=ucasa&ei=1YoLaPf_Cdqs6rQPsK2_qQc&scisig=AFWwaeaaYojv3qVU6ctdjPhF3nGM.

[25] Genís Majoral, Andrés Reyes, and Sergi Saurí. “Lessons from Reality on Automated Container Terminals: What Can Be Expected from Future Technological Developments?” In: *Transportation Research Record* 2678.2 (Feb. 2024), pp. 401–415. ISSN: 21694052. DOI: 10.1177/03611981231174422/ASSET/B81CFBB6-C83E-4942-9C9F-AEEB56FAA293/ASSETS/IMAGES/LARGE/10.1177{_}03611981231174422-FIG4.JPG. URL: https://scholar.google.com/scholar_url?url=https://journals.sagepub.com/doi/pdf/10.1177/03611981231174422%3Fcasa_token%3DHj5RJV6qOFIAAAAA:qXlSLBbtSYzPp-v1z9xxp0UyWg3LVZhnPip3pyDPM6EBotm-0VtaMRNkuQQEKSpMiNtwf-R3yz3Zyg&hl=nl&sa=T&oi=ucasa&ct=ucasa&ei=uIsLaLjRAseUywTHra_xBQ&scisig=AFWwaeYo9m9-mVxTmoANRcCi9NqF.

[26] Baicheng Yan et al. “Integrated Scheduling of Rail-Mounted Gantry Cranes, Internal Trucks and Reach Stackers in Railway Operation Area of Container Terminal”. In: *Transportation Research Record* 2672.9 (Dec. 2018), pp. 47–58. ISSN: 21694052. DOI: 10.1177/0361198118782754/ASSET/83FB9549-297B-4C12-8391-7A8E9FB5A9A0/ASSETS/IMAGES/LARGE/10.1177{_}0361198118782754-FIG6.JPG. URL: https://scholar.google.com/scholar_url?url=https://journals.sagepub.com/doi/pdf/10.1177/0361198118782754%3Fcasa_token%3DxuG_s2_nBO8AAAAA:O41Ub_nljcgUUdhn1TOF8gnmlbCelQ7-VKUYj4J9rehaHb4G3HoL6UBxudwEtZea2kyqK5ZgcLXNOw&hl=nl&sa=T&oi=ucasa&ct=ucasa&ei=-osLaI_9Ctqs6rQPsK2_qQc&scisig=AFWwaebez5iVoEq34yjPGQTfoWBW.

[27] N.E. Mutters. *The relation between stochasticity and terminal stacking performance of import containers*. Tech. rep. Delft: TU Delft, Apr. 2019, pp. 1–137. URL: https://repository.tudelft.nl/record/uuid:46743128-dd15-4811-8893-60792bd969cc.

[28] Chenhao Zhou, Wencheng Wang, and Haobin Li. “Container reshuffling considered space allocation problem in container terminals”. In: *Transportation Research Part E: Logistics and Transportation Review* 136 (Apr. 2020), p. 101869. ISSN: 1366-5545. DOI: 10.1016/J.TRE.2020.101869. URL: https://www.sciencedirect.com/science/article/abs/pii/S1366554519305915.

[29] Hang Yu et al. “Flexible yard management in container terminals for uncertain retrieving sequence”. In: *Ocean & Coastal Management* 212 (Oct. 2021), p. 105794. ISSN: 0964-5691. DOI: 10.1016/J.OCECOAMAN.2021.105794. URL: https://www.sciencedirect.com/science/article/abs/pii/S0964569121002775.

[30] Vittorio Maniezzo, Marco A. Boschetti, and Walter J. Gutjahr. “Stochastic premarshalling of block stacking warehouses”. In: *Omega* 102 (July 2021), p. 102336. ISSN: 0305-0483. DOI: 10.1016/J.OMEGA.2020.102336. URL: https://www.sciencedirect.com/science/article/abs/pii/S0305048320306903.

[31] Tobias Oelschlägel and Sigrid Knust. “Solution approaches for storage loading problems with stacking constraints”. In: *Computers & Operations Research* 127 (Mar. 2021), p. 105142. ISSN: 0305-0548. DOI: 10.1016/J.COR.2020.105142. URL: https://www.sciencedirect.com/science/article/abs/pii/S0305054820302598.

[32] Jana Lehnfeld and Sigrid Knust. “Loading, unloading and premarshalling of stacks in storage areas: Survey and classification”. In: *European Journal of Operational Research* 239.2 (Dec. 2014), pp. 297–312. ISSN: 0377-2217. DOI: 10.1016/J.EJOR.2014.03.011. URL: https://www.sciencedirect.com/science/article/pii/S0377221714002252?casa_token=tbnGlXNDIJcAAAAA:CZ19eVvA6ZtsBbBQ0cc82mMrlqEO7h4cmK0dEtjaE_knGiCbQ9s8xcrQRQ2rNK3rf40Zen2G.

[33] Erhan Karakaya. “Container Handling and Layout Optimization in Empty Container Depots”. PhD thesis. Auburn: Auburn University, Nov. 2020, pp. 1–203. URL: https://etd.auburn.edu//handle/10415/7471.

[34] Erhan Karakaya, Alexander Vinel, and Alice E. Smith. “Relocations in container depots for different handling equipment types: Markov models”. In: *Computers & Industrial Engineering* 157 (July 2021), p. 107311. ISSN: 0360-8352. DOI: 10.1016/J.CIE.2021.107311. URL: https://www.sciencedirect.com/science/article/pii/S0360835221002151?casa_token=rVOIJ8OvnrMAAAAA:cghv1_jRTeO1Mae8BCOEqXTq2cr3ya8D8adFV7xAb6xpy5hunL9mo2ax7QrrfWpNC-33bA1PIec.

[35] R. Ryan Alvita. *A Tool for Container Terminal Design*. Tech. rep. Delft: TU Delft, Oct. 2020, pp. 1–106. URL: https://repository.tudelft.nl/record/uuid:52214175-671b-4155-ba7d-1377a17df0c3.

[36] Q Mili. *Designing a Terminal Layout with Systematic Layout Planning: A Case Study for Tank Container Storage Services in Hengelo*. Tech. rep. Enschede: University of Twente, Feb. 2025, pp. 1–65. URL: https://essay.utwente.nl/106063/.

[37] Amir Gharehgozli, Nima Zaerpour, and Rene de Koster. “Container terminal layout design: transition and future”. In: *Maritime Economics and Logistics* 22.4 (Dec. 2020), pp. 610–639. ISSN: 1479294X. DOI: 10.1057/S41278-019-00131-9/FIGURES/13. URL: https://link.springer.com/article/10.1057/s41278-019-00131-9.

[38] David Goldsman et al. “Discrete-Event Simulation”. In: (2015), pp. 103–109. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}10. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_10.

[39] Margaret L Loper et al. “Introduction to Modeling and Simulation”. In: (2015). Ed. by Margaret L Loper, pp. 3–16. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}1. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_1.

[40] Robert G. Sargent. “Model Verification and Validation”. In: (2015). Ed. by Margaret L Loper, pp. 57–65. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}6. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_6.

[41] Elizabeth T Whitaker and E T Whitaker. “Agent-Based Simulation”. In: (2015), pp. 139–155. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}12. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_12.

[42] Andy Register and A Register. “Monte Carlo Analysis”. In: (2015), pp. 217–224. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}18. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_18.

[43] Margaret L. Loper. “Distributed Simulation”. In: (2015), pp. 241–253. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}20. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_20.

[44] Steven Gordon and S Gordon. “Design of Experiments”. In: (2015), pp. 187–200. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}16. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_16.

[45] Val Lowndes and Stuart Berry. “Introduction to the Use of Queueing Theory and Simulation”. In: (2017), pp. 145–171. ISSN: 2195-2825. DOI: 10.1007/978-3-319-55417-4{_}5. URL: https://link.springer.com/chapter/10.1007/978-3-319-55417-4_5.

[46] Hans P.M. Veeke, Gabriël Lodewijks, and Jaap A. Ottjes. “The delft systems approach: Analysis and design of industrial systems”. In: *The Delft Systems Approach: Analysis and Design of Industrial Systems* (2008), pp. 1–223. DOI: 10.1007/978-1-84800-177-0/COVER.

[47] S. Robinson. “Conceptual modelling for simulation Part I: Definition and requirements”. In: *Journal of the Operational Research Society* 59.3 (2008), pp. 278–290. ISSN: 14769360. DOI: 10.1057/PALGRAVE.JORS.2602368;WGROUP:STRING:PUBLICATION. URL: https://www.tandfonline.com/doi/pdf/10.1057/palgrave.jors.2602368.

[48] S. Robinson. “Conceptual modelling for simulation Part II: A framework for conceptual modelling”. In: *Journal of the Operational Research Society* 59.3 (2008), pp. 291–304. ISSN: 14769360. DOI: 10.1057/PALGRAVE.JORS.2602369;WGROUP:STRING:PUBLICATION. URL: https://www.tandfonline.com/doi/pdf/10.1057/palgrave.jors.2602369.

[49] Stewart Robinson. “A tutorial on conceptual modeling for simulation”. In: *Proceedings - Winter Simulation Conference* 2016-February (Feb. 2016), pp. 1820–1834. ISSN: 08917736. DOI: 10.1109/WSC.2015.7408298.

[50] Amine Drira, Henri Pierreval, and Sonia Hajri-Gabouj. “Facility layout problems: A survey”. In: *Annual Reviews in Control* 31.2 (Jan. 2007), pp. 255–267. ISSN: 1367-5788. DOI: 10.1016/J.ARCONTROL.2007.04.001. URL: https://www.sciencedirect.com/science/article/pii/S1367578807000417.

[51] Maina E C et al. “Improvement of Facility Layout Using Systematic Layout Planning”. In: *IOSR Journal of Engineering (IOSRJEN) www.iosrjen.org ISSN* 08 (2018), pp. 2278–8719. ISSN: 2250-3021. URL: https://repository.dkut.ac.ke:8080/xmlui/handle/123456789/861.

[52] Xian Fong Low and Kuan Yew Wong. “Redesign and Simulation of Facility Layout in A Manufacturing Company”. In: *Jurnal Mekanikal*. Lecture Notes in Management and Industrial Engineering 40 (2017), pp. 53–60. ISSN: 2289-3873. DOI: 10.1007/978-3-319-50702-6. URL: https://jurnalmekanikal.utm.my/index.php/jurnalmekanikal/article/view/354.

[53] Jennifer Rowley. “Conducting research interviews”. In: *Management Research Review* 35.3-4 (Mar. 2012), pp. 260–271. ISSN: 20408269. DOI: 10.1108/01409171211210154/FULL/PDF.

[54] Hossein Baharmand et al. "A methodology for developing evidence-based optimization models in humanitarian logistics". In: *Annals of Operations Research* 319.1 (Dec. 2022), pp. 1197–1229. ISSN: 15729338. DOI: 10.1007/S10479-022-04762-9/TABLES/2. URL: https://link.springer.com/article/10.1007/s10479-022-04762-9.

[55] Robert G. Sargent. "Types of Models". In: (2015), pp. 51–55. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}5. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_5.

[56] Charles Turnitsa. "Conceptual Modeling". In: (2015), pp. 39–49. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}4. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_4.

[57] Margaret L. Loper. "Modeling Time". In: (2015), pp. 89–101. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}9. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_9.

[58] Qing Li and Yu-Liu Chen. "IDEF0 Function Modeling". In: *Modeling and Analysis of Enterprise and Information Systems* (2009), pp. 98–122. DOI: 10.1007/978-3-540-89556-5{_}5. URL: https://link.springer.com/chapter/10.1007/978-3-540-89556-5_5.

[59] Susan Dadakis Horn. "Goodness-of-Fit Tests for Discrete Data: A Review and an Application to a Health Impairment Scale". In: *Biometrics* 33.1 (Mar. 1977), p. 237. ISSN: 0006341X. DOI: 10.2307/2529319.

[60] Raul H. C. Lopes. "Kolmogorov-Smirnov Test". In: *International Encyclopedia of Statistical Science* (2011), pp. 718–720. DOI: 10.1007/978-3-642-04898-2{_}326. URL: https://link.springer.com/rwe/10.1007/978-3-642-04898-2_326.

[61] Stewart Robinson. "Simulation model verification and validation: Increasing the users' confidence". In: *Proceedings of the 1997 Winter Simulation Conference*. Ed. by S Andradbttir et al. IEEE, 1997, pp. 53–59. DOI: https://doi.org/10.1145/268437.268448.

[62] Osman Balci. "Validation, verification, and testing techniques throughout the life cycle of a simulation study". In: *Annals of Operations Research* 53.1 (Dec. 1994), pp. 121–173. ISSN: 02545330. DOI: 10.1007/BF02136828/METRICS. URL: https://link.springer.com/article/10.1007/BF02136828.

[63] Stewart Robinson. "A statistical process control approach to selecting a warm-up period for a discrete-event simulation". In: *European Journal of Operational Research* 176.1 (Jan. 2007), pp. 332–346. ISSN: 0377-2217. DOI: 10.1016/J.EJOR.2005.07.014. URL: https://www.sciencedirect.com/science/article/pii/S0377221705005643?casa_token=QVHkuZ-ImYsAAAAA:Q0fwK6SGlPJ4qMWO81k0nrq7Ul5AJzqU6ooKDiUCdqZZiE62hMCDB7bX9VcEQnzAa0tsvKOm.

A

Scientific paper

Adaptive layout and stacking strategies for improving an empty container depot

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Abstract*—Despite their critical role in maintaining container availability, Empty Container Depot (ECD) operations remain underexplored in academic research, specifically when focused on layout design and stacking strategies. This research presents a simulation framework that helps improve ECD operations and system dynamics understanding. By applying the approach to a real-world case, the MedRepair Smirnoffweg depot, this study not only contributed to the academic understanding of ECD operations, but also supports informed decision-making for improving depot efficiency. By developing a generic model and applying the theories discussed, this research provided valuable support for planning both existing and new depot facilities with similar operational characteristics and challenges. Adaptive layout configurations and stacking strategies help depots respond better to seasonal demand fluctuations and varying truck interarrival patterns. By testing different designs in realistic scenarios, improvements can be made in equipment use, driving distances and bottleneck control within the system. Shipping companies that own their own depots are advised to apply the framework to proactively manage layout transitions and stacking strategies in alignment with forecasted flows. This enables more resilient operations and improves the coordination between logistics agents and depot personnel.

***Keywords*—Empty Container Depot, Conceptual modelling, Layout configurations, Discrete-Event Simulation, Simulation framework, Strategic decision-making**

I. Introduction

Container transport is expected to grow in the years to come. This is confirmed by the United Nations Conference on Trade and Development (UNCTAD), projecting an average annual increase of 2.7% between 2025 and 2029 [1]. This growth is driven by the recovery of global trade, technological progress and infrastructure developments. This development has direct implications for the infrastructure and operational processes within maritime and hinterland logistics. This expected growth will particularly put pressure on existing resources, like container terminals, yards and depots.

To maintain operational efficiency under these conditions, strategies are needed to manage future container flows effectively. These strategies must not only consider the handling of full containers, but also the handling of empty containers, because they account for a significant share of the total container movements. Especially in Europe this share is high, due to higher import volumes compared to export volumes. The extra-EU export trade that happened via sea is almost half of the total amount of goods transported between EU and other continents, from an import perspective this share is even larger than 50% of the total imported amount value of goods [2].

For shipping companies, tailored empty container management is essential in keeping operational costs under control. This is about both the strategic repositioning of empty containers across terminals and the handling of containers that arrive at depots for storage and maintenance & repair (M&R) activities. Empty Container Depots (ECDs) play a vital role in the logistic chain as they are responsible for inspecting, maintaining and if necessary repairing containers before they are redeployed. The expected increase in container volume implies that depots will face a significant rise in the number of container units processed as well. Factors such as yard configuration, spatial organisation of stacking areas and container stacking strategies are becoming more important in overall facility performance.

Depot operations have to deal with different seasonal supply and demand situations and strategic decisions related to movements of empty containers within the supply chain network itself [3]. Depending on the situation, shipping companies may choose to absorb flows using extra storage capacity or evacuate container more rapidly by adjusting routing and scheduling. In both cases, ECDs play a critical role. This raises the question of how operational efficiency can be improved under high capacity utilisation, while still allowing the depot to adapt to changing market conditions with sufficient flexibility. The goal of this research is to improve operational processes within an ECD facility, focused on adaptive layout and stacking strategies, by following a simulation framework applied on a case study. From a layout perspective, layout configurations should be adaptive, meaning that storage blocks could change shape and size or even locations within the depot to best fit the specific needs of each operational scenario. This adaptiveness support operational flexibility, accounts for infrastructural constraints and enables the depot to respond effectively to shifts in container flows and regional repositioning needs.

By adopting a broader perspective on ECD operations, additional effective solutions can be identified. When considered and studied, ECD systems have the potential to significantly improve their ability in handling container volumes in the future. This evolution could transform ECDs into multifunctional facilities that go beyond traditional M&R and storage roles. These facilities could help relief terminals or other facilities from handling empty containers by taking on a more active role in container delivery and pick-up. Strategically planning of ECDs allows carriers to use them as alternative access points, reducing pressure on terminals, which supports more flexible operations.

This paper follows the following structure. In Section II, a comprehensive literature review will be presented on ECD and related literature. Section III, build on this gap defined by introducing a simulation framework that is tailored to break down ECDs and similar systems. Section IV, applies the constructed framework by analysing system relationships in combination with a data analysis. Section V, builds on this analysis by implementing these findings into a Discrete-Event Simulation (DES) model tailored to a case study depot. Section VI, applies this model to a highly relevant scenario to ECD operations with corresponding settings. These analyses together are further discussed in Section VII and Section VIII in the conclusion and discussion section.

II. Literature review

The continued growth of global container transport increases the pressure on the logistics chain. This development has direct implications for the infrastructure and operational processes within terminals, yards and depots. As demand rises, ECDs face growing challenges related to storage space, process efficiency and equipments use. Despite their critical role in maintaining container availability, ECD operations remain underexplored in academic research. Most literature is focused on full container terminals and repositioning flows of empty containers. A few studies, such as the paper by *Hidalgo et al. (2017)* [4] and *Pascual and Smith (2020)* [5], addresses the specific operational dynamics within ECDs.

A. Foundational studies in ECD operations

After carefully reviewing the literature, it becomes clear that research directly focused on ECD operations is still very limited. This section will further elaborate on the key findings from the available literature. Studies that show the strongest connection to this research area are: *Hidalgo et al. (2017) [4]*, *Pascual and Smith (2020) [5]*, *Karakaya (2020) [6]*, *Karakaya et al. (2021) [7]* and *Karakaya et al. (2023) [8]*. A particular attention will be on the paper written by *Hidalgo et al. (2017)* [4], which provides a valuable and closely related methodological starting point for this research. Their simulation-based approach offers a structured way to evaluate operational policies related to ECD operations, using real-world data and statistical analysis that support decision-making.

Many aspects of their research approach are highly relevant and will be applied in this research as well. Think of the use of stochastic inputs, the use of empirical distributions representing how long different processes take based on data, as well as, scenario based testing. However, there are several important differences between their study and the focus of this research. *Hidalgo et al. (2017)* [4] examine a multi-user depot with fixed layout configurations and detailed transactional data, focusing on operational decisions within designated storage blocks per shipping company. In contrast, this research is focused on a single-user depot, emphasising tactical decisions around layout flexibility and container grouping based on type or conditions. Historical data should inform the comparative analysis of alternative layout and stacking strategies under varying scenarios.

Despite these differences, several methodological components from *Hidalgo et al. (2017)* [4] remain highly relevant. The structure of their simulation experiments and statical evaluation techniques offer valuable insights that could inform the modelling approach in this study. In their conclusion, they state that the underlying methods used in their research are widely applicable. This perspective supports the notion that a simulation framework can offer insights for similar ECD facilities facing similar operational challenges. Moreover, their conclusion highlights the potential to extend their model towards the analysis of different depot layouts. This aligns closely with the core objective of this research, which is primarily focused on evaluating alternative layout configurations.

B. Methodological insight from related fields

Before exploring the specific components and processes within an ECD, it is critical to first clarify what the definition of a ”system” is. This concept forms the foundation for understanding the depot's structure and interactions. The concepts and terms used in this research are informed by *The Delft Systems Approach* by *Veeke et al (2008)* [9], and are considered highly relevant for understanding and modelling the operations of an ECD.

Adding to the understanding of the system by analysing its components and relationships, the steps towards a simulation model is to start with a simplified version of the real-world context using conceptual modelling. To support this transition, two different sources provide practical guidance. The first edition of *Conceptual modelling for simulation: Definition and requirements* by *Robinson S. (2008)* [10] describes that a well-defined conceptual model is essential to make sure all stakeholders share a common understanding of the model's structure, scope and purpose. Providing also guidance on which elements to include inside the conceptual model. The second edition builds on this by presenting a framework for developing a conceptual model [11]. Which is supported by a later work of *Robinson S (2016)* [12], which helps defining the appropriate level of abstraction when modelling complex systems with practical examples. These insights help guide the correct development of a conceptual model for complex systems such as ECDs.

Building on the conceptual model developed through the systems thinking approach, the current layout of an ECD could be analysed and opportunities for layout improvements could be discovered. While optimisation is not the focus of this research, literature on Facility Layout Problems (FLP) helps guide layout analysis. A comprehensive survey by *Drira et al. (2007)* [13] represents different types of FLP and presents a tree structure that can be used for narrowing down the scope of the problem. Besides this information, different layout designs are briefly discussed which could be applicable on ECDs, such as an open-field or loop layout. Another paper by *Maina et al (2018)* [14] applies Muther's Systematic Layout Planning (SLP) method to improve layouts based on activity relationships and flow analysis. Translating this to different path configurations for containers inside an ECD, an activity relationship chart could help defining new layouts. This is further underlined in the paper by *Low and Wong (2017)*, where they also implement Muther's SLP to minimise total distance travelled by machinery. Highlighting internal transport as key metric, focusing on reducing driving distances within a facility can lead to better system performance.

To evaluate layout configurations and stacking strategies under varying capacity conditions in ECD, a suitable modelling approach is essential. The operational environment of an ECD is characterised by uncertainty, dynamic interactions between processes and resource constraints. Container flows are subject to considerable variability in arrival times, handling requirements and retrieval patterns, contributing to the overall uncertainty in the system. These conditions make analytical modelling therefore complex and often difficult to apply effectively. One way to address this complexity is through simulation, with Discrete-Event Simulation (DES) being specifically well suited to such systems. DES models systems in which state changes happen at distinct points in time, triggered by events. Examples of such events could be, truck arrival, inspections or container movements inside the depot. Therefore, DES is well suited for modelling operational systems like logistics and inventory environments. As explained by *Goldsman and Goldsman (2015)* [15] in the book *Modeling and Simulation in the Systems Engineering Life Cycle,* by *Margaret L. Loper (2015)*, inventory systems where products are received, stored, picked and restocked are applicable for DES. ECD operations share many similarities with those inventory systems. This makes it particularly suitable for modelling logistics environments involving queues, resource allocation and stochastic process durations.

C. Conclusion literature review

Literature on Empty Container Depots (ECDs) is limited, specifically when focused on layout design and stacking strategies. This review has shown that many principles from related logistical contexts have potential relevance for ECD operations. Although originally developed for alternative systems such as, container terminals or warehouse systems, these concepts offer useful perspectives for analysing and improving depot performance. While informative, these concepts are not tailored to the unique complexities of individual ECDs. Therefore, alternative methods need to be considered to gain operational insight about ECD systems, for example through expert consultation. The reviewed literature supports the idea that simulation-based analysis can generate valuable insights for ECD facilities operating in different layout and stacking scenarios. The relevance of this research lies in its ability to bridge a clear literature gap while also offering practical value. By applying the approach to a real-world case, the MedRepair Smirnoffweg depot, this study will not only contribute to the academic understanding of ECD operations, but also supports informed decision-making for improving depot efficiency. By developing a generic model and applying the theories discussed, this research provides valuable support for planning both existing and new depot facilities with similar operational characteristics and challenges.

III. Methodology

This research produced three key deliverables. First, a general framework for analysing and improving operations within ECDs, focusing on layout adaptability, process efficiency and scenario-based planning. Second, a simulation model developed as part of the framework, capable of evaluating different layout configurations and stacking strategies under various operational scenarios and different depot environments. Third, the application of the framework and the model in a case study at MedRepair Smirnoffweg (Rotterdam), evaluating different layout configurations and stacking strategies under various operational scenarios in a real-world context.

A. Case study

Given the complexity and specific nature of the research topic, this study focused on analysing a single empty depot to gain insights into general operational patterns. Factors such as depot layout, the variety of container movements and the varying conditions of arriving containers differ depending on demand fluctuations and truck arrival patterns. Each depot is unique, making it impractical to generalise findings without first conducting a detailed case study at one location. MedRepair Smirnoffweg was therefore an ideal case for collecting historical data on all activities occurring at this site. The analysis of this data, and the system analysis conducted, supported the development of realistic layout scenarios, which were crucial for testing and refining the simulation model. By focusing on MedRepair Smirnoffweg, scenarios were tailored to the specific container movements and spatial challenges of this depot. Making the output both valuable and directly applicable for improving efficiency at this location, while also contributing to a broader understanding of general depot operations.

B. Simulation framework

A refined simulation framework is developed, which was based on a earlier developed research framework, that helps to analyse and improve operations in ECD operations. This improved version offers a generalised structure for breaking down similar systems, which is focused on ECD operations but could also be applied to other M&R facilities or warehousing environments in comparable operational settings. This simulation framework, presented in Figure 1, serves as a practical guideline for researchers aiming to identify operational

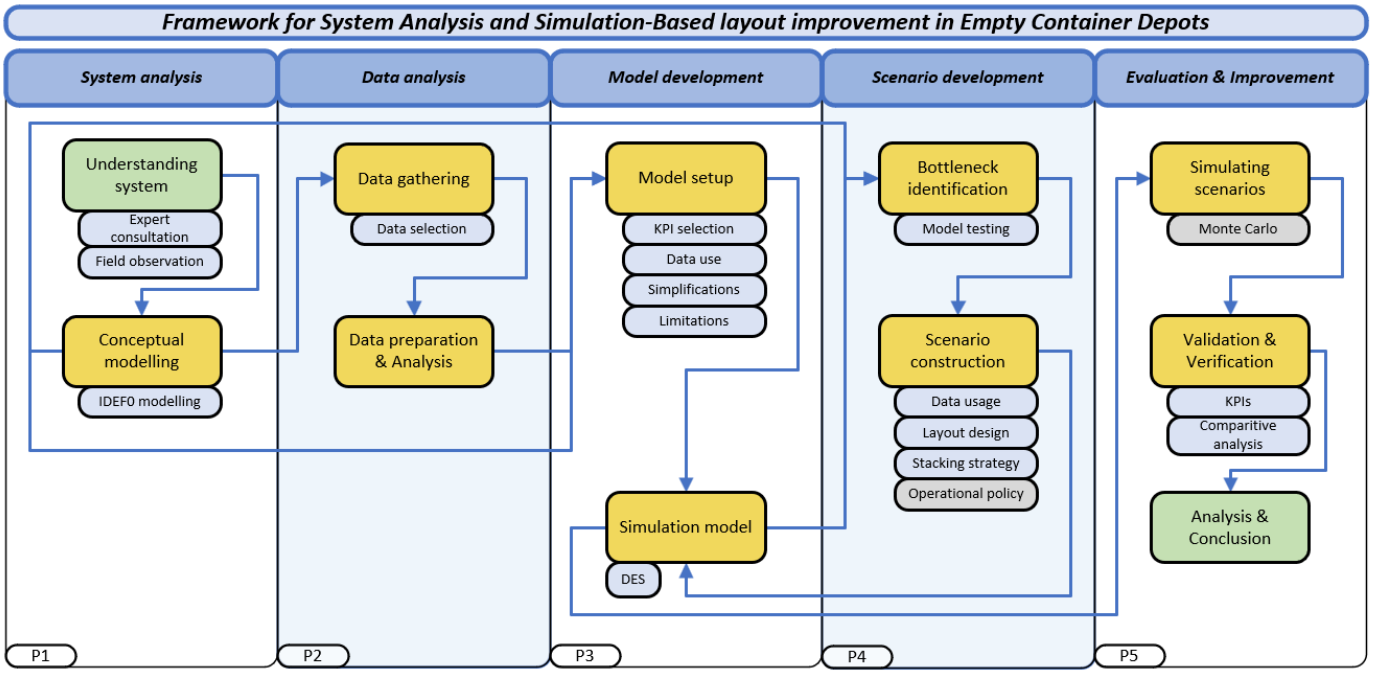

Fig. 1. Simulation Framework

inefficiencies, test different operational, tactical and strategic scenarios, and focus on improving facilities. The core steps taken in the framework are coloured in yellow, representing a key phase in the analysis process. Specific methods or considerations are assigned to these step to support their execution, coloured in light blue. Grey boxes highlight methods and considerations that can complement to the analysis, which are considered in this research but not implemented.

IV. System analysis

ECDs are essential nodes in the global logistics chain, yet they vary significantly in size, layout and operational complexity. Despite these differences, many ECDs share a core set of activities and processes. To better understand and improve operations across such depots, a layered breakdown of the system is presented, that captures the key components and dynamics of a typical ECD. While the system structure is designed to be broadly applicable, it is grounded in the operational reality of a specific case: The MedRepair depot at Smirnoffweg in the port of Rotterdam. This depot is selected because of its representativeness in ECD operations. By using this location to structure, test and validate system components, this research makes sure that both practical relevance and generalisability is obtained.

A. Empty Container Depot (ECD)

The layered breakdown of the system is structured in four layers. Starting from a high-level (macro) view of the ECD system, down to the detailed behaviour of individual entities within the depot. This layered approach supports a comprehensive analysis of ECD operations. Within each level, a combination of structural configurations and analytical modelling approaches is used to describe the system. Structural elements, such as Job Shop or Flow Shop representations, help capture the sequencing of activities. While analytical components, such as queueing models, represent waiting times, service dynamics and system performance. Together, these elements define how events link to activities and how activities link to processes. While the system shows characteristics of these models, this research does not aim to solve these models. Instead, their structural and analytical elements are used to describe and understand the operational behaviour of the ECD.

Starting with the lowest level of detail, defining the concept of ECD operations as a system. Based on the literature findings the ECD system is defined as a set of coherent elements that can be distinguished from the broader reality. These elements are interconnected and some of them interact with that broader reality [9]. The ECD system could be defined as a facility where containers (entities) with unknown dimensions and conditions enter the system (Input). Inside the depot multiple activities are performed (Process) before that same container moves out of the system again, with known dimensions and condition (Output). This can best be described using the IDEF0 modeling method, as explained in the book *Modeling and Analysis of Enterprise and Information Systems* by Li Q. and Chen Y. [16]. The boundaries of an ECD system are defined by the gate-in and gate-out of containers, they represent the interaction of the system with its environment. ECD operations are focused on two different entity types, dry containers and reefer containers. Therefore, whole the depot operations could be split into two operational entity streams, see Figure 2. For dry and reefer containers multiple activity combinations are possible that together form the system

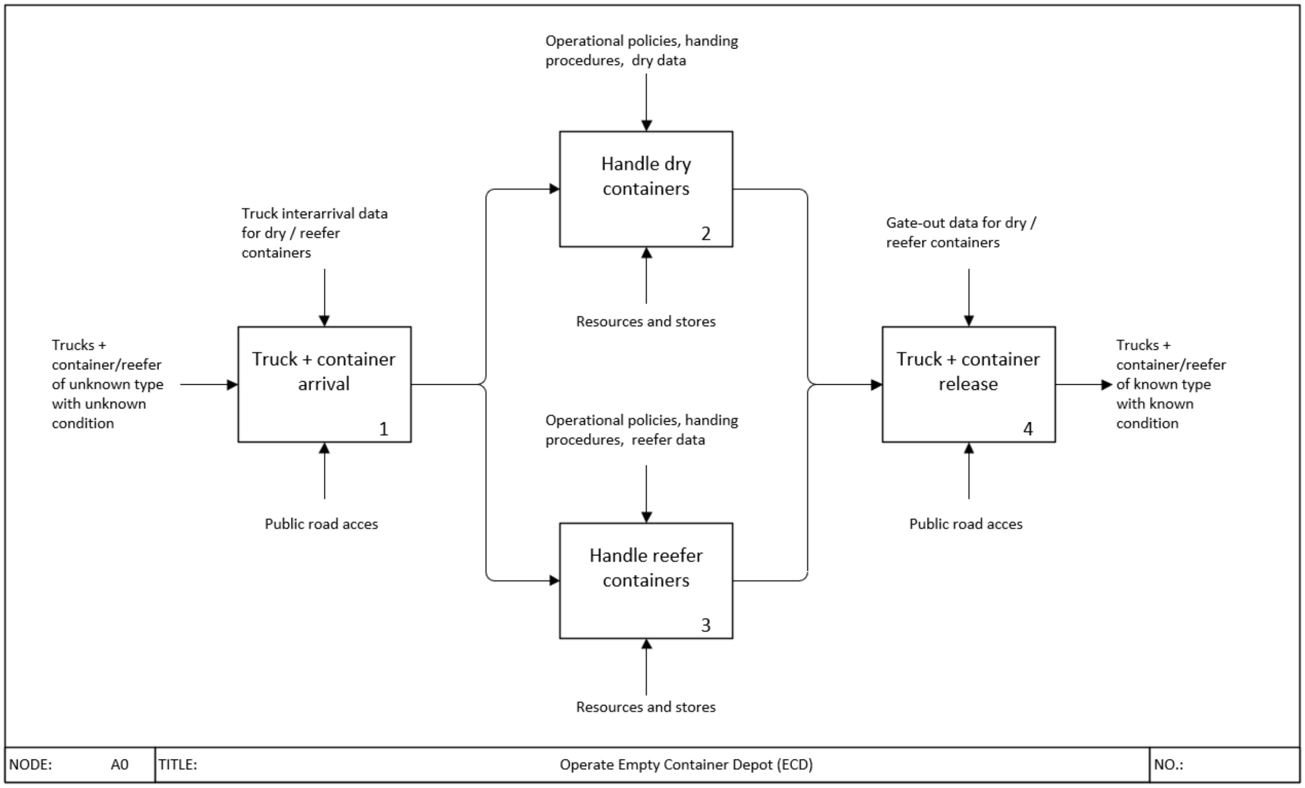

Fig. 2. IDEF0 A0 representation of the ECD system (meso) level

processes. All subsystems for dry and reefer containers are mentioned and numbered according to the IDEF0 modelling representation, these subsystems and there relationships are presented in Figures 13 and 14 in Appendix A.

Following the IDEF0 modelling method, the system at meso-level is further decomposed into a set of operations specific to each subsystem for dry operations. This micro-level representation provides a more detailed view of internal processes. For every box inside IDEF0 A2 and A3 different control and mechanism elements are used. To gain insights into these process durations, depot procedures and operational data are analysed to describe the ECD system as it functions in reality. The conducted analysis will serve as a foundational input for the conceptual modelling phase.

B. Data analysis

Process durations and procedures are analysed for all subsystems described in the IDEF0 figures. Most subsystems use statistical distribution functions based on observed company data, other subsystems rely on procedural knowledge gained through expert consultations of the case study depot. An important analysis is related to the interarrival of trucks with both dry and reefer containers. For dry containers, no significant fluctuations in demand were observed for a full year, suggesting that the pattern of truck interarrival is similar during this analysed period. For reefer containers, significant fluctuations in the interarrival pattern were observed for a full year, dividing the year into three different sections. Resulting in an easy, normal and stressed flow period for the interarrival of trucks with reefer containers.

The data that were analysed are discrete, so a Chi-Square goodness-of-fit test was conducted to identify suitable probability distribution functions [17]. The distributions that best fitted the data according to these tests are different geometric distributions.

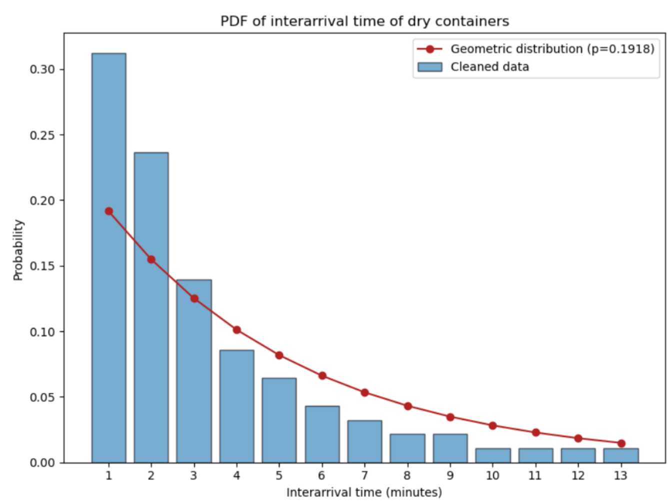

Fig. 3. Fitted PDF to the interarrival times of trucks with dry containers

The dataset used for these analyses reflect actual operational behaviour, including ad hoc decision making that influences depot performance. Due to the structured modelling approach followed in this chapter, this detailed operational variability is not fully captured. Therefore, a slightly different interpretation of the data is applied, to ensure that insight into process relationships is maintained. This was done by using an adjusted version of the Maximum Likelihood Estimator (MLE) used for geometric distributions, where δ represents an integer offset which underestimates the probability of shorter interarrival times.

Although this equation deviates from the original MLE used, it still effectively captures the overall shape and logic of the empirical distribution. The conceptual model should be designed to explore process relationships and layout dynamics, rather then replicate exact operational behaviour. Using the original MLE equation would result in a high rate of container generation, preventing meaningful insights into these relationships. This adjusted MLE equation helps with maintaining interpretable results by underestimating low interarrival time values and overestimating high interarrival time values. This principle is shown in Figure 3 as an example for the interarrival times for dry containers.

For processes that happen within depot subsystems a different technique is used to evaluate the data. Taking into account the fact that these processes are continuously measured and not rounded in real life, these data are fitted using a continuous distribution. An Empirical Cumulative Distribution Function (ECDF) is constructed based on observed data of the year 2024 for all subsystems. These empirical distributions were then statistically compared with multiple theoretical distributions using a Kolmogorov-Smirnov (K-S) test [18]. This in order to identify the Probability Density Functions (PDFs) that best fits the data. These PDFs provide a simplified and generalisable form suitable for simulation. By translating these observations into continuous statistical distributions, process durations can be stochastically generated, when applied in a simulation model as in this research.

In addition to the analysis conducted on process durations and procedures, further insights were gained regarding container quality and characteristics. This analysis served as input for the simulation model by supporting realistic flows within the system. By identifying the share of containers with specific qualities and characteristics, the model is able to simulate operational flows more accurately, which is an essential step to reflect system performance.

C. Conclusion system analysis

This system analysis focused on analysing the ECD system's (operational) characteristics and relationships. The system was broken down into four levels complemented by the use of the IDEF0 method, providing a structured overview of the components. A distinction was made between dry and reefer containers, each with their own specific relationships and processes. This layered approach offered valuable insights into subsystem interactions and helped identify operational bottlenecks through the visual inspection of the IDEF0 diagrams. All subsystems defined represent the core processes within an ECD system for both container types mentioned. At the micro-level (highest level of detail), each subsystem and its internal processes were described in detail. This system and data analysis helped with understanding depot procedures, which further clarified how the system functions in the real-world practice. For the data analysis, both discrete and continuous data were examined to accurately capture process durations. Statistical tests, including the Kolmogorov-Smirnov and Chi-square tests, were used to determine the probability distributions that best fit the data. In some cases, these tests were adapted to better reflect the system's behaviour. This because the conceptual model is intended to explore process relationships and layout dynamics, rather than replicate exact operational behaviour. To conclude, this combined analysis serves as the foundational input for the conceptual modelling phase.

V. Simulation Modelling

The aim of the model is to provide insight into ECD operations by testing various layout structures and stacking strategies through a flexible and easily adaptable DES simulation model. The testing of these layout structures and stacking strategies are carried out using a baseline simulation model. This baseline model is the direct translation of a conceptual model. The goal is to uncover and understand the operational relationships between subsystems, identify bottlenecks and analyse internal movement dynamics, such as congestion and flow disruption within the depot. Although tailored to the operations of MedRepair Smirnoffweg, the model was built in a generic and flexible way, allowing adaptation to different path configurations, layout designs, stacking strategies and operational policies. The model was created using the simulation framework presented in Figure 1, which defined core concepts and guided the modelling process.

For the modelling of the baseline model several inputs were used. Starting with the first determination of all subsystems included in the model. Supported by the different control and mechanisms for each subsystem. Taking into account relevant experimental factors that were identified based on an extensive data analysis of the case study depot. For the baseline model operational insight of the case study depot of the year 2024 is used. In addition to this, a filter was applied to both dry and reefer containers, focusing on the primary flows within the system. Therefore, these values do not accurately reflect the system's throughput of the year 2024.

A. Model implementation

Following the simulation framework presented in Figure 1, this paragraph outlines the steps taken to move from system and data analysis to the actual construction of the simulation model. It reflects one possible approach to building a model based on operational understanding and structured design. The conceptual model defined is translated into a Python model using SimPy which is a DES library in Python. The first important step was to define what to model, based on the identified entities, resources and their relationships.

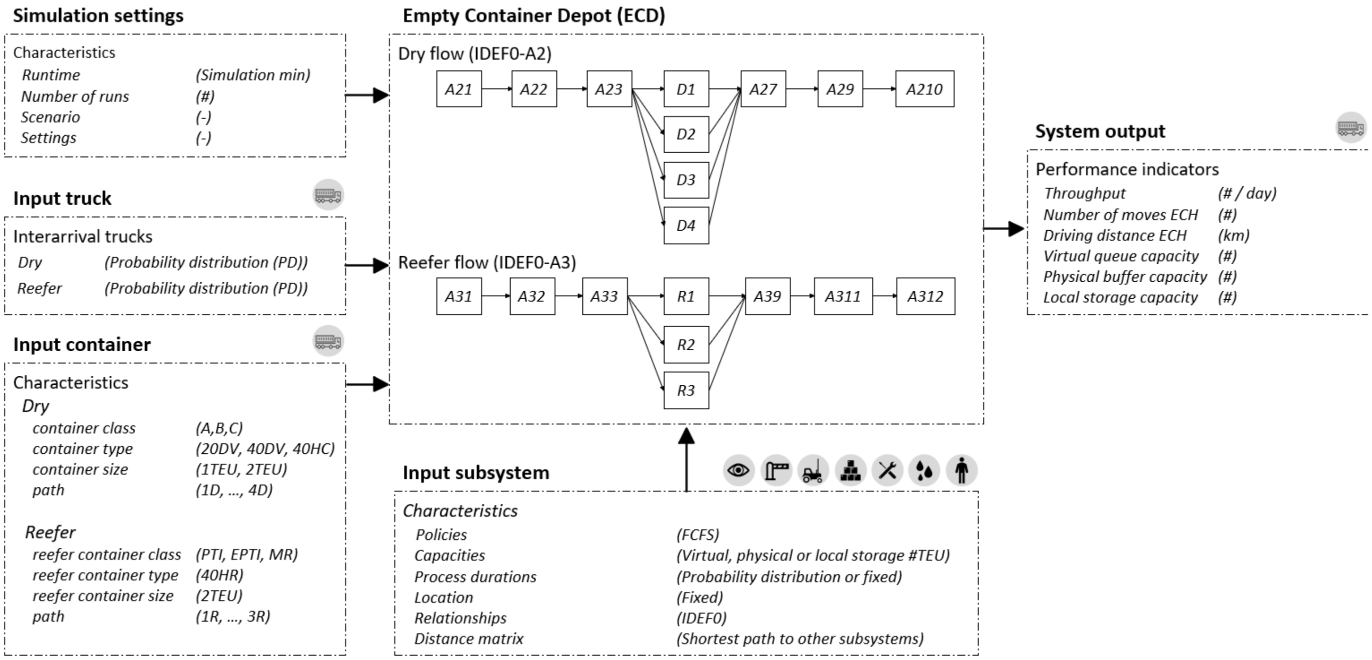

Fig. 4. Model overview

Starting with the construction of setting up the simulation environment in Python. This included the setup of the whole simulation environment with its components such as, time structure, container generator and resource definition. The development started with the dry container flow of the ECD, building classes for subsystems with tailored policies. Subsystems were created one by one, to test flow logic and timing. This choice was made to verify the correct behaviour of the system. Once the dry container flow was functioning, the model was made more realistic by adding operational constraints. Such as, implementing different path configurations and probability distributions or time durations per subsystem. After finalising the dry container setup, the same structure was extended to reefer containers, using the IDEF0 A3 diagram.

This approach allowed for controlled testing and ensured the model remained focused on capturing system flows and identifying bottlenecks. This by correctly logging all relevant information used to evaluate the KPIs identified. In Figure 4 an overview is presented of the whole model, including its inputs and outputs.

B. Key Performance Indicators

The model generated outputs that reflected the system's operational performance. To assess performance, a set of Key Performance Indicators (KPIs) was defined and is presented in Table I. These outputs were essential for evaluating how well the system functioned under the original layout (baseline) and scenario-specific conditions. These parameters provided insight into important aspects of the system, focussing on throughput, utilisation and ECH usage. Throughput indicates how efficiently the system processes containers, with higher throughput generally linked to better operational performance. ECH handling activity and driving distance are directly linked to labour and fuel costs, minimising movements while maximising handling efficiency contributes to cost reduction. This is especially important since ECD operations represent a cost for shipping lines which own there own depots. Logging subsystem occupations helps identify bottlenecks and assess whether capacities are being fully utilised.

TABLE I
OVERVIEW OF PERFORMANCE INDICATORS

Name	Description	Unit	Calculation
Throughput	Number of dry/reefer containers processed	# / day	Count of outgoing containers
Handling capacity ECH	Number of dry/reefer containers handled by an ECH	#	Count per ECH + sum all ECHs
Driving distance ECH	Total distance covered by ECH	km	Count per ECH + sum all ECHs
Max virtual queue occupation	Number of dry/reefer containers in virtual queue ECH	#	Log simulation
Max physical buffer occupation	Number of dry/reefer containers in physical buffer subsystems	#	Log simulation
Max local storage occupation	Number of dry/reefer containers in local storage location subsystems	#	Log simulation

C. Assumptions, simplifications and limitations

Throughout the system analysis and conceptual modelling process, several assumptions and simplifications were made to streamline the development of the simulation model. These decisions helped reduce complexity while maintaining the core principles and dynamics of the real-world ECD system. Starting without an initial model, the first step was to construct a robust baseline capable of testing and adapting to different layout configurations under specific operational scenarios. Operational policies are fixed in this research, allowing for a focused analysis on how layout changes impact depot performance. All assumptions and simplifications related to system boundaries, data usage, subsystem processes and (path) relationships have been carefully examined and are validated through expert consultation. These elements are not individually listed here, but they are comprehensively addressed within the research. This inclusion of assumptions and simplifications ensures transparency and supports the robustness of the model setup and analysis.

The constructed simulation model is a static model, meaning that all scenarios, settings, principles and path configurations are defined prior to execution. These settings remain fixed during the run, once the simulation has started. Therefore, this model does not support real-time or dynamic decision-making, which is often present in ECD operations. The design choice of a static model was made on purpose, to remain focus on understanding the structural relationships between subsystems, rather than simulating the full complexity of dynamic operations. By doing so, the model is not capable of reallocating resources (ECHs), adjusting flows, or modifying capacities based on the operational needs. Another important aspect of the simulation is the interarrival rate of dry and reefer containers, which was based on real-world data. Due to the static behaviour of the simplified model, the real interarrival rates were intentionally adjusted. Including the real interarrival rates would have stressed the model before meaningful insight could be drawn. Including a slightly less powerful arrival pattern following similar characteristics, helped capturing the objective of the model: understanding system relationships and identifying bottlenecks. As a result, the model is used as a comparative tool that could analyse different layout configurations to different scenarios and settings. This to support strategic thinking and system redesign.

D. Conclusion model

This section presented the simulation model developed to represent the operations of the ECD at MedRepair Smirnoffweg. The model serves as a direct translation of a conceptual model, which is based on literature, expert consultation, system analysis and data insights. While it focuses on the specific context of the case study depot, the model is designed to be flexible. The model is capable of adapting to various layout configurations, stacking strategies, path designs and operational policies.

The primary objective of the model is to uncover and understand operational relationships between subsystems. Adding to that, the model helps identify bottlenecks and support analysis of internal movement dynamics such as congestion and flow disruptions. This is achieved by providing a wide range of input parameters, including subsystem and container specific parameters, path configurations and distances between subsystems for evaluating driving distance by ECHs. Assumptions and simplifications are applied to maintain and create a balance between model complexity and interpretability, while respecting the goal of the model, which is capturing essential dynamics of the system.

To evaluate the system performance, several indicators were defined, focusing on system throughput, occupation rates of subsystems and ECH usage. By comparing outcomes to these indicators, insights into the operational efficiency of the depot can be provided. It is important to note that the model is static in nature, relying on fixed inputs and therefore the model is unable to adapt dynamically during runtime. The primary value of the model lies in the comparative analysis of layout configurations and stacking strategies. Putting this all together, this model is a powerful tool that supports tactical and strategic decision-making and informs the rethinking of layout configurations.

VI. Scenario design and analysis

The goal of these simulation experiments is to gain insight into the operational dynamics of an ECD, rather than optimise its performance. By simulating various layout configurations and stacking strategies under different seasonal characteristics, the aim is to evaluate whether alternative settings can lead to improved performance, as defined through the KPIs. These different settings are compared to the current layout of the case study depot of MedRepair Smirnoffweg, which will act as a baseline in every scenario. While each layout and stacking strategy remains fixed during individual simulations runs, the model allows for the development of tailored configurations that better suit specific operational conditions. This adaptive process helps identify layouts that avoid exceeding depot capacities and maintain or improve efficiency under both peak, regular and easy conditions. Simulation allows exploring system behaviour under different operational scenarios, revealing system dynamics and bottlenecks. Based on findings derived from system analysis, data analysis, model-based testing and literature, simulation helps improve understanding of the ECD system. Combining these elements will result in new layout configurations tailored to the case study conducted.

To conclude, these experiments are designed to compare the performance of different layout and stacking strategies in four different scenarios. With the goal of identifying configurations that improve ECD operations based on KPI analysis.

A. Scenarios and settings

The core objective is to evaluate how different layout designs and stacking strategies perform under varying seasonal characteristics of empty container logistics. By simulating both peak and regular operational periods, the model should identify configurations that help avoid exceeding depot operational capacities, maintain depot efficiency or improve efficiency. A clear distinction into two categories can be made for the four different scenarios. Scenario 1 focused on the peak months for reefer container arrival, with its goal to test the system resilience under stress conditions. Scenario 2,3 and 4, represent regular operations, which help explore strategic decisions to improve performance in off-season periods. During this period a stable interarrival rate pattern for both dry and reefer containers is observed. Scenario 3 is focused on maximising the storing function of the depot for dry containers. In scenario 4 the strategy is to generate fast throughput and depot storing function is minimised. As scenario 1 is most relevant to the analysis presented in this paper, this will be described in more detail. The focus will be on the setting setup, including the analysis of this scenario afterwards.

For evaluating the scenarios, nine different layout settings including the current baseline setting are developed. The development of these settings is based on insights from system analysis, data analysis, model testing and literature. These designs are the result of combining findings from phases 1 to 3 of the simulation framework, providing realistic, tailored and data-driven configurations. The goal of layout development is to design performance oriented settings tailored to ECD operations. These settings focus only on spatial configuration and subsystem capacities, keeping all other simulation parameters constant. By doing so, a clear comparison of layout and stacking strategies can be made against the baseline model. Where the aim is to design new configurations that improve performance across the four scenarios described. Below three of the nine settings are visualised in Figures 5, 6 and 7, dividing subsystems into dry (red), reefer (yellow) and shared (green) systems. Figure 5 acts as a baseline for the setting comparison. After carefully evaluating these findings setting 2 is created following similar perimeter configurations as the baseline setting, see Figure 6.

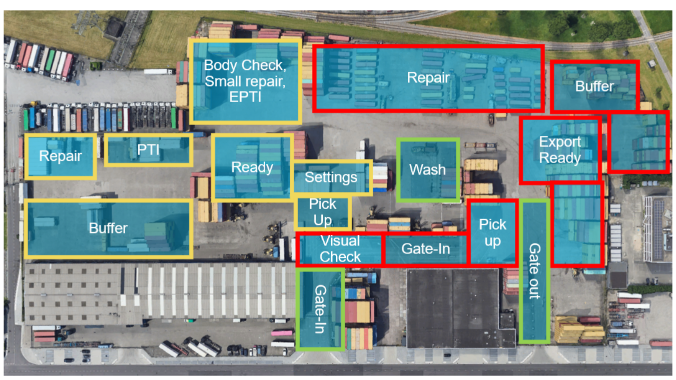

Fig. 5. Schematic overview of baseline layout ECD

Following the setup approach it was possible to develop new configurations that focuses on two main goals. First, reducing internal driving distances of ECHs responsible for the internal movements of both dry and reefer containers. Second, provide a strategy that is better in controlling the bottleneck dynamics within the system. By rethinking the current system, which is constrained by its current shape and perimeter configuration, a complete new layout setup can be designed presented in Figure 7. This conceptual redesign excludes consideration of the financial investment required to implement such structural changes. This setting will

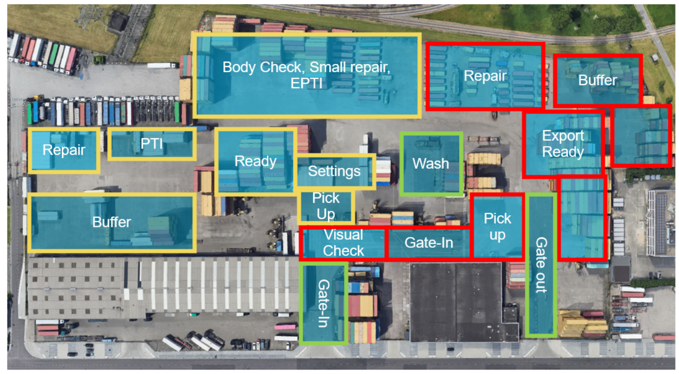

Fig. 6. Schematic overview of setting 2 layout ECD

adjust the current shape and perimeter configuration, while maintaining the same surface area. The setting construction of this setting follows the same approach as described for setting 5 in the research, but complements this setting by an improved version of setting 5 which is derived by iteratively model-testing. Key adaptations are that the redesigned layout follows a more rectangular perimeter with a hybrid loop and open-field configuration to streamline ECH movement and reduce driving distances. This with a separate clockwise and counter-clockwise flows for reefer and dry containers respectively. Additionally, washing facilities are separated to eliminate bottlenecks and supporting infrastructure was repositioned for operational efficiency based on flow analysis.

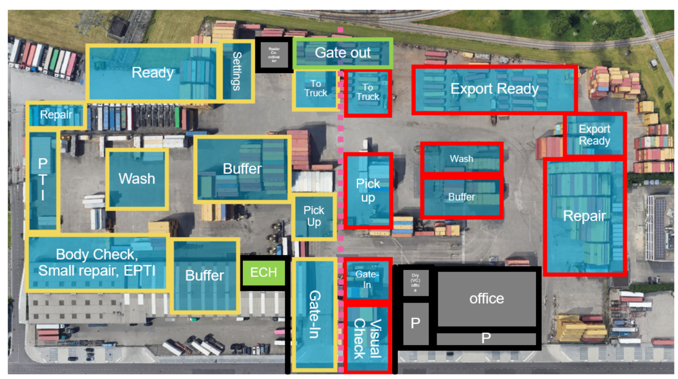

Fig. 7. Schematic overview of setting 6 layout ECD

Expected is that this improved strategy is better in controlling bottlenecks dynamics for this specific scenario. It needs to be addressed that this layout and configuration is completely different and unrealistic to adjust to, because of the currently fixed perimeter configurations. Therefore shifting to this layout is not possible for this current location. It could be possible when new facilities are analysed. Respecting the same volumes, processes, relationships and similar factors.

B. Reefer season analysis

This scenario is evaluated using the KPIs defined in Table I, following the same structure as presented in this table.

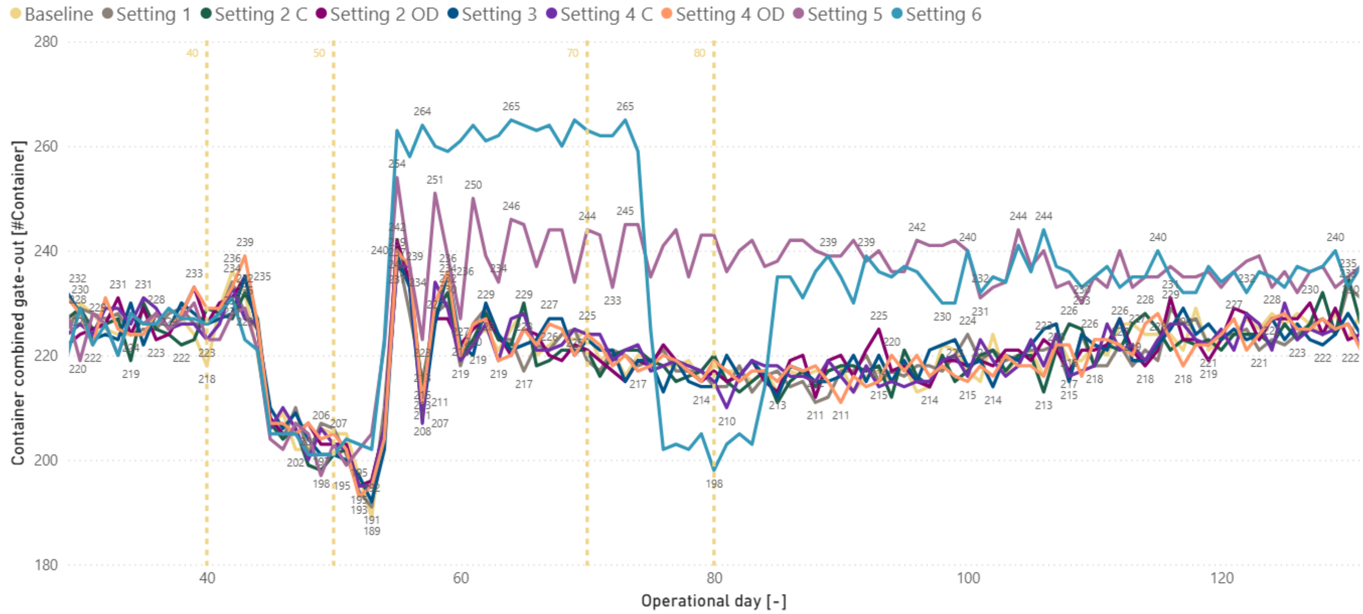

Fig. 8. Scenario 1: Average reefer and dry container gate-out per operational day

The KPIs are grouped into three main categories: throughput, ECH usage and subsystem occupation rates. To provide a clear understanding of the system dynamics, it is important to evaluate the KPIs together. This combined view helps explain the scenario outcomes more effectively.

TABLE II
SCENARIO 1: SIMULATION SETTINGS

Characteristics	Value	Unit
Runtime	230.400	Simulation minutes
Number of runs	25	-
Measurement interval	780	Simulation minutes
Depot open	780	Operating minutes
Depot closed	660	Non-operating minutes
Driving speed ECH	10	km / h
Occupation all subsystems at start	0	#TEU used

TABLE III
SCENARIO 1: INTERARRIVAL CONTAINERS

Type	Probability distribution	Interval [min]	# Operational days
Dry	Geom(p=0.1918)	$0 < 201.600$	140
Dry	Geom(p=0.0001)	≥ 201.600	20
Reefer	Geom(p=0.0964)	$0 < 57.600$	40
Reefer	Geom(p=0.0645)	$57.600 < 72.000$	10
Reefer	Geom(p=0.1453)	$72.000 < 100.800$	20
Reefer	Geom(p=0.0645)	$100.800 < 115.200$	10
Reefer	Geom(p=0.0964)	$115.200 < 201.600$	60
Reefer	Geom(p=0.0001)	≤ 201.600	20

Following the model in Figure 4, several key input parameters are listed in Tables II and III to support understanding of scenario outcomes. This scenario is a simplified representation of the reefer season, capturing the same dynamics over a shorter period, focussing on truck arrival patterns and simulation setup. Based on the conducted data analysis it is shown that reefer container arrivals show fluctuations, unlike dry container arrival. Truck interarrival times follow a probability distribution, see Table III, shifting between normal, easy and stressed periods. A higher p-parameter indicates shorter interarrival times. These shifts are visualised using yellow dotted lines in the figures, helping to interpret system dynamics.

As shown in Figure 8, settings B to 4 follow the same throughput pattern. The same holds for the occupation rates and bottleneck dynamics for these settings. Although ECH usage (number of moves and driven distance) across settings is different, this is not directly reflected in the throughput. Movements of containers within the depot account for a small percentage of the total dwell time of containers inside the depot, therefore this is not directly visible in the throughput. Meaning that process durations within subsystems highly influences throughput of similar settings, as they account for a large share of the total dwell time inside the system. For settings 5 and 6 the throughput pattern, bottleneck dynamics and ECH usage are different. Besides the process durations within subsystems, throughput is influenced by bottleneck occurrence. Settings 5 and 6 are better in handling and preventing bottlenecks for this scenario. Therefore the varying generation rates of reefer containers are better reflected in the different periods, this pattern is clearly visible in Figure 8.

Adding to this analysis, the next KPI category is focused on the usage of ECHs. As shown in Table IV and Table V, the total number of moves and distance covered by ECH, is lowered for most settings. The settings focus on the reduction of driving distances for ECHs responsible for the internal movement of (reefer) containers, which account for the highest share of differences between the settings. Settings 1 to 4 have similar characteristics, with same bottleneck occurrence, but slightly different ECH use. This is related to the differences in driving distance between subsystems. Values do not deviate much because similar container flows occur for settings B to 4.

TABLE IV
SCENARIO 1: DIFFERENCES IN MOVES ACROSS SETTINGS (S2 C, S5, S6), COMPARED TO THE BASELINE SETTING

Metric	S2 C	S5	S6
$\sum$ Moves [#]	120,496	117,604	116,383
$\sum$ difference [#]	– 19	– 2,912	– 4,133

TABLE V
SCENARIO 1: DIFFERENCES IN DISTANCE ACROSS SETTINGS (S2 C, S5, S6), COMPARED TO THE BASELINE SETTING

Metric	S2 C	S5	S6
$\sum$ distance [m]	23,274,009	20,253,505	20,513,883
$\sum$ difference [m]	– 1,432,531	– 4,453,035	– 4,192,657

Settings 5 and 6 follow a totally different layout setup where bottleneck dynamics are better handled and driving distances are lowered, especially for the reefer part. This combination improves the flow of containers inside the system, which is reflected by throughput under different interarrival rates of containers. For this flow less containers are redirected to buffer areas, which results in less moves made by ECH responsible for internal movements. To conclude, both settings 5 and 6, result in fewer total moves, reduced internal movement driving distances and improved throughput under varying container interarrival rates.

To complement the analysis of throughput and ECH movements, subsystem occupation rates are examined to provide insights into spatial utilisation and bottleneck formation within the depot. Visual inspection of subsystem occupation rates helps identify bottlenecks. By iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks by changing the layout structures and stacking strategies. An example of this analysis is provided in Appendix A, representing for scenario 1 the occupation rates for four different settings are presented. Following the four different settings presented in this paper, it is clearly visible that occupation of (reefer) subsystems are better handled after iteratively comparing model outcomes.

C. Conclusion scenario design and analysis

Based on research findings, eight different settings were constructed and tested to the four different scenarios. The aim of these tests was to identify new configurations that could improve performance in these scenarios. Several important findings emerged for each scenario and related settings. The general conclusion is that by iteratively comparing model outcomes to the identified KPIs, it is possible to overcome bottlenecks, improve ECH usage and maintain or improve throughput of the system. These improvements are achieved through targeted changes in settings. This demonstrates that by following the simulation framework and conducting the described steps as intended, ECD operations can be improved and system dynamics can be better understood.

D. Discussion scenario design and analysis

This chapter focuses on a few selected scenarios and settings, where only small changes are made one at a time. This choice was made to maintain visibility into system dynamics, making it easier to see how specific changes affect the outcomes. In the real-world, many factors such as policies or ECH usage can change simultaneously, which makes it difficult to identify what is actually influencing results when multiple input parameters are changed at once. Still, several key questions remain after this analysis. Is layout the most influential factor to system performance, or do other factors drive throughput, bottleneck occurrence or other related parameters? While the results show that layout can indeed improve selected KPIs, adopting a broader perspective on depot operations might be beneficial for an additional deeper understanding of how various factors interacts. Reconsideration of some assumptions and simplifications is therefore justified, because the results suggest that other parameters also contribute to further improvements. Adding to this, not only improvements need to be further researched, also financial considerations should be taken into account in further analysis of the layout configurations and stacking strategy choices.

A renewed interpretation of the results adds to the analysis above, as it introduces an alternative perspective on operational decision-making. The visualisation of container flows provides stakeholders with a clear view of system dynamics and occupations rates. During the reefer season, operational focus should shift towards reefer handling by structurally dividing the depot into two separates streams. This approach addresses the bottleneck caused by the washing area if both used for dry and reefer containers. A recommended strategy is to allocate additional space for reefers and redirect dry containers during this period if possible. Redirection could involve assigning dry containers to alternative terminal or depots, particularly when M&R actions are not required or expected based on available data and forecasts. This would reduce the operational pressure on the dry container operation side.

Alternatively, and in line with the previous approach, process durations within the depot can be improved. For example, favouring blow-out procedures over full washing if possible, this allows for increased container flow. Another complementary strategy is to reduce the number of minor repairs conducted within the Electronic Pre-Trip Inspection (EPTI) subsystems. Service should only be provided when containers fail to meet essential quality standards. This would shorten container dwell times, relieve pressure on this subsystem and improve flow to other operational areas. This strategic consideration raises the question if the depot should consistently deliver fully refurbished containers intended for long-term use, or prioritise flow efficiency while still meeting safety and quality standards for gate-out? This line of reasoning support early engagement with targeted solutions to overcome bottlenecks within the ECD.

Although the proposed layout and stacking configurations offer improvements, they are based on a simplified system. Real-time decision-making and operational flexibility, such as dynamic ECH assignment, mitigate inefficiencies in practice. Dynamic behaviour has not yet been addressed in this research. This is due to the initial focus on providing a foundational understanding of system relationships, which is essential before incorporating more complex elements into the analysis.

VII. Conclusion

Both system and scenario analyses demonstrates that following the simulation framework and conducting all 5 steps of the framework will help improve ECD operations and system dynamics understanding. Referring this back to the main research question of the research:

"How can adaptive layout configurations and stacking strategies contribute to the improvement of operations within an empty container depot, considering global/regional logistics strategies, demand requirements and infrastructural constraints?"

it is shown that adaptive layout configurations and stacking strategies help depots respond better to seasonal demand fluctuations and varying truck interarrival patterns. By testing different designs in realistic scenarios, improvements can be made in equipment use, driving distances and bottleneck control within the system. This together supports more flexible operations that will result in improved overall performance.

Based on the findings in this research, shipping companies that own their own depots are advised to apply the framework to proactively manage layout transitions and stacking strategies in alignment with forecasted flows. This enables more resilient operations and improves the coordination between logistics agents and depot personnel. Section VIII expands on this recommendation by providing a more detailed explanation of the relevance for shipping companies and depot owners.

VIII. Discussion

If considered and studied, ECD systems are likely to become better in handling container volumes in the future. Making ECD systems interesting facilities that could serves an additional purpose beside providing M&R activities and storage. These facilities could help relief terminals or other facilities from handling empty containers by taking on a more active role in container delivery and pick-up. Strategic planning of ECDs allows carries to use them as alternative access points, reducing pressure on terminals, which supports more flexible operations. This could strengthen terminal operations, especially in disrupted scenarios as shown in the past. When focused on future container volumes this makes an ECD an interesting facility to further investigate. Below some recommendations are provided for future research.

A. Future research recommendations

While the results show that layout can indeed improve selected KPIs, adopting a broader perspective on depot operations might be beneficial for an additional deeper understanding of how various factors interacts. A more detailed discussion on further improvements is stated below, starting with the first recommendation which is more of a validation of choices.

This is related to the investments required for shifting to different layout configurations and/or strategies. Analysis of the different settings show that setting 5 and 6 consistently improve operations, but these improvements come with significant investments. Therefore proposed is, that in future research, a comprehensive cost-benefit analysis should be conducted. This analysis should consider investments in machinery, infrastructure (electricity points and washing facilities), labour hours, fuel and ECH depreciation. This analysis complements to this research by providing insight into a fair financial comparison between settings.

Another recommendation to future research should be related to the division of ECH responsibility to different areas. Taken as a core assumption in this research is that ECHs are responsible for a selected area. Based on the results, driving distance and number of moves, proves that this ECH usage is unrealistic. In real operations these values should be more or less similar, with deviates from the findings in this research using that fixed policy. Future research therefore should focus on dynamic ECH assignment, aiming for a more balanced distribution of driving distances. This could improve bottleneck control even further.

Adding to that, dynamic behaviour could be extended towards the operational policies for ECHs. Processes are now FCFS, which is unrealistic in real life. If ECH handlers could self-assign tasks, task management and selection will be better handled. Incorporating this into the existing model could further improve depot operations. To conclude, developing a more dynamic model for ECH usage and internal logistics is a promising direction for future work.

Final directions might include researching slot systems for truck arrival. Shown in the analysis this is a key factor to the performance of the depot. If controlled for truck arrival, operations within the depot can be more structured. Or incorporation of different gate-in and gate-out possibilities, think of barge connections, where multiple containers can gate-in or gate-out in a short period of time.

B. Strategic recommendations for key stakeholders

As highlighted in section VI-D, the simulation outcomes emphasise the importance of a collaborative strategy between empty container depots and shipping companies. When both parties have a shared understanding of system dynamics, targeted improvements can be implemented. From a logistics perspective, the developed model serves as a decision-support tool for simulating operational strategies and forecasting future demand scenarios. This facilitates stakeholders with a tool that help evaluate the impact of layout changes, resource allocation and scheduling adjustments before implementation. Collaboration becomes more critical given the increasing reliance on data-driven solutions, including predictive flow forecasting and accurate stock management. These new insights help aligning the strategies of logistics agents and managers more effectively. It is recommended to schedule bi-weekly coordination meetings, where several aspects are important to discuss. These meetings should include a review of current performance indicators, followed by an evaluation of the effectiveness of recent adjustments. Followed by a discussion on market developments and volume changes, which informs the planning for the upcoming weeks.

Adding to the benefits of collaboration, it is equally important to understand how this framework and model translates into the day-to-day operations at the depot level. How can these model insights support depot operators in improving their processes while maintaining service quality. Depots function primarily to execute the logistics strategies set by shipping lines, and their ability to do so efficiently has direct cost implications. Their core responsibility is to provide the correct container at the right time while respecting the quality standards. By doings so, operational costs are generated. The ideal scenario is to maintain service quality while minimising these costs. The model helps depot operators identify where adjustments can be made, offering insight into process efficiency and strategic alignment. It supports a broader view of operations, focussing on reflection on current practices. This would help guide improvements taking into account data-driven forecasts or shipping line strategies.

REFERENCES

[1] United Nations Conference on Trade and Development (UNCTAD). *Review of Maritime Transport 2024*. Tech. rep. Geneva, Oct. 2024, pp. 1–38. URL: https://unctad.org/topic/transport-and-trade-logistics/review-of-maritime-transport.

[2] Eurostat. *Globalisation patterns in EU trade and investment*. Tech. rep. Luxembourg: Publications Office of the European Union, Oct. 2017, pp. 1–220. DOI: 10.2785/65836. URL: https://ec.europa.eu/eurostat/en/web/products-statistical-books/-/ks-06-17-380.

[3] Olcay Polat and Hans-Otto Günther—. "The impact of seasonal demand fluctuations on service network design of container feeder lines". In: *Journal of Transportation and Logistics* 1.1 (Apr. 2016), pp. 39–58. ISSN: 2459-1718. DOI: 10.22532/JTL.237886. URL: https://dergipark.org.tr/en/pub/jtl/issue/22136/237886.

[4] Felipe Hidalgo et al. "Empty container stacking operations: Case study of an empty container depot in valparaiso chile". In: *Proceedings - Winter Simulation Conference* (June 2017), pp. 3114–3125. ISSN: 08917736. DOI: 10.1109/WSC.2017.8248031.

[5] Jimena Pascual and Alice E. Smith. "Using Simulation to Improve Container Depot Operations". In: (2020), pp. 487–513. ISSN: 2509-6435. DOI: 10.1007/978-3-030-11866-2{_}21. URL: https://link.springer.com/chapter/10.1007/978-3-030-11866-2_21.

[6] Erhan Karakaya. "Container Handling and Layout Optimization in Empty Container Depots". PhD thesis. Auburn: Auburn University, Nov. 2020, pp. 1–203. URL: https://etd.auburn.edu//handle/10415/7471.

[7] Erhan Karakaya, Alexander Vinel, and Alice E. Smith. "Relocations in container depots for different handling equipment types: Markov models". In: *Computers & Industrial Engineering* 157 (July 2021), p. 107311. ISSN: 0360-8352. DOI: 10.1016/J.CIE.2021.107311. URL: https://www.sciencedirect.com/science/article/pii/S0360835221002151?casa_token=rVOIJ8OvnrMAAAAA:cghv1_jRTeO1Mae8BCOEqXTq2cr3ya8D8adFV7xAb6xpy5hunL9mo2ax7QrrfWpNC-33bA1PIec.

[8] Erhan Karakaya et al. "Design of empty container depot layouts using data and analytics". In: *Flexible Services and Manufacturing Journal* 35.1 (Mar. 2023), pp. 196–240. ISSN: 19366590. DOI: 10.1007/S10696-022-09452-Z/FIGURES/18. URL: https://link.springer.com/article/10.1007/s10696-022-09452-z.

[9] Hans P.M. Veeke, Gabriël Lodewijks, and Jaap A. Ottjes. "The delft systems approach: Analysis and design of industrial systems". In: *The Delft Systems Approach: Analysis and Design of Industrial Systems* (2008), pp. 1–223. DOI: 10.1007/978-1-84800-177-0/COVER.

[10] S. Robinson. "Conceptual modelling for simulation Part I: Definition and requirements". In: *Journal of the Operational Research Society* 59.3 (2008), pp. 278–290. ISSN: 14769360. DOI: 10.1057/PALGRAVE.JORS.2602368;WGROUP:STRING:PUBLICATION. URL: https://www.tandfonline.com/doi/pdf/10.1057/palgrave.jors.2602368.

[11] S. Robinson. "Conceptual modelling for simulation Part II: A framework for conceptual modelling". In: *Journal of the Operational Research Society* 59.3 (2008), pp. 291–304. ISSN: 14769360. DOI: 10.1057/PALGRAVE.JORS.2602369;WGROUP:STRING:PUBLICATION. URL: https://www.tandfonline.com/doi/pdf/10.1057/palgrave.jors.2602369.

[12] Stewart Robinson. "A tutorial on conceptual modeling for simulation". In: *Proceedings - Winter Simulation Conference* 2016-February (Feb. 2016), pp. 1820–1834. ISSN: 08917736. DOI: 10.1109/WSC.2015.7408298.

[13] Amine Drira, Henri Pierreval, and Sonia Hajri-Gabouj. "Facility layout problems: A survey". In: *Annual Reviews in Control* 31.2 (Jan. 2007), pp. 255–267. ISSN:

1367-5788. DOI: 10.1016/J.ARCONTROL.2007.04.001. URL: https://www.sciencedirect.com/science/article/pii/S1367578807000417.

[14] Maina E C et al. "Improvement of Facility Layout Using Systematic Layout Planning". In: *IOSR Journal of Engineering (IOSRJEN) www.iosrjen.org ISSN* 08 (2018), pp. 2278–8719. ISSN: 2250-3021. URL: https://repository.dkut.ac.ke:8080/xmlui/handle/123456789/861.

[15] David Goldsman et al. "Discrete-Event Simulation". In: (2015), pp. 103–109. ISSN: 2195-2825. DOI: 10.1007/978-1-4471-5634-5{_}10. URL: https://link.springer.com/chapter/10.1007/978-1-4471-5634-5_10.

[16] Qing Li and Yu-Liu Chen. "IDEF0 Function Modeling". In: *Modeling and Analysis of Enterprise and Information Systems* (2009), pp. 98–122. DOI: 10.1007/978-3-540-89556-5{_}5. URL: https://link.springer.com/chapter/10.1007/978-3-540-89556-5_5.

[17] Susan Dadakis Horn. "Goodness-of-Fit Tests for Discrete Data: A Review and an Application to a Health Impairment Scale". In: *Biometrics* 33.1 (Mar. 1977), p. 237. ISSN: 0006341X. DOI: 10.2307/2529319.

[18] Raul H. C. Lopes. "Kolmogorov-Smirnov Test". In: *International Encyclopedia of Statistical Science* (2011), pp. 718–720. DOI: 10.1007/978-3-642-04898-2{_}326. URL: https://link.springer.com/rwe/10.1007/978-3-642-04898-2_326.

Appendix A
Appendices

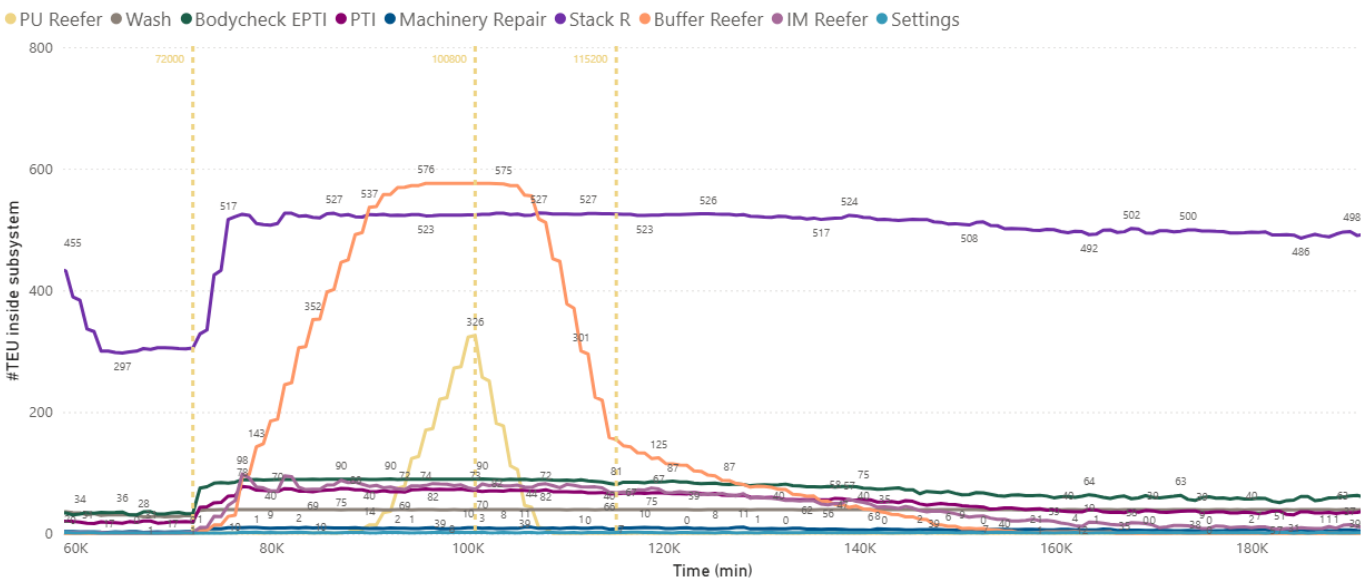

Fig. 9. Scenario 1: Occupation subsystems (reefer) setting baseline

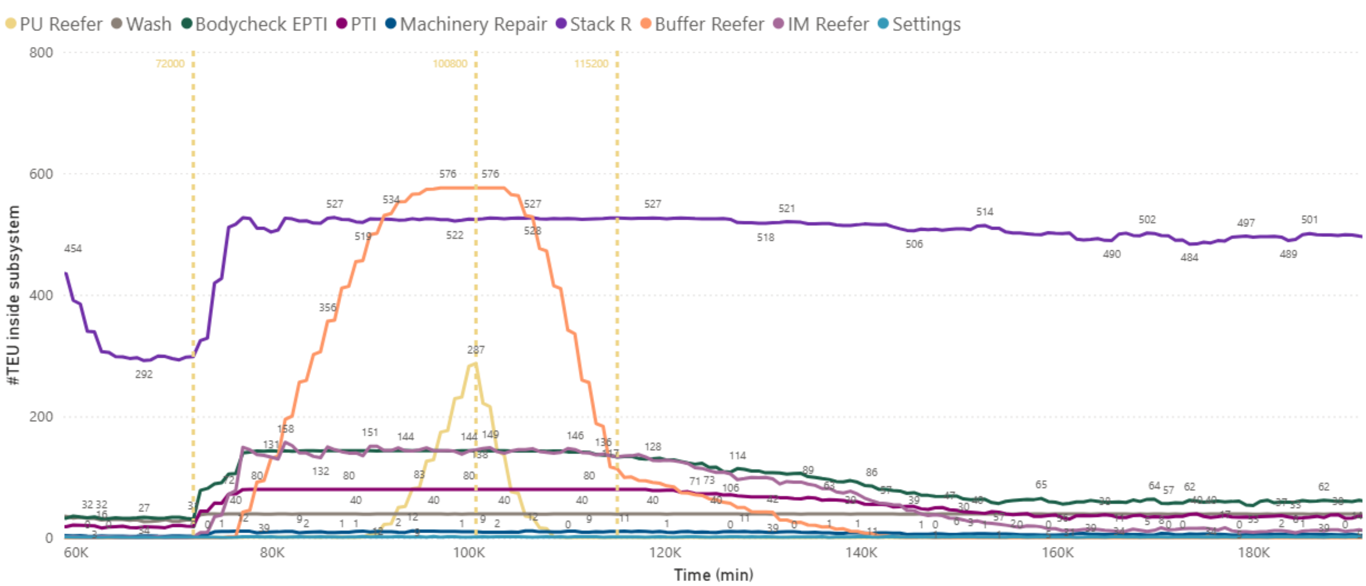

Fig. 10. Scenario 1: Occupation subsystems (reefer) setting 2 C

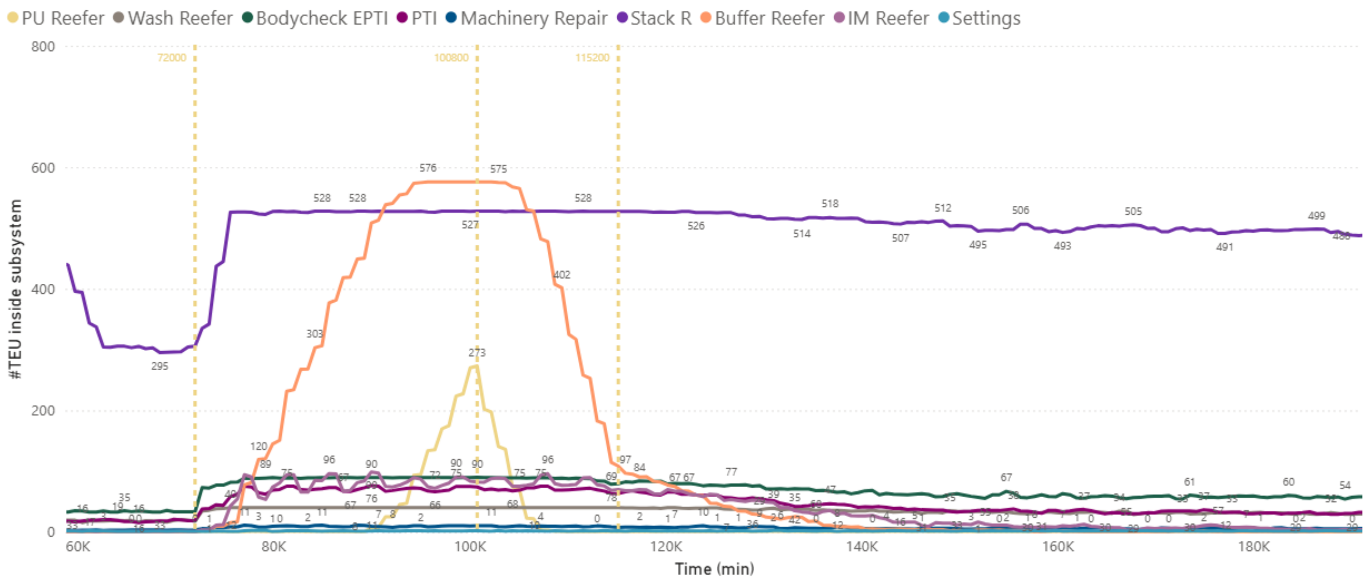

Fig. 11. Scenario 1: Occupation subsystems (reefer) setting 5

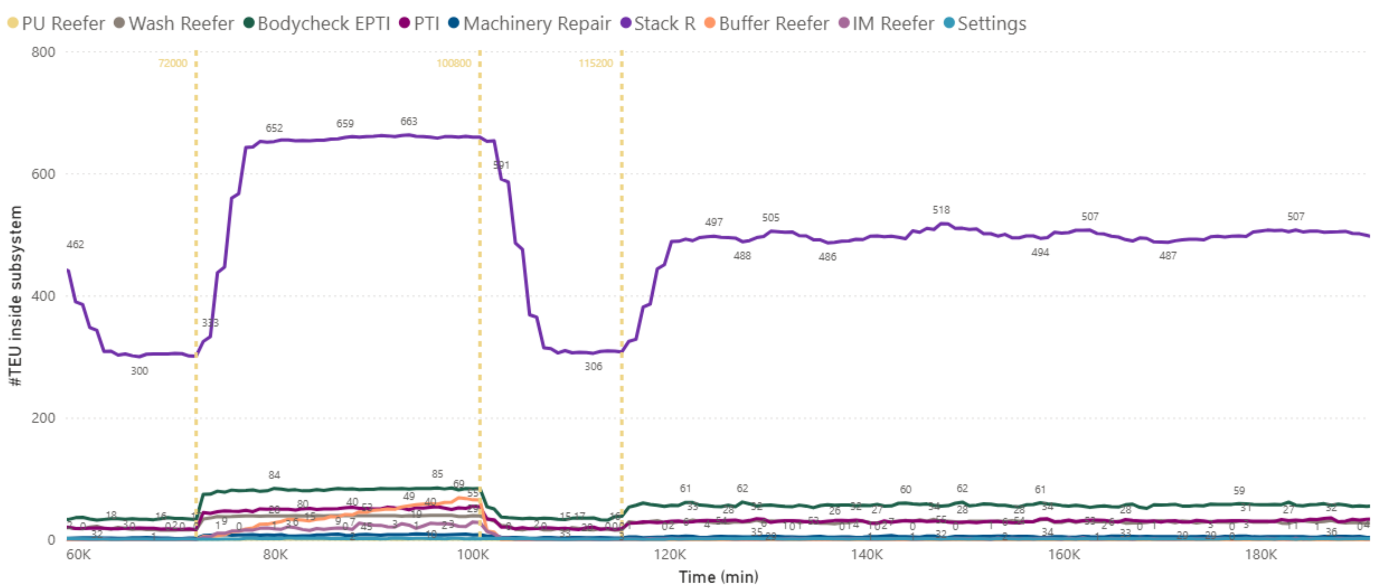

Fig. 12. Scenario 1: Occupation subsystems (reefer) setting 6

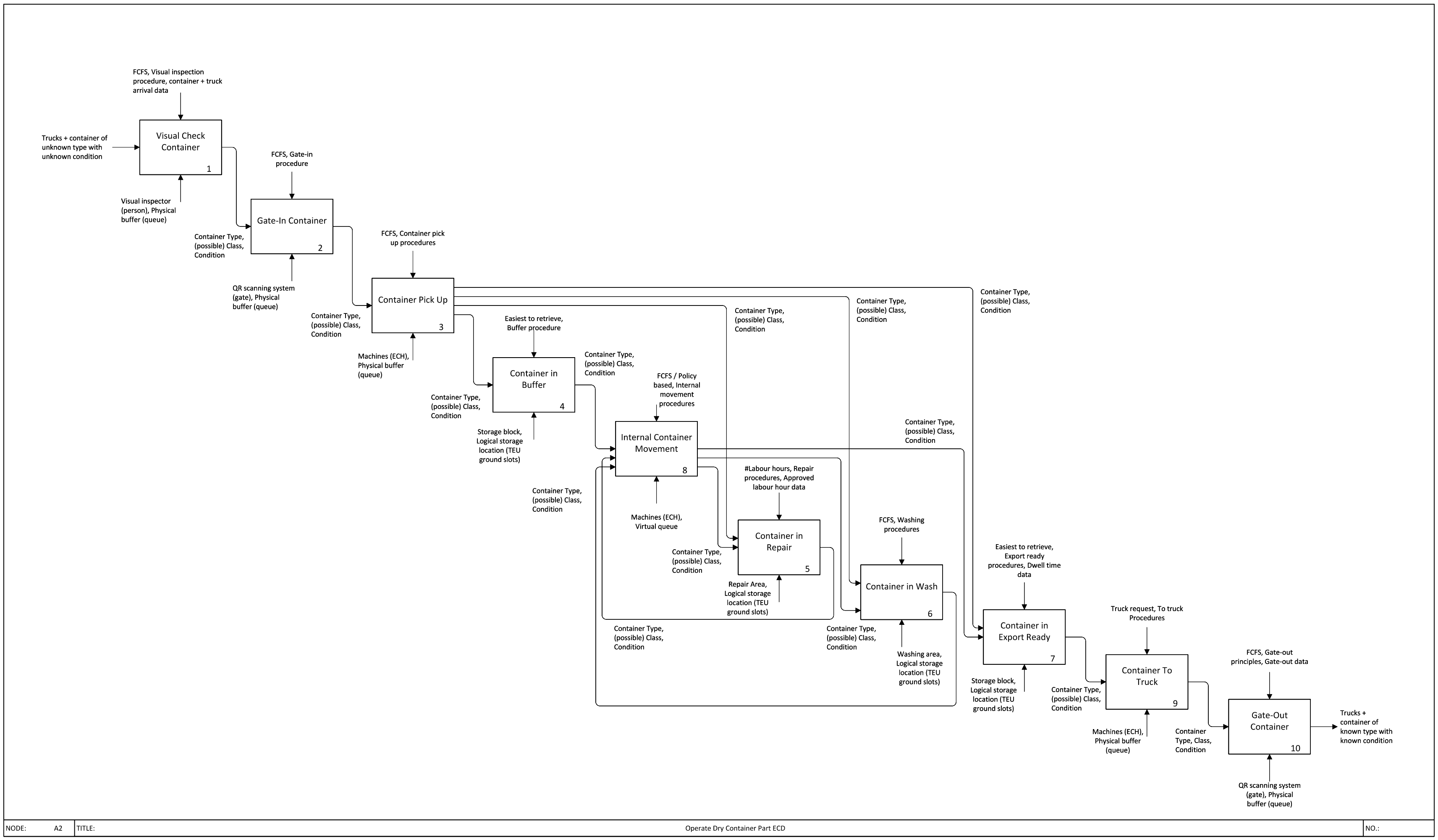

Fig. 13. IDEF0 A2 representation of the ECD system (meso) level

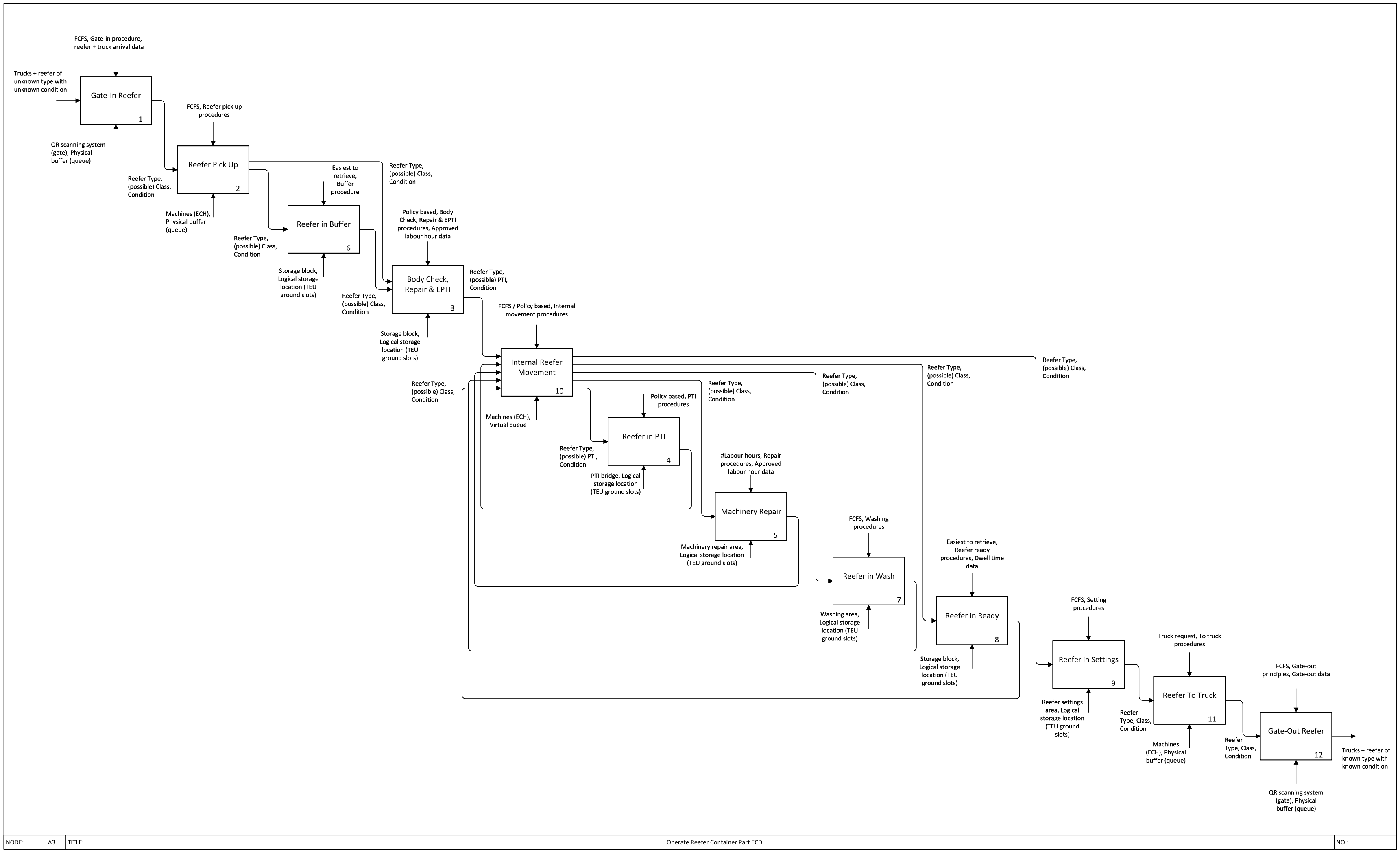

Fig. 14. IDEF0 A3 representation of the ECD system (meso) level

B

System analysis: IDEF0 A2 and A3 decomposition

This appendix provides an overview of subsystems that were not discussed in detail in chapter 4. These subsystems are equally relevant to the functioning of the system, but the selection presented in chapter 4 focuses on subsystems for which a detailed data analysis was conducted or meaningful considerations were taken into account.

B.1. IDEF0-A2

Gate-in Container

In Figure B.1 the gate-in process for dry containers is presented. In Box 1: Queue Entry, there is controlled for the truck arrival interval for dry containers, which is the output of the Visual Check subsystem.

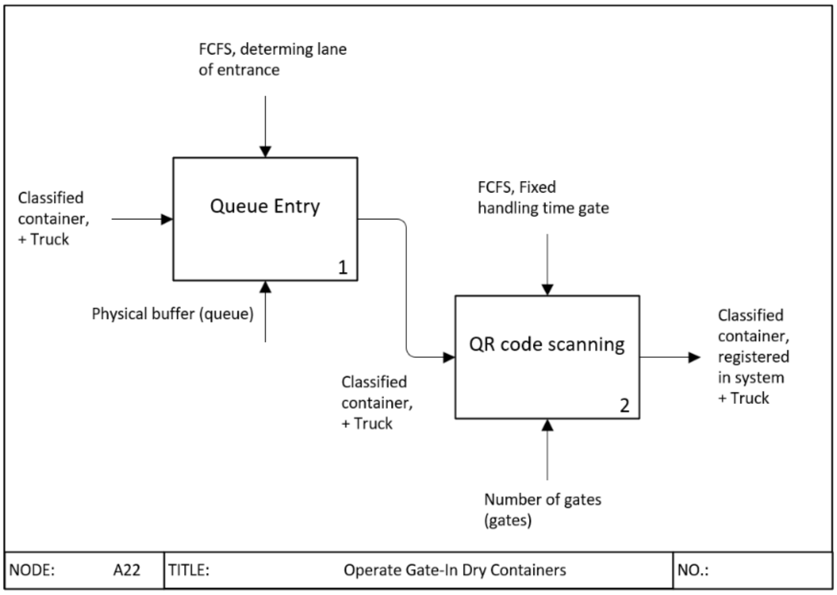

Figure B.1: IDEF0 A22 representation of container in Gate-In (micro-level)

Based on depot procedures, the actual time durations of the container gate-in can be set equal to a fixed value. Time durations of trucks inside the physical buffer (queue) can differ depending on the occupation of the depot.

Container Pick-Up

In Figure B.2 the container pick up process for dry containers is presented. In Box 3: Driving to next subsystem, there is controlled for ECH procedures. Driving time durations can differ for ECHs, taking into account yard density, driving distance and traffic rules.

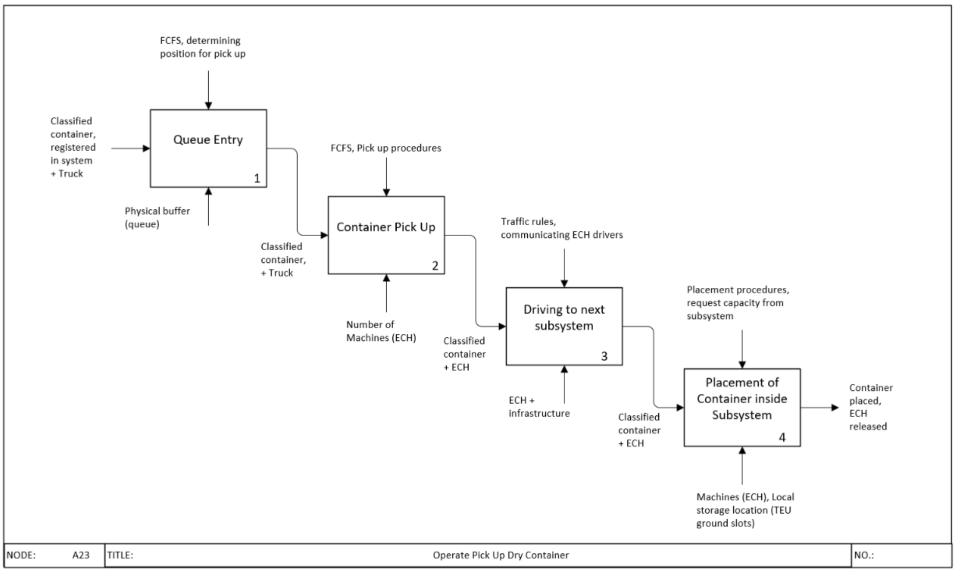

Figure B.2: IDEF0 A23 representation of container in Pick Up (micro-level)

Driving distance between subsystems are closely related to depot layout configurations. For this research, an estimate of the driving speed was made based on measurements taken at MedRepair Smirnoffweg, represented in Figure B.3. This in order to validate the assumptions derived from expert consultations.

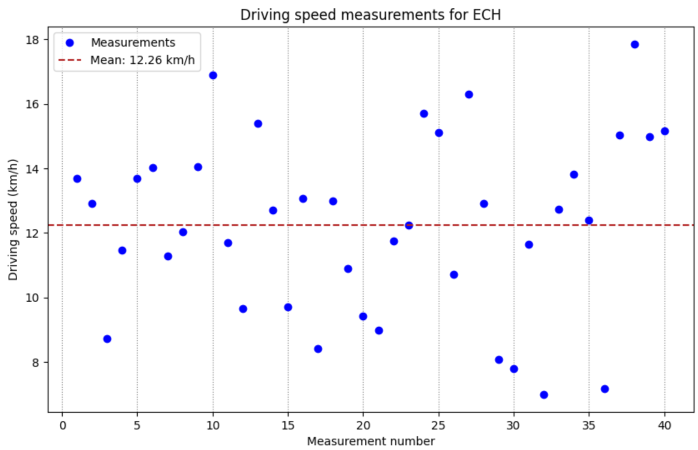

Figure B.3: Average driving speed ECH inside case study depot

Container in Buffer

In Figure B.4 the buffer operations are presented. In Box 1: Entering Storage Block, there is controlled for buffer procedures. Depending on strategy the retrieval off containers is policy based, but here stated as easiest to retrieve.

The waiting time inside the buffer system is influenced by the availability of TEU ground slots inside the next (work)station. When a TEU ground slot becomes available, there should a decision be made to fill this slot with a container from the buffer zone.

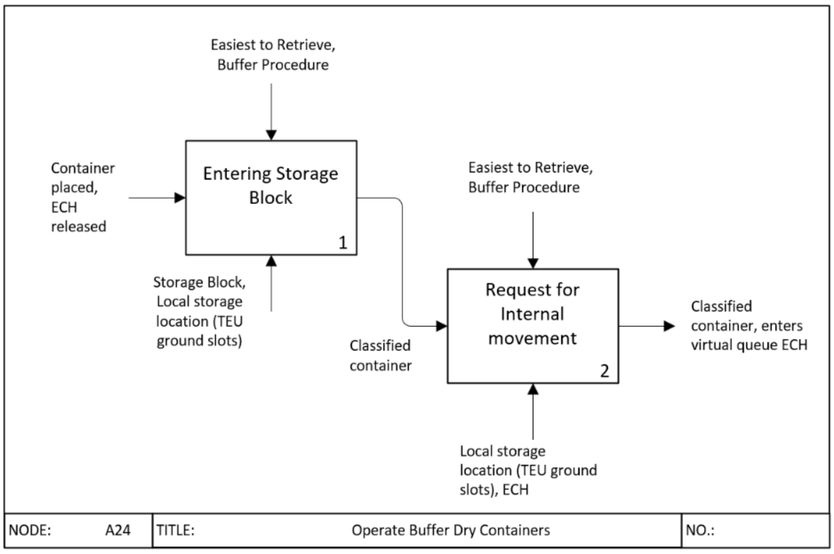

Figure B.4: IDEF0 A24 representation of container in Buffer (micro-level)

Internal Movement container

In Figure B.5 the internal movement process for dry containers is presented. In Box 1: Queue Entry, there is controlled for policy-based handling of queue order for dry containers.

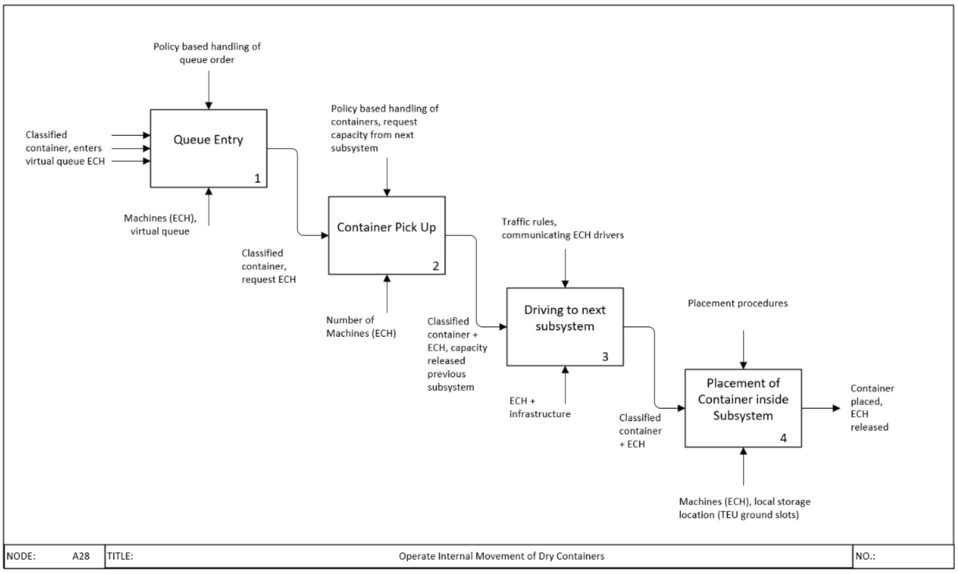

Figure B.5: IDEF0 A28 representation of container in Internal Movement (micro-level)

As shown in Figure B.5, many entities request an internal movement after being handled by other subsystems, resulting in large virtual queues when dealing with a low number of resources.

When a container is picked by an ECH, there is checked if a TEU ground slot is available inside the next workstation. This TEU ground slot is reserved, so that during internal movement no other container can be assigned to that specific slot.

Container in Wash

In Figure B.6 the washing process for dry containers is presented. In Box 2: Wash Actions, there is controlled for washing procedures and handling time durations. Based on depot procedures the time duration of the actual washing of the container can be fixed to a single value. Depending on the container type, 20-feet or 40-feet, the actual time duration of a washing can vary. Based on expert consultations and depot procedures an estimate should be made for the time durations of this step. This is highly relevant when adopting these washing durations in a conceptual model.

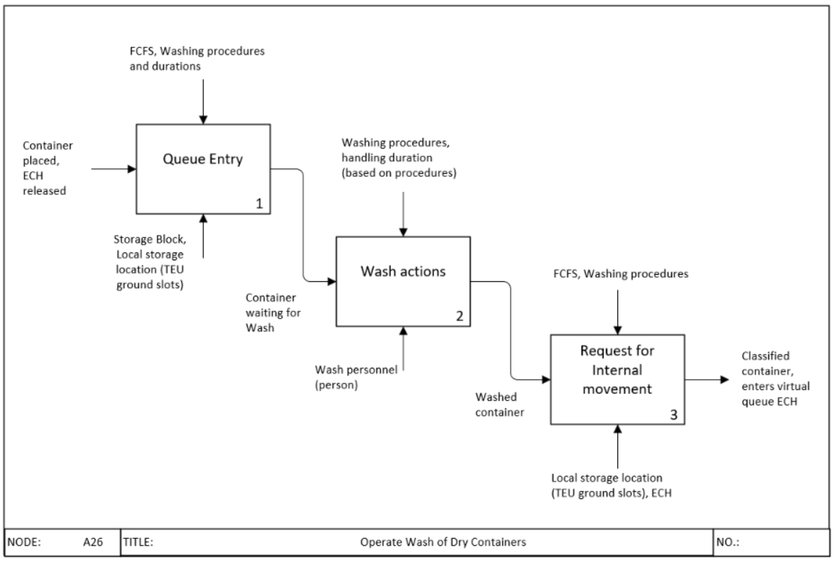

Figure B.6: IDEF0 A26 representation of container in Wash (micro-level)

Container To Truck

In Figure B.7 the container to truck process is presented. In Box 1: Queue Entry, there is controlled for policy-based handling of queue order for dry containers.

Based on MSC data, containers are released from the Export Ready stack after the container completed their assigned dwell time. Entities request a resource (ECH) to move between the Export Ready stack and the truck. Truck arrival patterns may vary over time and can be taken into account if data on truck arrival is available. For real-world representation this truck arrival pattern could then be adopted into a conceptual model.

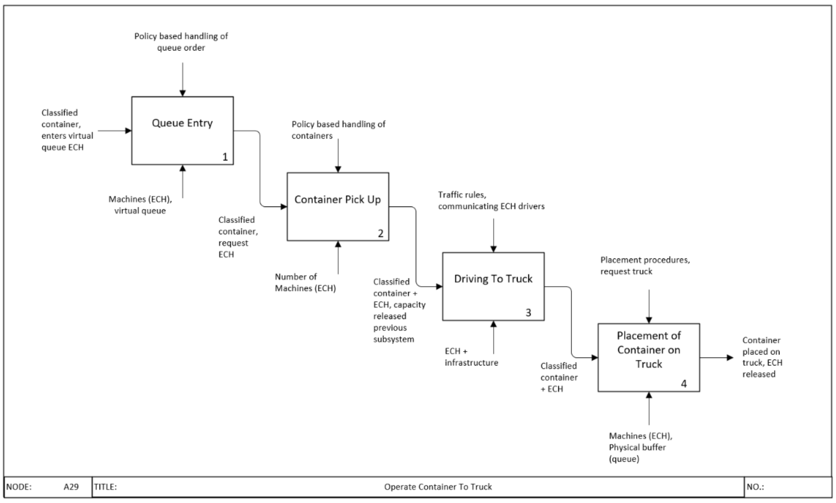

Figure B.7: IDEF0 A29 representation of container in To Truck (micro-level)

Gate-Out Container

In Figure B.8 the process of the container gate-out is presented. In Box 1: Queue Entry, there is controlled for the truck arrival interval for dry container pick up for gate-out. Truck arrival patterns can be adopted in conceptual modelling, if data is available.

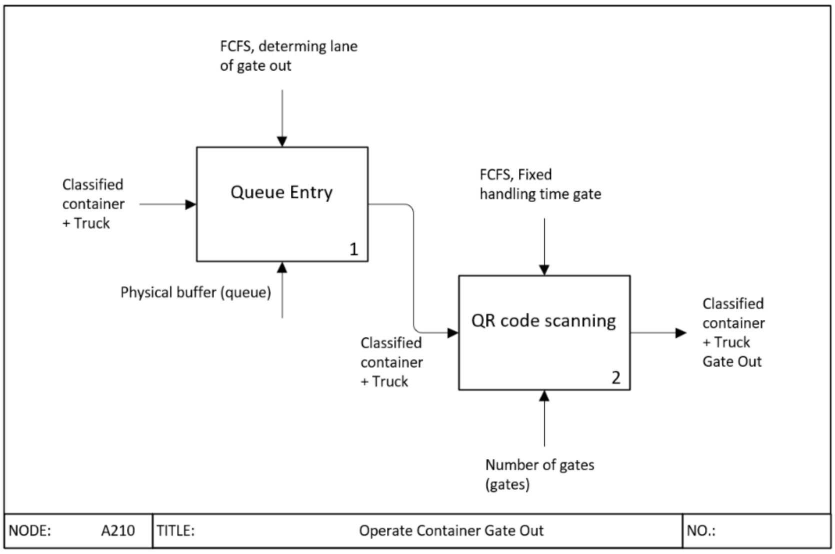

Figure B.8: IDEF0 A210 representation of container in Gate-Out (micro-level)

B.2. IDEF0-A3

Reefer Pick-Up

In Figure B.9 the container pick up process for reefer containers is presented. In Box 3: Driving to next subsystem, there is controlled for ECH procedures.

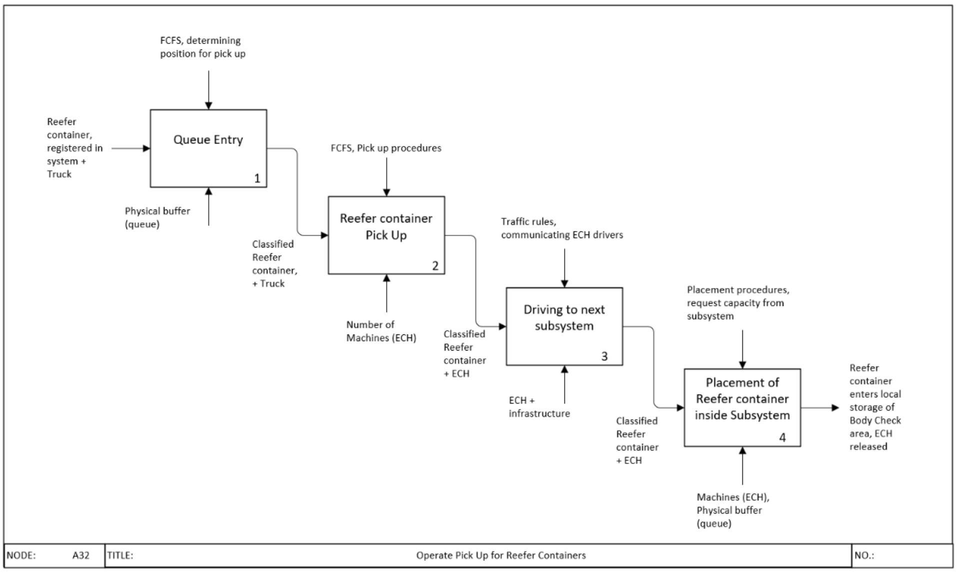

Figure B.9: IDEF0 A32 representation of reefer container in Pick Up (micro-level)

Driving time durations can differ for ECHs, taking into account yard density, driving distance and traffic rules. There is no division made in driving speed for ECHs with dry or reefer containers.

Reefer container in Buffer

In Figure B.10 the buffer operations are presented. In Box 1: Entering Storage Block, there is controlled for buffer procedures. Depending on strategy the retrieval off reefer containers is policy based, but here stated as easiest to retrieve.

The waiting time inside the buffer system is influenced by the availability of TEU ground slots inside the Body Check, EPTI & Repair station. When a TEU ground slot becomes available, a decision should be made to fill this slot with a container from the buffer zone.

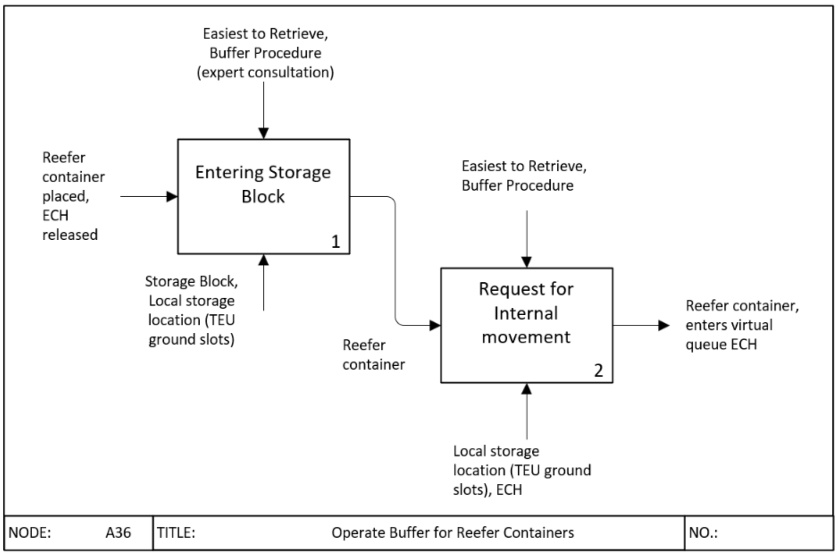

Figure B.10: IDEF0 A36 representation of reefer container in Buffer (micro-level)

Reefer container in PTI

In Figure B.11 the PTI process for reefer containers is presented. In Box 2: PTI actions, there is controlled for the PTI procedures. Based on expert consultation, several PTI actions can be taken. Resulting in different time durations for the actual computation of the PTI.

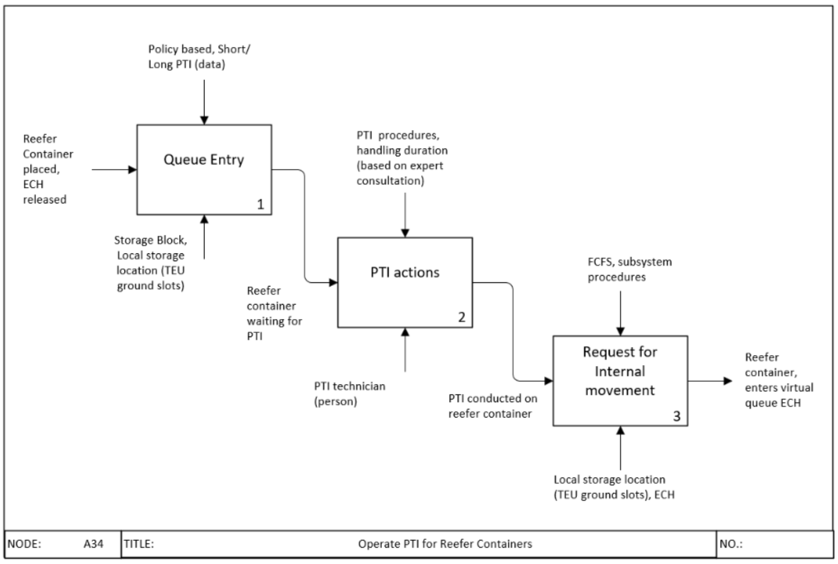

Figure B.11: IDEF0 A34 representation of reefer container in PTI (micro-level)

Internal movement reefer container

In Figure B.12 the internal movement process for reefer containers is presented. In Box 1: Queue Entry, there is controlled for policy-based handling of queue order for reefer containers. As shown in Figure B.12, many entities request an internal movement after being handled by other subsystems, resulting in large virtual queues when dealing with a low number of resources.

When a container is picked by an ECH, there is checked if a TEU ground slot is available inside the next workstation. This TEU ground slot is reserved, so that during internal movement no other container can be assigned to that specific slot.

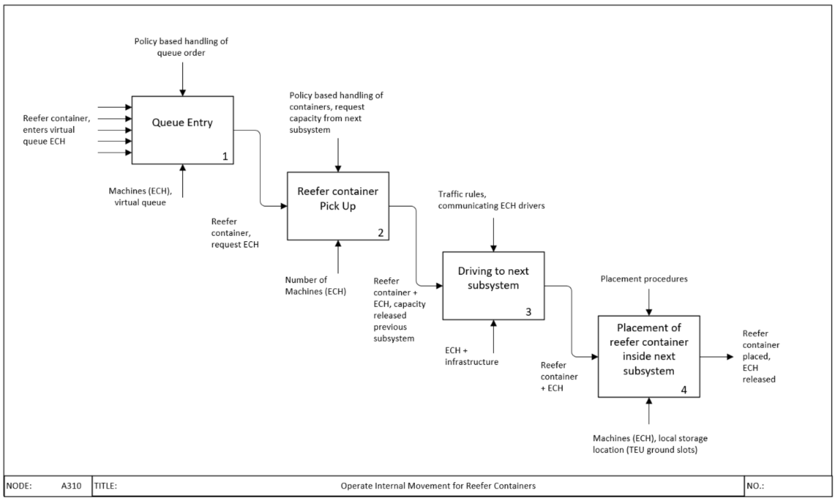

Figure B.12: IDEF0 A310 representation of reefer container in Internal Movement (micro-level)

Reefer container in Machinery Repair

In Figure B.13 the Machinery Repair (MR) process for reefer containers is presented. In Box 2: MR actions, there is controlled for the handling durations of the repairs.

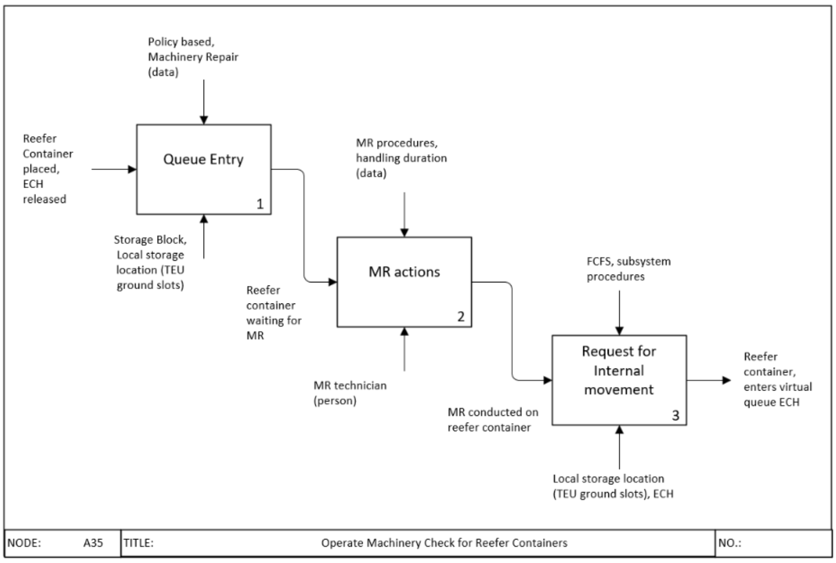

Figure B.13: IDEF0 A35 representation of reefer container in Machinery Check (micro-level)

If data is available, there should be a clear division between body repair and machinery repair. This in order to correctly assign approved labour minutes to this step.

Reefer container in Wash

In Figure B.14 the washing process for reefers containers is presented. In Box 2: Wash Actions, there is controlled for washing procedures and handling time durations. Based on depot procedures the time duration of the actual washing of the container can be fixed to a single value. Depending on the container type, 20-feet or 40-feet, the actual time duration of a washing can vary. Based on expert consultations and depot procedures an estimate should be made for the time durations of this step. This is highly relevant when adopting these washing durations in a conceptual model.

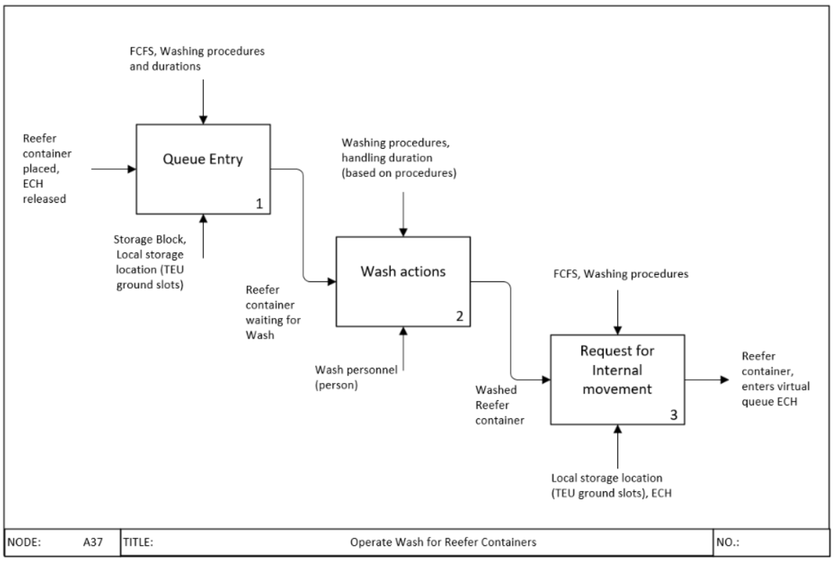

Figure B.14: IDEF0 A37 representation of reefer container in Wash (micro-level)

Reefer container in Settings

In Figure B.15 the setting process for reefer containers is presented. In Box 2: Settings durations, there is controlled for the settings time. Based on depot procedures, the actual time durations of the reefer settings can be set equal to a fixed value.

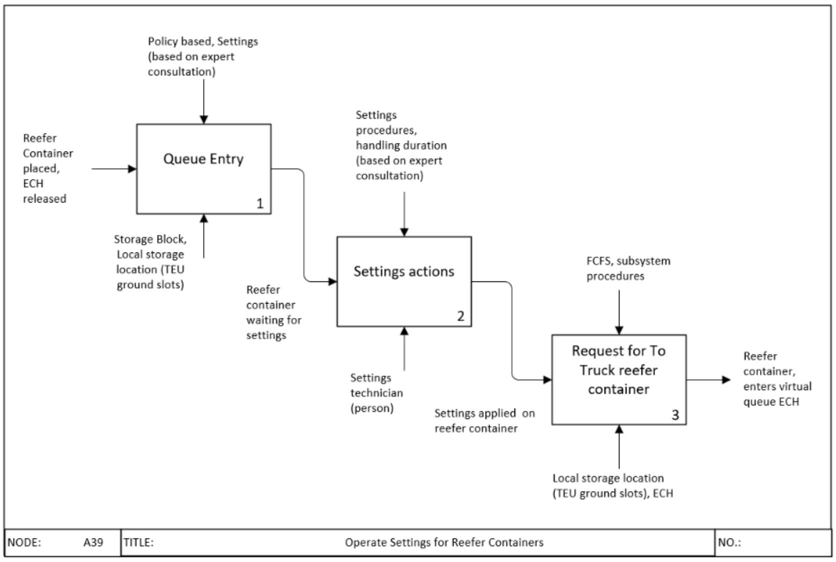

Figure B.15: IDEF0 A39 representation of reefer container in Settings (micro-level)

Reefer container To Truck

In Figure B.16 the reefer container to truck process is presented. In Box 1: Queue Entry, there is controlled for policy-based handling of queue order for reefer containers.

Based on MSC data, reefer containers are released from the Settings area stack after correct implementation of the setting matched to a booking. Entities request a resource (ECH) to move between the settings area and the truck. Truck arrival patterns may vary over time and can be taken into account if data on truck arrival is available. For real-world representation this truck arrival pattern could then be adopted into a conceptual model.

In Figure B.16 the process of the reefer container to truck is presented In Box 1: Queue Entry, there is controlled for policy-based handling of queue order for dry containers. Based on MSC data containers

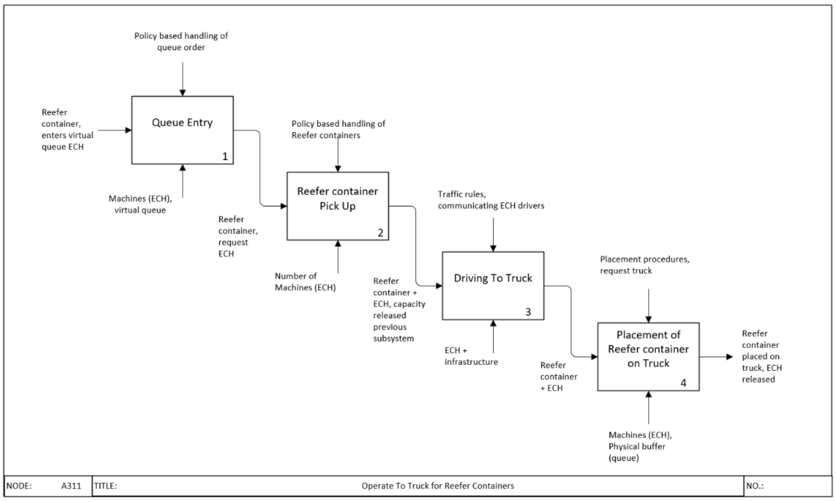

Figure B.16: IDEF0 A311 representation of reefer container in To Truck (micro-level)

are released from the settings area after the complete there settings. Entities request a resource (ECH) to move between the settings area to the truck.

Reefer container Gate-Out

In Figure B.17 the reefer container gate-out process is presented. In Box 1: Queue Entry, there is controlled for the truck arrival interval for reefer container pick up for gate-out. Truck arrival patterns can be adopted in conceptual modelling, if data is available.

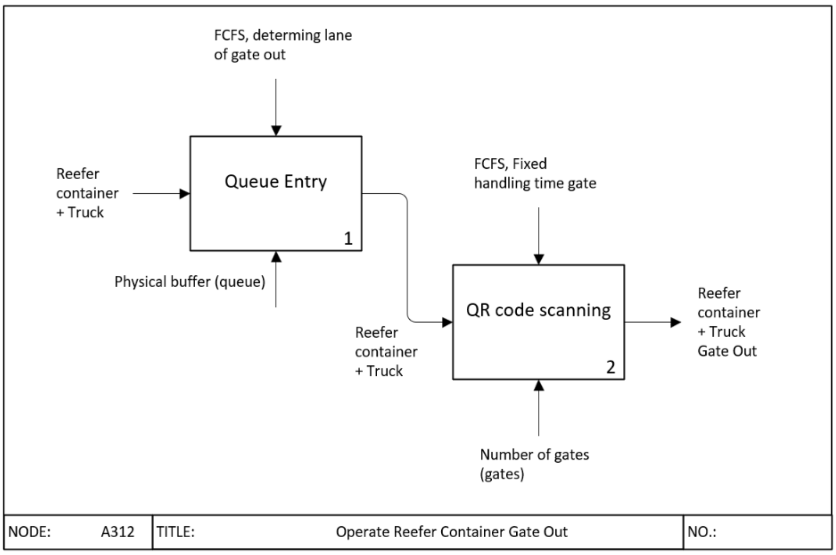

Figure B.17: IDEF0 A39 representation of reefer container in Gate-Out (micro-level)

C

Extended model setup

C.1. Distance matrices

Table C.1: Distance matrix [in m] between depot subsystems used in the baseline model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R
ECHstorage	0	150	165	185	190	270	220	190	205	50	185	125	190	160	185	90	60
PickUpDry	150	0	20	120	125	125	70	50	45	110	240	305	365	350	230	140	100
ToTruckDry	165	20	0	125	130	125	65	40	25	130	240	320	370	340	240	155	120
WashingArea	185	120	125	0	55	140	130	150	165	135	160	240	290	260	160	135	135
RepairYard	190	125	130	55	0	150	130	150	165	135	170	240	290	260	160	135	135
BufferDry	270	125	125	140	150	0	135	150	165	220	260	330	390	350	250	230	220
Stack A	220	70	65	130	130	135	0	90	105	170	240	315	375	335	240	210	160
Stack B	190	50	40	150	150	150	90	0	80	145	250	340	395	355	250	180	145
Stack C	205	45	25	165	165	165	105	80	0	150	280	340	395	355	250	180	140
PickUpReefer	50	110	130	135	135	220	170	145	150	0	125	200	255	215	125	30	10
EPTI	185	240	240	160	170	260	240	250	280	125	0	140	195	155	60	130	125
PTI	125	305	320	240	240	330	315	340	340	200	140	0	90	55	115	200	200
MachineryRepair	190	365	370	290	290	390	375	395	395	255	195	90	0	85	180	270	260
BufferReefer	160	350	340	260	260	350	335	355	355	215	155	55	85	0	155	230	230
ReeferReady	185	230	240	160	160	250	240	250	250	125	60	115	180	155	0	135	130
ReeferSettings	90	140	155	135	135	230	210	180	180	30	130	200	270	230	135	0	35
ToTruckReefer	60	100	120	135	135	220	160	145	140	10	125	200	260	230	130	35	0

Table C.2: Distance matrix [in m] between depot subsystems used in 1st setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R
ECHstorage	0	150	165	185	190	270	220	190	205	50	185	125	190	160	145	190	60
PickUpDry	150	0	20	230	125	125	70	50	45	110	240	305	365	350	150	95	100
ToTruckDry	165	20	0	240	130	125	65	40	25	130	240	320	370	340	160	105	120
WashingArea	185	230	240	0	160	250	240	250	250	125	60	115	180	155	130	170	130
RepairYard	190	125	130	160	0	150	130	150	165	135	170	240	290	260	80	50	135
BufferDry	270	125	125	250	150	0	135	150	165	220	260	330	390	350	160	115	220
Stack A	220	70	65	240	130	135	0	90	105	170	240	315	375	335	155	110	160
Stack B	190	50	40	250	150	150	90	0	80	145	250	340	395	355	175	130	145
Stack C	205	45	25	250	165	165	105	80	0	150	280	340	395	355	185	140	140
PickUpReefer	50	110	130	125	135	220	170	145	150	0	125	200	255	215	100	145	10
EPTI	185	240	240	60	170	260	240	250	280	125	0	140	195	155	130	170	125
PTI	125	305	320	115	240	330	315	340	340	200	140	0	90	55	210	250	200
MachineryRepair	190	365	370	180	290	390	375	395	395	255	195	90	0	85	265	300	260
BufferReefer	160	350	340	155	260	350	335	355	355	215	155	55	85	0	225	265	230
ReeferReady	145	150	160	130	80	160	155	175	185	100	130	210	265	225	0	90	100
ReeferSettings	190	95	105	170	50	115	110	130	140	145	170	250	300	265	90	0	145
ToTruckReefer	60	100	120	130	135	220	160	145	140	10	125	200	260	230	100	145	0

Table C.3: Distance matrix [in m] between depot subsystems used in 2nd setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R
ECHstorage	0	150	165	185	205	270	220	190	205	50	135	125	190	160	185	90	60
PickUpDry	150	0	20	120	80	125	70	50	45	110	190	305	365	350	230	140	100
ToTruckDry	165	20	0	125	90	125	65	40	25	130	200	320	370	340	240	155	120
WashingArea	185	120	125	0	75	140	130	150	165	135	120	240	290	260	160	135	135
RepairYard	205	80	90	75	0	100	80	100	110	150	155	260	310	275	190	160	150
BufferDry	270	125	125	140	100	0	135	150	165	220	210	330	390	350	250	230	220
Stack A	220	70	65	130	80	135	0	90	105	170	200	315	375	335	240	210	160
Stack B	190	50	40	150	100	150	90	0	80	145	220	340	395	355	250	180	145
Stack C	205	45	25	165	110	165	105	80	0	150	230	340	395	355	250	180	140
PickUpReefer	50	110	130	135	150	220	170	145	150	0	90	200	255	215	125	30	10
EPTI	135	190	200	120	155	210	200	220	230	90	0	160	210	175	90	80	90
PTI	125	305	320	240	260	330	315	340	340	200	160	0	90	55	115	200	200
MachineryRepair	190	365	370	290	310	390	375	395	395	255	210	90	0	85	180	270	260
BufferReefer	160	350	340	260	275	350	335	355	355	215	175	55	85	0	155	230	230
ReeferReady	185	230	240	160	190	250	240	250	250	125	90	115	180	155	0	135	130
ReeferSettings	90	140	155	135	160	230	210	180	180	30	80	200	270	230	135	0	35
ToTruckReefer	60	100	120	135	150	220	160	145	140	10	90	200	260	230	130	35	0

Table C.4: Distance matrix [in m] between depot subsystems used in 3rd setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R
ECHstorage	0	150	165	185	190	270	220	190	205	50	160	125	190	185	185	90	60
PickUpDry	150	0	20	120	125	125	70	50	45	110	350	305	365	240	230	140	100
ToTruckDry	165	20	0	125	130	125	65	40	25	130	340	320	370	240	240	155	120
WashingArea	185	120	125	0	55	140	130	150	165	135	260	240	290	160	160	135	135
RepairYard	190	125	130	55	0	150	130	150	165	135	260	240	290	170	160	135	135
BufferDry	270	125	125	140	150	0	135	150	165	220	350	330	390	260	250	230	220
Stack A	220	70	65	130	130	135	0	90	105	170	335	315	375	240	240	210	160
Stack B	190	50	40	150	150	150	90	0	80	145	355	340	395	250	250	180	145
Stack C	205	45	25	165	165	165	105	80	0	150	355	340	395	280	250	180	140
PickUpReefer	50	110	130	135	135	220	170	145	150	0	215	200	255	125	125	30	10
EPTI	160	350	340	260	260	350	335	355	355	215	0	55	85	155	155	230	230
PTI	125	305	320	240	240	330	315	340	340	200	55	0	90	140	115	200	200
MachineryRepair	190	365	370	290	290	390	375	395	395	255	85	90	0	195	180	270	260
BufferReefer	185	240	240	160	170	260	240	250	280	125	155	140	195	0	60	130	125
ReeferReady	185	230	240	160	160	250	240	250	250	125	155	115	180	60	0	135	130
ReeferSettings	90	140	155	135	135	230	210	180	180	30	230	200	270	130	135	0	35
ToTruckReefer	60	100	120	135	135	220	160	145	140	10	230	200	260	125	130	35	0

Table C.5: Distance matrix [in m] between depot subsystems used in 4th setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R
ECHstorage	0	150	165	185	205	270	220	190	205	50	160	125	190	135	145	190	60
PickUpDry	150	0	20	230	80	125	70	50	45	110	350	305	365	190	150	95	100
ToTruckDry	165	20	0	240	90	125	65	40	25	130	340	320	370	200	160	105	120
WashingArea	185	230	240	0	190	250	240	250	250	125	155	115	180	90	130	170	130
RepairYard	205	80	90	190	0	100	80	100	110	150	275	260	310	155	100	60	150
BufferDry	270	125	125	250	100	0	135	150	165	220	350	330	390	210	160	115	220
Stack A	220	70	65	240	80	135	0	90	105	170	335	315	375	200	155	110	160
Stack B	190	50	40	250	100	150	90	0	80	145	355	340	395	220	175	130	145
Stack C	205	45	25	250	110	165	105	80	0	150	355	340	395	230	185	140	140
PickUpReefer	50	110	130	125	150	220	170	145	150	0	215	200	255	90	100	145	10
EPTI	160	350	340	155	275	350	335	355	355	215	0	55	85	175	225	265	230
PTI	125	305	320	115	260	330	315	340	340	200	55	0	90	160	210	250	200
MachineryRepair	190	365	370	180	310	390	375	395	395	255	85	90	0	210	265	300	260
BufferReefer	135	190	200	90	155	210	200	220	230	90	175	160	210	0	95	135	90
ReeferReady	145	150	160	130	100	160	155	175	185	100	225	210	265	95	0	90	100
ReeferSettings	190	95	105	170	60	115	110	130	140	145	265	250	300	135	90	0	145
ToTruckReefer	60	100	120	130	150	220	160	145	140	10	230	200	260	90	100	145	0

Table C.6: Distance matrix [in m] between depot subsystems used in 5th setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R	WR
ECHstorage	0	160	200	160	160	190	260	190	230	40	140	165	215	65	165	180	190	140
PU-Dry	–	0	–	80	105	130	160	110	135	–	–	–	–	–	–	–	–	–
TT-Dry	–	–	0	–	–	–	145	50	120	–	–	–	–	–	–	–	–	–
WashingArea	–	80	–	0	60	90	125	125	125	–	–	–	–	–	–	–	–	–
RepairYard	–	105	–	60	0	70	110	160	115	–	–	–	–	–	–	–	–	–
BufferDry	–	130	–	90	70	0	–	–	–	–	–	–	–	–	–	–	–	–
Stack A	–	160	145	125	110	–	0	–	–	–	–	–	–	–	–	–	–	–
Stack B	–	110	50	125	160	–	–	0	–	–	–	–	–	–	–	–	–	–
Stack C	–	135	120	125	115	–	–	–	0	–	–	–	–	–	–	–	–	–
PickUpReefer	–	–	–	–	–	–	–	–	–	0	145	–	–	60	–	–	–	–
EPTI	–	–	–	–	–	–	–	–	–	145	0	70	–	125	–	–	55	55
PTI	–	–	–	–	–	–	–	–	–	–	70	0	75	–	–	–	75	75
MachineryRepair	–	–	–	–	–	–	–	–	–	–	–	75	0	–	–	–	125	125
BufferReefer	–	–	–	–	–	–	–	–	–	60	125	–	–	0	–	–	–	–
ReeferReady	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	110	–	135
ReeferSettings	–	–	–	–	–	–	–	–	–	–	–	–	–	–	110	0	45	–
ToTruckReefer	–	–	–	–	–	–	–	–	–	–	55	75	125	–	135	–	0	0
WashReefer	–	–	–	–	–	–	–	–	–	–	55	75	125	–	135	–	0	0

Table C.7: Distance matrix [in m] between depot subsystems used in 6th setting model

	ECH-S	PU-Dry	TT-Dry	W	R	B-Dry	ER-A	ER-B	ER-C	PU-R	EPTI	PTI	MR	B-R	R-R	R-Set	TT-R	WR
ECHstorage	0	160	200	160	190	150	260	190	230	40	140	165	215	65	165	180	190	140
PU-Dry	–	0	–	80	130	60	160	110	135	–	–	–	–	–	–	–	–	–
TT-Dry	–	–	0	–	–	–	145	50	120	–	–	–	–	–	–	–	–	–
WashingArea	–	80	–	0	90	85	125	125	125	–	–	–	–	–	–	–	–	–
RepairYard	–	130	–	90	0	70	100	135	105	–	–	–	–	–	–	–	–	–
BufferDry	–	60	–	85	70	0	–	–	–	–	–	–	–	–	–	–	–	–
Stack A	–	160	145	125	100	–	0	–	–	–	–	–	–	–	–	–	–	–
Stack B	–	110	50	125	135	–	–	0	–	–	–	–	–	–	–	–	–	–
Stack C	–	135	120	125	105	–	–	–	0	–	–	–	–	–	–	–	–	–
PickUpReefer	–	–	–	–	–	–	–	–	–	0	145	–	–	60	–	–	–	–
EPTI	–	–	–	–	–	–	–	–	–	145	0	70	–	125	–	–	55	55
PTI	–	–	–	–	–	–	–	–	–	–	70	0	75	–	–	–	75	75
MachineryRepair	–	–	–	–	–	–	–	–	–	–	–	75	0	–	–	–	125	125
BufferReefer	–	–	–	–	–	–	–	–	–	60	125	–	–	0	–	–	–	–
ReeferReady	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	110	–	135
ReeferSettings	–	–	–	–	–	–	–	–	–	–	–	–	–	–	110	0	45	–
ToTruckReefer	–	–	–	–	–	–	–	–	–	–	55	75	125	–	135	–	0	0
WashReefer	–	–	–	–	–	–	–	–	–	–	55	75	125	–	135	–	0	0

C.2. Facility layout design: Driving lanes

Driving distances are calculated using the existing driving lane setup presented in Figure C.1. This core structure is used for determining distances for settings B, 1, 2, 3 and 4.

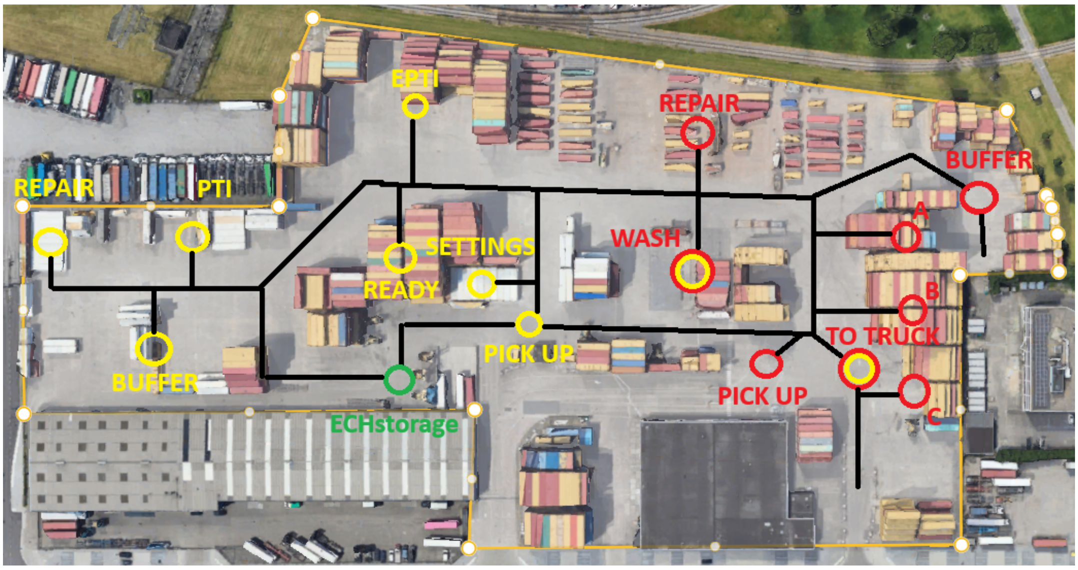

Figure C.1: Layout design, driving lanes baseline model

Driving distances are calculated using the existing driving lane setup presented in Figure C.2. This core structure is used for determining distances of setting 5 and 6. Where setting 6 is slightly different then this setup, but uses the same driving lanes.

Figure C.2: Layout design, driving lanes alternative layout setting 5 and 6

C.3. Assumptions & Simplifications

In Table C.8 all assumptions and/or simplifications from a (conceptual) modelling perspective will be presented.

Table C.8: Assumptions and simplifications

Number	Scope	Assumption description	Justification and Impact
1S	System boundary	95% of dry container Classes are considered in the model taking into account Class A, B and C	-
2S	System boundary	5% of dry container Classes are not considered in the model, excluding Class FLEX, For Off-Hire and Claim	-
3S	System boundary	98% of dry container Types are considered in the model taking into account Type 20DV, 40DV and 40HC	-
4S	System boundary	2% of dry container Types are not considered in the model excluding Type 40OT, 20OT, 40FL, 40HF, 20FL, 40HO and 40HP	-
5S	System boundary	Both sizes 1 TEU and 2 TEU are included into the model for dry containers	-
6S	System boundary	97% of reefer container Classes are considered in the model taking into account Class PTI and ePTI	-
7S	System boundary	3% of reefer container Classes are not considered in the model, excluding Class Heavy Damaged and NON	-
8S	System boundary	97.50% of reefer container Types are considered in the model taking into account Type 40HR	-
9S	System boundary	2.50% of reefer container Types are not considered in the model excluding Type 20RE	-
10S	System boundary	Only size 2 TEU is included into the model for reefer containers, excluding 1 TEU	-
11A	System	All subsystems related to the handling of dry containers are taking into account in the model (for all Classes, Types and Sizes included in the model)	-

Number	Scope	Assumption description	Justification and Impact
12A	System	Subsystems defined for dry containers: Visual Check, Gate-In Dry, Pick-Up Dry, Buffer Dry, Repair Dry, Wash, Export Ready Dry, Internal movement Dry, Container To Truck and Gate-Out	-
13A	System	All subsystems related to the handling of reefer containers are taking into account in the model (for all Classes, Types and Sizes included in the model)	-
14A	System	Subsystems defined for reefer containers: Gate-In Reefer, Pick-Up Reefer, EPTI, PTI, Machinery Repair, Buffer Reefer, Wash, Ready Reefer, Settings, Internal movement Reefer, Reefer To Truck and Gate-Out	-
15S	Data (Visual Check)	Process durations are based on depot procedures and expert consultations; duration is distributed according to a Normal distribution	No data available, Normal distribution accounts for randomness included in inspection durations
16S	Process (Visual Check)	Policy of incoming trucks with containers is FCFS	According to real operations
17S	Data (Gate-In Dry)	Process durations are based on depot procedures and expert consultations; duration is distributed according to a Normal distribution	No data available, Normal distribution accounts for randomness included in actual gate-in times for trucks
18S	Process (Gate-In Dry)	Policy of incoming trucks with containers is FCFS	According to real operations
19S	Process (Pick-Up Dry)	Process durations are based on depot procedures and expert consultations; The composition of Pick-Up procedures included actual handling on container + driving times according to driving distances between subsystems	Handling durations on containers are estimated and discussed with MedRepair personnel, including driving speed at the depot
20S	Process (Pick-Up Dry)	Policy of incoming trucks with containers is FCFS	According to real operations
21S	Process (Pick-Up Dry)	ECH can only handle 1 request at a time; lifting 1 container	According to real operations
22S	Process (Pick-Up Dry)	ECH is assigned to subsystem that have a direct connection with the pick-up area (following predefined path structures)	According to real operations
23S	Process (General)	All available ECH are assigned for the full operational time period	In real operations a selection of ECH is used per time period within the operational hours; meaning that productivity of all ECH together is overestimated in the model

Number	Scope	Assumption description	Justification and Impact
24S	Process (Buffer Dry)	Containers are placed inside the buffer area only when the next subsystem (considering the predefined path for that unique ID_number) reached its capacity at that moment in time	According to real operations
25S	Process (Buffer Dry)	Containers that are inside the buffer area are prioritised to move to the next subsystem when capacity becomes available	The buffer area is therefore seen as a waiting area before moving on along the predefined path for that specific ID_number
26S	Data (Repair Dry)	Process durations are based on data; process durations are picked from a probability distribution and assigned to a specific ID_number in the beginning of the simulation	-
27S	Process (Repair Dry)	Policy of incoming containers is FCFS	Deviates from real operations, depending on the amount of labour minutes and available personnel, materials and equipment a decision is made which container to repair first
28S	Process (Repair Dry)	When a container is placed inside the repair yard, the assigned labour minutes immediately start for that specific container	This will overestimate the subsystem performance, because the assigned labour minutes are the actual computed labour minutes for that specific ID_number / container
29S	Process (Repair Dry)	When a container is placed inside the repair yard, the container is immediately repaired by personnel, assuming that personnel is always available	In real operations the repair is limited to the number of personnel working, meaning the actual time for a container inside the repair yard is underestimated, increasing system performance
30S	Process (Repair Dry)	When assigned labour minutes are finished for a container, the container immediately request an ECH for internal movement, assuming that the container can directly be picked from the ground	In real operations the configuration of the repair yard influences the availability for container pick up, meaning containers could block other containers, not taking remarshalling of storage space into account
31S	Data (Wash)	Process durations are based on depot procedures and expert consultations; including actual washing times, policies and drying time	-

Number	Scope	Assumption description	Justification and Impact
32S	Process (Wash)	Policy of incoming (reefer) containers is FCFS	Deviates from real operations, where first the washing area is completely filled and the all the (reefer) containers are washed. Meaning that actual the actual dwell time of (reefer) containers inside the washing area are underestimated, leading to increased performance of the washing area. Is accounted for by lengthening the washing durations, such that an approximation of correct washing times is obtained
33S	Process (Wash)	When a (reefer) container is placed inside the washing area, the (reefer) container is immediately washed by personnel, assuming that personnel is always available	In real operations the washing area is limited to the number of personnel working, meaning the actual time for a (reefer) container inside the washing area is underestimated, increasing system performance
34S	Process (Wash)	When assigned wash minutes are finished for a (reefer) container, the (reefer) container immediately request an ECH for internal movement, assuming that the (reefer) container can directly be picked from the ground	In real operations the washing area is first fully filled before conducting the washing. Then the whole subsystem is emptied when personnel is out of this area for safety reasons. Actual internal movements are happening in batches instead of individual (reefer) containers, overestimating the system performance
35S	Process (Wash)	Drying time of the (reefer) container is not taking into account as a constraint.	In real life the actual drying time of the container is highly influenced by the season. Drying time could differ for winter and summer periods. (reefer) Containers are ideally are provided in complete dry conditions, but for simulation purposes not included
36S	Process (Export Ready Dry)	Process durations are based on a combination of data and previous process durations; process durations are picked from a probability distribution and assigned to a specific ID_number in the beginning of the simulation	Exact data on dwelling of containers inside Export Ready Stack is missing, available data is the difference between gate-out and gate-in for a specific ID_number. Accounting for time spend in other subsystems.
37S	Process (Export Ready Dry)	When assigned dwell minutes are finished for a container, the container immediately request an ECH for internal movement to truck, assuming that the container can directly be picked from the storage block	In real operations the configuration of the export ready stack influences the availability for container pick up, meaning containers could block other containers, not taking remarshalling of storage space into account

Number	Scope	Assumption description	Justification and Impact
38S	Process (Internal movement)	Process durations are based on depot procedures and expert consultations; the composition of internal movement procedures includes handling on (reefer) container + driving times according to driving distances between subsystems	Handling durations on (reefer) containers are estimated and discussed with MedRepair personnel, including driving speed at the depot
39S	Process (Internal movement)	Policy of transport of (reefer) containers is FCFS	Deviating from real operations where ECH drivers can manually select tasks. Assuming convenient task management by drivers, this assumption will lead to higher driving distances and lower ECH utilisation. Assumption is justified because this helps reflect the dynamics of the ECD system, which is in line with research goals, understanding system dynamics rather than optimising ECD operations
40S	Process (Internal movement)	ECH can only handle 1 request at a time; lifting 1 (reefer) container	In real operations it is common to handle 2 request at a time, combining tasks, not considered in the simulation model
41S	Process (Internal movement)	ECH is assigned to specific areas in the system	According to real operations
42S	Process (Container To Truck)	Process durations are based on depot procedures and expert consultations; The composition of To Truck procedures included actual handling on container + driving times according to driving distances between subsystems	Handling durations on containers are estimated and discussed with MedRepair personnel, including driving speed at the depot
43S	Process (Container To Truck)	Policy of outgoing containers to trucks is FCFS	Deviating from real operations; demand driven export influences arrival of truck with specific container requests, left out in the model
44S	Process (Container To Truck)	ECH can only handle 1 request at a time; lifting 1 container	Following real operations in general, but could differ when occupations of the yard is high
45S	Process (Container To Truck)	ECH is assigned to subsystem that have a direct connection with the container to truck area (following predefined path structures)	According to real operations
46S	Data (Gate-Out)	Process durations are based on depot procedures and expert consultations; duration is distributed according to a Normal distribution	No data available, Normal distribution accounts for randomness included in actual gate-in times for trucks
47S	Process (Gate-Out)	Policy of outgoing trucks with containers is FCFS	According to real operations

Number	Scope	Assumption description	Justification and Impact
48A	Process (Gate-Out)	When a (reefer) container wants to gate out a truck is always available	Deviates from real operations, therefore overestimating system performance, but for simplicity not included in the model because of unknown arrival patterns of trucks without containers
49S	Process (Gate-In Reefer)	Process durations are based on depot procedures and expert consultations; duration is distributed according to a Normal distribution	No data available, Normal distribution accounts for randomness included in actual gate-in times for trucks
50S	Process (Gate-In Reefer)	Policy of incoming trucks with containers is FCFS	According to real operations
51S	Process (Pick-Up Reefer)	Process durations are based on depot procedures and expert consultations; The composition of Pick-Up procedures included actual handling on reefer containers + driving times according to driving distances between subsystems	Handling durations on reefer containers are estimated and discussed with MedRepair personnel, including driving speed at the depot
52S	Process (Pick-Up Reefer)	Policy of incoming trucks with reefer containers is FCFS	According to real operations
53S	Process (Pick-Up Reefer)	ECH can only handle 1 request at a time; lifting 1 reefer container	Following real operations in general, but could differ when occupations of the yard is high
54S	Process (Pick-Up Reefer)	ECH is assigned to subsystem that have a direct connection with the pick-up reefer area (following predefined path structures)	According to real operations
55S	Process (Buffer Reefer)	Reefer containers are placed inside the buffer area only when the next subsystem (considering the predefined path for that unique ID_number) reached its capacity at that moment in time	According to real operations
56S	Process (Buffer Reefer)	Reefer containers that are inside the buffer area are prioritised to move to the next subsystem when capacity becomes available	The buffer area is therefore seen as a waiting area before moving on along the predefined path for that specific ID_number
57S	Process (EPTI)	Inside EPTI area several actions are conducted, including body check, small repairs and the EPTI. Following this order of actions described	According to real operations
58S	Data (EPTI)	Process durations are based on a combination of labour minute data and estimated process duration for body check and EPTI; process durations are picked from a probability distribution and assigned to a specific ID_number	Data on body check and repair is available, but actual EPTI time is missing and therefore assumed according to expert knowledge

Number	Scope	Assumption description	Justification and Impact
59S	Process (EPTI)	Policy of incoming reefer containers is FCFS	Deviates from real operations, depending on the amount of labour minutes and available personnel, materials and equipment a decision is made which reefer container to body check first
60S	Process (EPTI)	When a reefer container is placed inside the EPTI area, the assigned labour minutes immediately start for that specific reefer container	This will overestimate the subsystem performance, because the assigned labour minutes are the actual computed labour minutes for that specific ID_number / reefer container
61S	Process (EPTI)	When a reefer container is placed inside the EPTI area, the reefer container is immediately checked by personnel, assuming that personnel is always available	In real operations the actions happening in this zone are limited to the number of personnel working, meaning the actual time for a container inside the EPTI area is underestimated, increasing system performance
62S	Process (EPTI)	When all assigned actions are finished for a reefer container, the reefer container immediately request an ECH for internal movement, assuming that the reefer container can directly be picked from the ground	In real operations the configuration of the EPTI area influences the availability for reefer container pick up, meaning reefer containers could block other reefer containers, not taking remarshalling of storage space into account
63A	Process (EPTI)	First step in the EPTI area is the body check, if a small repair is needed is conducted directly on sight. Heavy damaged reefer containers are not taking into account	According to system boundaries
64S	Process (PTI)	Inside the PTI area the PTI is conducted, if the PTI fails then the machinery need to be repaired, this will happen in another area	According to real operations
65S	Data (PTI)	Process durations are based on a combination of labour minute data and estimated process duration for PTI; process durations are picked from a probability distribution and assigned to a specific ID_number	Data on machinery repair is available, but actual PTI time is missing and therefore assumed according to expert knowledge
66S	Process (PTI)	Policy of incoming reefer containers is FCFS	Deviates from real operations, depending on the PTI and available personnel, materials and equipment a decision is made which reefer container to PTI first

Number	Scope	Assumption description	Justification and Impact
67S	Process (PTI)	When a reefer container is placed inside the PTI area, the assigned labour minutes immediately start for that specific reefer container	This will overestimate the subsystem performance, because the assigned labour minutes are the actual computed labour minutes for that specific ID_number / reefer container
68S	Process (PTI)	When a reefer container is placed inside the PTI area, the reefer container is immediately checked by personnel, assuming that personnel is always available	In real operations the actions happening in this zone are limited to the number of personnel working, meaning the actual time for a container inside the PTI area is underestimated, increasing system performance
69S	Process (PTI)	When all assigned actions are finished for a reefer container, the reefer container immediately request an ECH for internal movement, assuming that the reefer container can directly be picked from the ground	In real operations the configuration of the PTI area influences the availability for reefer container pick up, meaning reefer containers could block other reefer containers, not taking remarshalling of storage space into account
70S	Process (PTI)	Actual time durations to conduct a PTI is different throughtout the year due to the temperature outside, but not considered in the simulation	-
71A	Process (Machinery Repair)	Inside the machinery repair area the replacement of parts is conducted, assumed that the repair can always be fixed	-
72S	Data (Machinery Repair)	Process durations are based on a combination of labour minute data and estimated process duration for MR; process durations are picked from a probability distribution and assigned to a specific ID_number. Small repairs are excecuted inside the MR subsystem instead of EPTI bodycheck area	Data on machinery repair is available
73S	Process (Machinery Repair)	Policy of incoming reefer containers is FCFS	Deviates from real operations, depending on the machinery repair and available personnel, materials and equipment a decision is made which reefer container to repair first
74S	Process (Machinery Repair)	When a reefer container is placed inside the machinery area, the assigned labour minutes immediately start for that specific reefer container	This will overestimate the subsystem performance, because the assigned labour minutes are the actual computed labour minutes for that specific ID_number / reefer container

Number	Scope	Assumption description	Justification and Impact
75S	Process (Machinery Repair)	When a reefer container is placed inside the machinery repair area, the reefer container is immediately checked by personnel, assuming that personnel is always available	In real operations the actions happening in this zone are limited to the number of personnel working, meaning the actual time for a container inside the machinery repair area is underestimated, increasing system performance
76S	Process (Machinery Repair)	When all assigned actions are finished for a reefer container, the reefer container immediately request an ECH for internal movement, assuming that the reefer container can directly be picked from the ground	In real operations the configuration of the machinery repair area influences the availability for reefer container pick up, meaning reefer containers could block other reefer containers, not taking remarshalling of storage space into account
77S	Process (Ready Reefer)	Process durations are based on a combination of data and previous process durations; process durations are picked from a probability distribution and assigned to a specific ID_number	Exact data on dwelling of reefer containers inside Ready Stack is missing, available data is the difference between gate-out and gate-in for a specific ID_number. Accounting for time spend in other subsystems.
78S	Process (Ready Reefer)	Within the data analysis dwell time possibilities for reefer containers are divided into short and long dwell times. In all settings the assigned dwell time is picked from the distribution representing the short dwell times	To prevent immediate bottlenecks and loss of visibility in reefer operations, only ”short” dwell time assignments are used. This simplification helps maintain consistent tracking and aligns with the model’s goal of analysing internal flow dynamics and identifying bottlenecks.
79S	Process (Ready Reefer)	When assigned dwell minutes are finished for a reefer container, the reefer container immediately request an ECH for internal movement to truck, assuming that the reefer container can directly be picked from the storage block	In real operations the configuration of the ready stack influences the availability for reefer container pick up, meaning reefer containers could block other reefer containers, not taking remarshalling of storage space into account
80S	Data (Settings)	Process durations are based on depot procedures and expert consultations; including estimated setting times, policies and specific procedures	-
81S	Process (Settings)	Policy of incoming reefer containers is FCFS	Deviates from real operations, because of stacking order and classification of reefer containers (which is left out) setting procedures differ and therefore FCFS not applicable. Dwell time inside settings area is therefore both under and overestimated

Number	Scope	Assumption description	Justification and Impact
82S	Process (Settings)	When assigned setting minutes are finished for a reefer container, the reefer container immediately request an ECH for internal movement, assuming that the reefer container can directly be picked from the ground	Deviating from real operations, related to stacking order but no included in the simulation model
83S	Process (Reefer To Truck)	Process durations are based on depot procedures and expert consultations; The composition of To Truck procedures included actual handling on reefer container + driving times according to driving distances between subsystems	Handling durations on reefer containers are estimated and discussed with MedRepair personnel, including driving speed at the depot
84S	Process (Reefer To Truck)	Policy of outgoing reefer containers to trucks is FCFS	Deviating from real operations; demand driven export influences arrival of truck with specific reefer container requests, left out in the model
85S	Process (ECH)	Driving speed is adjusted to 10 km per hour deviating from in field measurements	Driving speed remains fixed to compare correctly between different settings. This to gain insight into process relationships and conditions rather than providing a perfect fit to reality
86S	Process (ECH)	In the simulation, a container releases its TEU ground slot in a subsystem at the moment an ECH is already assigned and dispatched for movements. This assumes that the time it takes for the ECH to arrive and lift the container is sufficient to prevent another container from being assigned and placed to that same slot	No container can instantly occupy the slot because assigned containers would also require a movement towards this area. In real operations this could cause waiting time for ECH, which is excluded in the model.
87A	Path (Flows)	Visual inspection for dry containers and class determination for reefer containers are assumed to be conducted always in the correct way. Ensuring that containers correctly follow each path assigned. No deviations from this path are possible inside the model	-

C.4. Verification & Validation

This section provides a series of targeted tests corresponding to the key techniques described in chapter 5. The examples presented below illustrate how each method was used to ensure model correctness. The results of these tests confirm that the simulation logic, process flows and parameter setting function as intended.

Debugging: *Iteratively identifying and correcting logic errors and misconfiguration in the code.*

The execution monitoring example below serves as proof that the debugging process has resulted in correct model behaviour.

Execution monitoring: *Tracking of container movements and subsystem occupation during simulation runs.*

The example provided below illustrates how the simulation logic is verified against the input characteristic. The goal is to assess whether the model behaves as intended based on predefined parameters. In this example, the flow of dry container number 1 is traced throughout the system. The container follows a predefined route, route 1D, as specified in Table 5.2. This path includes visits to the repair yard, washing area and export ready stack.

The time-based flow of this container is presented in the output below. By analysing these outcomes, multiple insights can be gained:

- Does the container follow the correct path?
- Are all required subsystems visited?
- Does the container leave the system?
- Are process durations consistent with the input parameters set? In other words, do the events follow the assigned probability distributions?

This output is the result of prior debugging efforts, which ensured that the model logic was correctly implemented.

```
--- Simulation start (following container 1) ---

[0] DEPOT OPENS
Container 1 (TEU=1) enters waiting queue at 1.00 [min]
Container 1 (TEU=1) enters depot at 1.00 [min],
and waits in queue for entering VC area
Container 1 (TEU=1) enters Visual Check area at 1.00 [min]
Container 1 (TEU=1) visually checked, and leaves Visual Check area at 2.91 [min]
Container 1 (TEU=1) enters queue waiting for Gate-In at 2.91 [min]
Container 1 (TEU=1) Gate-In at 2.91 [min]
Container 1 (TEU=1) through gate at 3.37 [min]
Container 1 (TEU=1) assigned to space in Repair Yard at 3.37 [min]
Container 1 (TEU=1) on truck is driven towards pick-up area 3.37 [min]
Container 1 (TEU=1) picked from truck at 3.37 [min]
Container 1 (TEU=1) and ECH drive towards Repair Yard at 3.37 [min]
['ECHpickup_1 busy: False']
ECHpickup_1 drives 150m to PickUpDry, then with Container 1,
125m to RepairYard at 3.37 [min]
Container 1 (TEU=1) placed in Repair Yard at 6.02 [min], releases ECH
Container 1 (TEU=1) undergoes M&R activities at 6.02 [min]
Container 1 (TEU=1) M&R activities finished at 198.31 [min]
Container 1 (TEU=1) request an ECH for Internal movement at 198.31 [min]
Container 1 (TEU=1) ECH request accepted at 198.31 [min]
Container 1 (TEU=1) checks for available space in Washing Area at 198.31 [min]
Container 1 (TEU=1) gets assigned space in Washing Area at 198.31 [min]
Container 1 (TEU=1) gives back TEU ground slot to Repair Yard at 198.31 [min]
Container 1 (TEU=1) picked by ECH from Repair Yard at 198.31 [min]
```

```
['ECHinternalmovement_1 busy: False']
ECHinternalmovement_1 drives 55m to RepairYard, then with Container 1,
55m to WashingArea at 198.31 [min]
Container 1 (TEU=1) is moved by ECH into Washing Area at 199.97 [min], release of ECH
Container 1 (TEU=1) undergoes washing activities at 199.97 [min]
Container 1 (TEU=1) Wash activities finished at 334.97 [min]
Container 1 (TEU=1) request an ECH for Internal movement at 334.97 [min]
Container 1 (TEU=1) ECH request accepted at 334.97 [min]
Container 1 (TEU=1) assigned to Stack C at 334.97 [min]
Container 1 (TEU=1) checks for available space in Stack C at 334.97 [min]
Container 1 (TEU=1) picked by ECH from Washing Area at 334.97 [min]
Container 1 (TEU=1) gives back TEU ground slot to Washing Area at 334.97 [min]
['ECHinternalmovement_1 busy: False']
ECHinternalmovement_1 drives 0m to WashingArea, then with Container 1,
165m to Stack C at 338.97 [min]
Container 1 (TEU=1) is moved by ECH into Stack C at 340.96 [min], ECH released
Container 1 (TEU=1) in Stack C start dwelling at 340.96 [min]
[780] DEPOT CLOSES
[1440] DEPOT OPENS
[2220] DEPOT CLOSES
[2880] DEPOT OPENS
[3660] DEPOT CLOSES
[4320] DEPOT OPENS
Container 1 (TEU=1) in Stack C completed dwelling at 4659.16 [min]
Container 1 (TEU=1) request an ECH for Gate-Out at 4659.16 [min]
Container 1 (TEU=1) ECH request accepted at 4659.16 [min]
Container 1 (TEU=1) picked by ECH from Stack C at 4659.16 [min]
Container 1 (TEU=1) is moved by ECH and driven towards truck at 4659.16 [min]
['ECHtotruck_1 busy: False']
ECHtotruck_1 drives 25m to Stack C, then with Container 1,
25m to ToTruckDry at 4659.16 [min]
Container 1 (TEU=1) is placed on truck by ECH at 4660.46 [min]
Container 1 (TEU=1) enters gate-out area at 4660.46 [min],
and waits in queue for Gate-Out
Container 1 (TEU=1) Gate-Out at 4660.46 [min]
Container 1 (TEU=1) through gate at 4661.27 [min], left the ECD system

--- Simulation end (following container 1) ---
```

Execution profiling: *Tracking containers along specified paths, ensuring that correct logic is followed.*

The stress testing example below shows how execution profiling has been conducted in a tailored example.

Stress testing: *Testing the model by influencing container generation intervals, path forcing and playing with subsystem elements and constraints. This to test robustness of the simulation, but more important for bottleneck identification.*

The example presented in Table C.9 shows the outcome of execution profiling and stress testing applied to the simulation model. In this test, the probability of selecting paht D2, as specified in Table 5.2, was set to 100 %. This configuration forces that all dry containers are routed through the washing area and export ready stacks.

By doing so, the occupation rate of the repair yard for dry containers is expected to be zero throughout the test. This would validate the correctness of the path. Adding to this, this setup stresses the washing area, since not all containers require a wash. The expectation is that its capacity will be fully utilised but not exceeded. This test therefore supports both verification techniques. Table C.9 presents a selection of dry container subsystems to illustrate the test outcomes.

Table C.9: Test: Occupation rates (number of TEU used) of selected subsystems

Time (min)	Visual Check	PU Dry	Buffer Dry	Repair	Wash	Stack A	Stack B	Stack C
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	1.0	2.0	0.0	0.0	33.0	0.0	0.0	0.0
200.0	3.0	0.0	10.0	0.0	36.0	2.0	3.0	2.0
300.0	0.0	0.0	11.0	0.0	40.0	2.0	19.0	3.0
400.0	0.0	3.0	11.0	0.0	33.0	4.0	32.0	7.0
500.0	0.0	1.0	14.0	0.0	40.0	4.0	31.0	9.0
600.0	0.0	1.0	18.0	0.0	40.0	4.0	38.0	13.0
700.0	1.0	2.0	21.0	0.0	35.0	5.0	38.0	13.0
800.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
900.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1000.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1100.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1200.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1300.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1400.0	0.0	0.0	22.0	0.0	39.0	5.0	37.0	11.0
1500.0	1.0	2.0	24.0	0.0	35.0	7.0	42.0	16.0
1600.0	1.0	4.0	31.0	0.0	40.0	5.0	44.0	15.0
1700.0	0.0	2.0	33.0	0.0	39.0	7.0	44.0	16.0
1800.0	1.0	0.0	36.0	0.0	38.0	6.0	47.0	14.0
1900.0	1.0	1.0	41.0	0.0	39.0	5.0	49.0	11.0
2000.0	4.0	1.0	46.0	0.0	39.0	6.0	51.0	10.0
2100.0	0.0	0.0	44.0	0.0	39.0	7.0	52.0	10.0
2200.0	0.0	0.0	48.0	0.0	37.0	6.0	55.0	8.0
2300.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2400.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2500.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2600.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2700.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2800.0	0.0	0.0	48.0	0.0	37.0	5.0	54.0	8.0
2900.0	0.0	2.0	46.0	0.0	40.0	5.0	55.0	8.0
3000.0	0.0	2.0	43.0	0.0	39.0	7.0	52.0	8.0
3100.0	2.0	2.0	39.0	0.0	39.0	9.0	48.0	8.0
3200.0	2.0	0.0	42.0	0.0	40.0	9.0	55.0	8.0
3300.0	0.0	0.0	41.0	0.0	39.0	9.0	52.0	9.0
3400.0	3.0	1.0	38.0	0.0	39.0	9.0	50.0	8.0
3500.0	0.0	0.0	35.0	0.0	39.0	8.0	51.0	8.0
3600.0	2.0	0.0	36.0	0.0	39.0	7.0	49.0	7.0
3700.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
3800.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
3900.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
4000.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
4100.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
4200.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
4300.0	2.0	0.0	37.0	0.0	40.0	7.0	44.0	7.0
4400.0	1.0	2.0	35.0	0.0	39.0	9.0	45.0	6.0
4500.0	1.0	2.0	35.0	0.0	40.0	7.0	37.0	9.0
4600.0	0.0	3.0	33.0	0.0	40.0	5.0	32.0	9.0
4700.0	2.0	0.0	28.0	0.0	39.0	4.0	31.0	8.0
4800.0	0.0	0.0	29.0	0.0	40.0	4.0	29.0	10.0
4900.0	0.0	3.0	33.0	0.0	40.0	4.0	26.0	9.0
5000.0	1.0	2.0	34.0	0.0	40.0	4.0	24.0	9.0
5100.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5200.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5300.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5400.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5500.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5600.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5700.0	0.0	4.0	30.0	0.0	40.0	4.0	21.0	11.0
5800.0	0.0	0.0	29.0	0.0	40.0	4.0	22.0	11.0
5900.0	0.0	0.0	28.0	0.0	39.0	1.0	21.0	10.0
6000.0	2.0	4.0	22.0	0.0	40.0	0.0	19.0	8.0

D

Scenario: Setup and analysis

D.1. Warm-up period analysis and steady-state identification

To correctly evaluate the KPIs defined in Table 5.5, the following method is proposed. Following the principles outlined in *Robinson (2007)* [63], a hybrid graphical and heuristics method is used to determine the warm-up period of the simulation. The two KPIs evaluated for determining the warm-up time, are the throughput and occupation rates of the system.

For both KPIs an average time-series was derived from 25 simulation replications. Following the hybrid approach, the first step is the visual inspection of these time-series which provided insight into the stabilisation of both KPIs over time. This analysis was complemented by conducting a moving average analysis to determine the end of the warm-up period, as the point where the moving average changes by less than 2%. This threshold of two percent is not intended to be precise, but rather to indicate behavioural stability. This aligns with the SPC method, mentioned in *Robinson (2007)* [63], which focus is on identifying when the system transitions into stable state.

Once the change is below this threshold, a visual inspection is performed to determine the most appropriate warm-up duration based on observed system behaviour. This approach allows for flexibility across the four different scenarios, while following a consistent method for assessing the stabilisation.

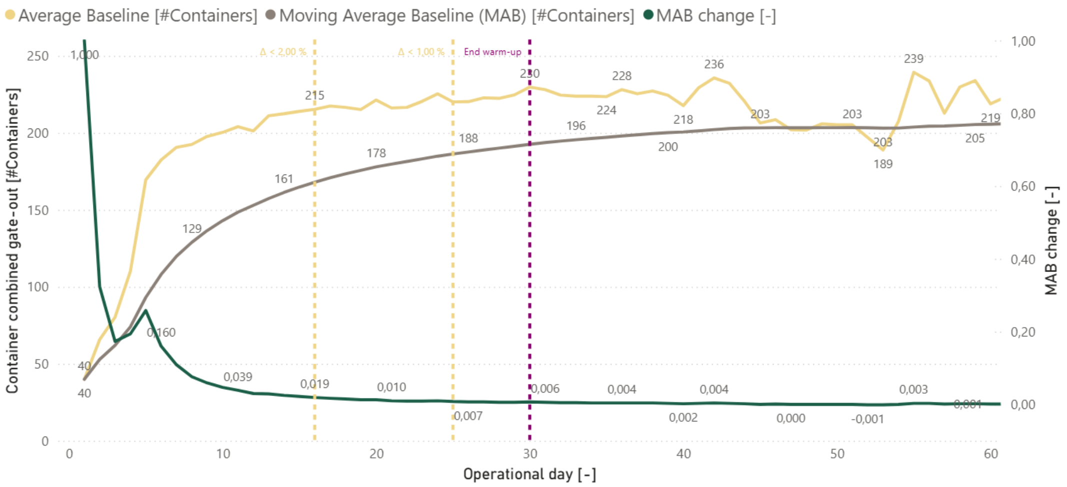

Figure D.1: Scenario 1: Warm-up time determination

In Figure D.1 the end of the warm-up period is defined after 30 days. The moving average changes with less than 1% and this is the starting point for comparing the settings to the baseline setting for scenario 1. For scenarios 2,3 and 4 the same approach is used. Here the end of the warm-up period is defined after 20 days. The moving average changes with less than 2% and this is the starting point for comparing the settings to the baseline setting for the corresponding scenarios. This is visualised in Figure D.2 to Figure D.4.

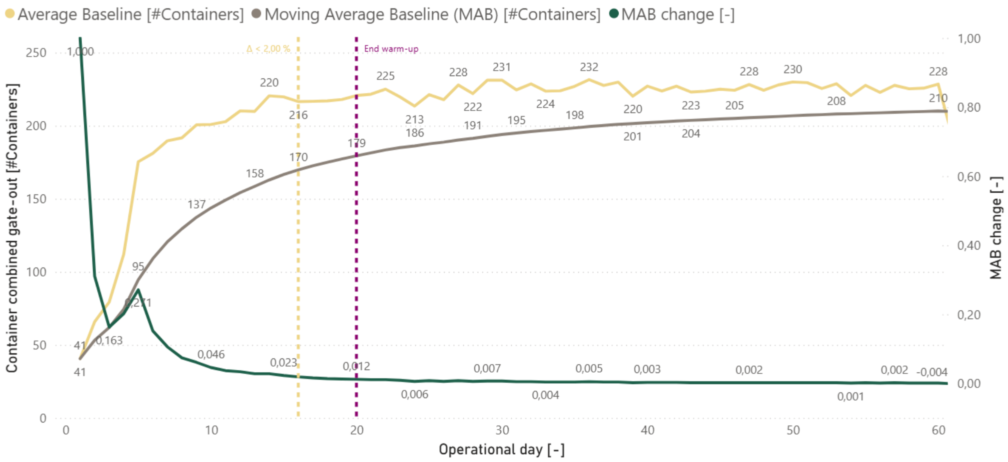

Figure D.2: Scenario 2: Warm-up time determination

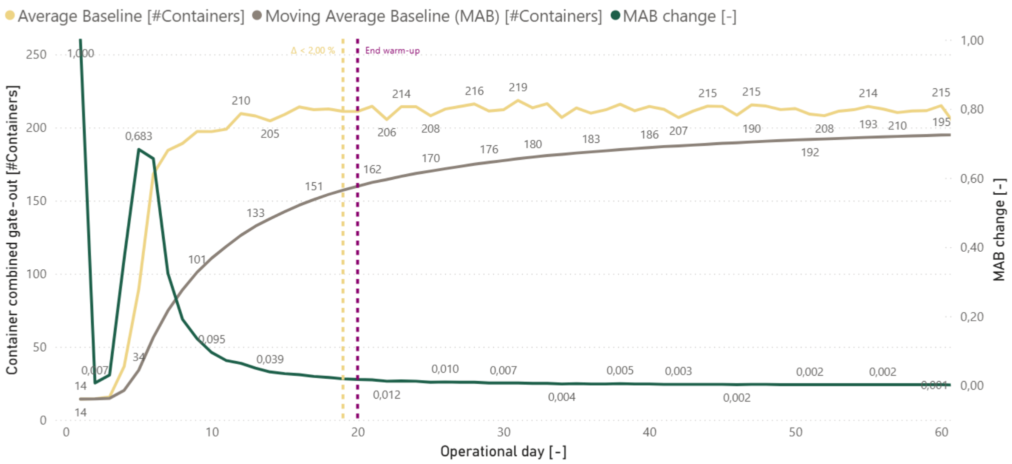

Figure D.3: Scenario 3: Warm-up time determination

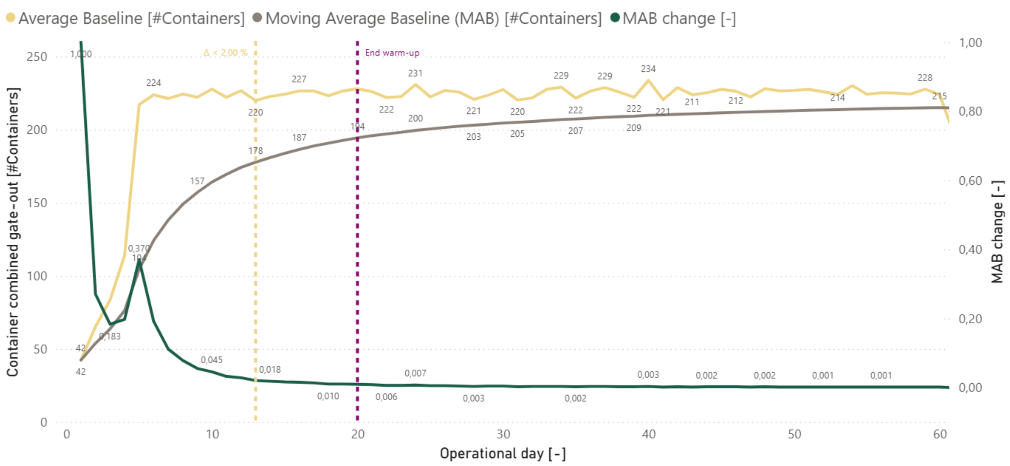

Figure D.4: Scenario 4: Warm-up time determination

D.2. Scenario 1: Occupation visualisations

This section highlights all occupation graphs that were not presented in the main report. Showing twelve different visualisations related to the dry and reefer occupation rates of different settings throughout the simulation.

Following the logic presented in the main report helps understand the outcomes presented in the figures. By visually inspecting occupation rates for both dry and reefer container subsystems, insights are gained into bottleneck dynamics inside the system. If aligned with other KPIs a comprehensive review can be provided for the different settings.

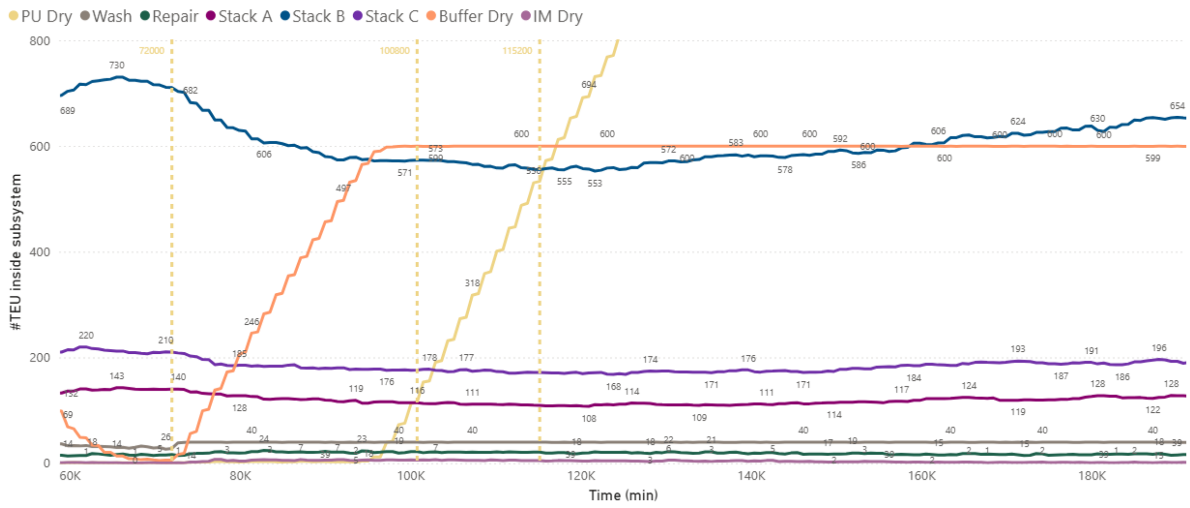

Figure D.5: Scenario 1: Occupation subsystems (dry) setting 1

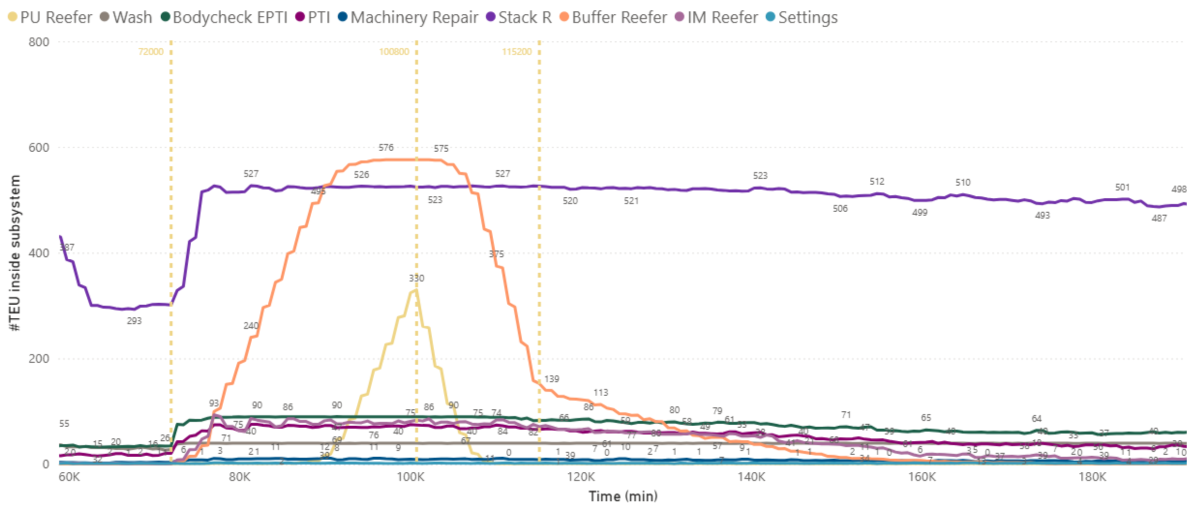

Figure D.6: Scenario 1: Occupation subsystems (reefer) setting 1

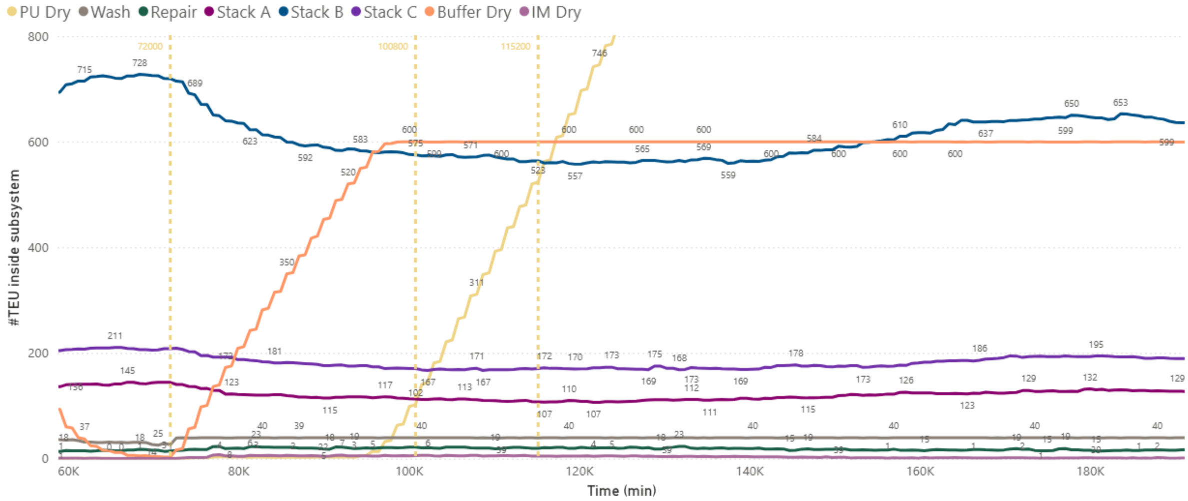

Figure D.7: Scenario 1: Occupation subsystems (dry) setting 2 OD

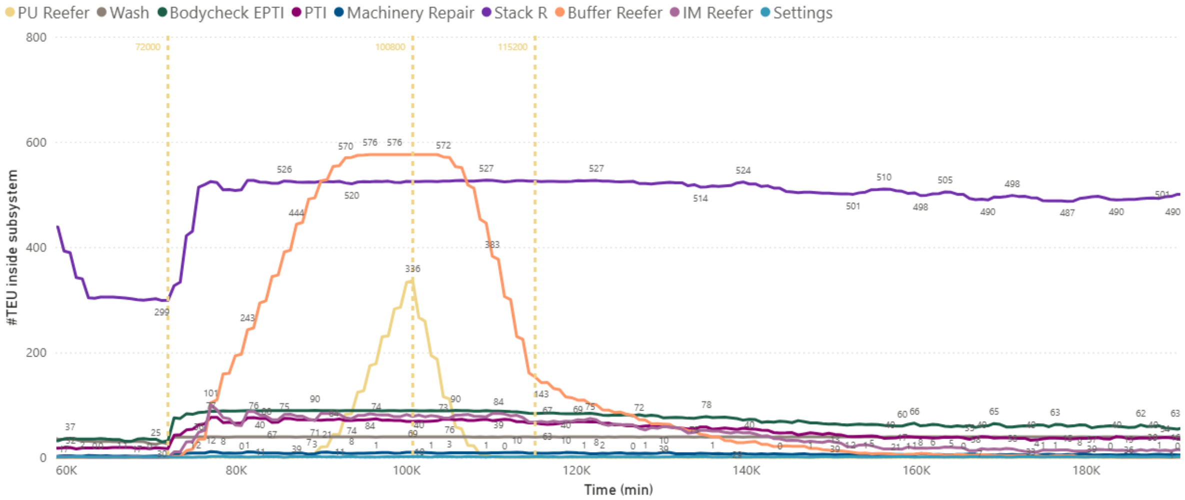

Figure D.8: Scenario 1: Occupation subsystems (reefer) setting 2 OD

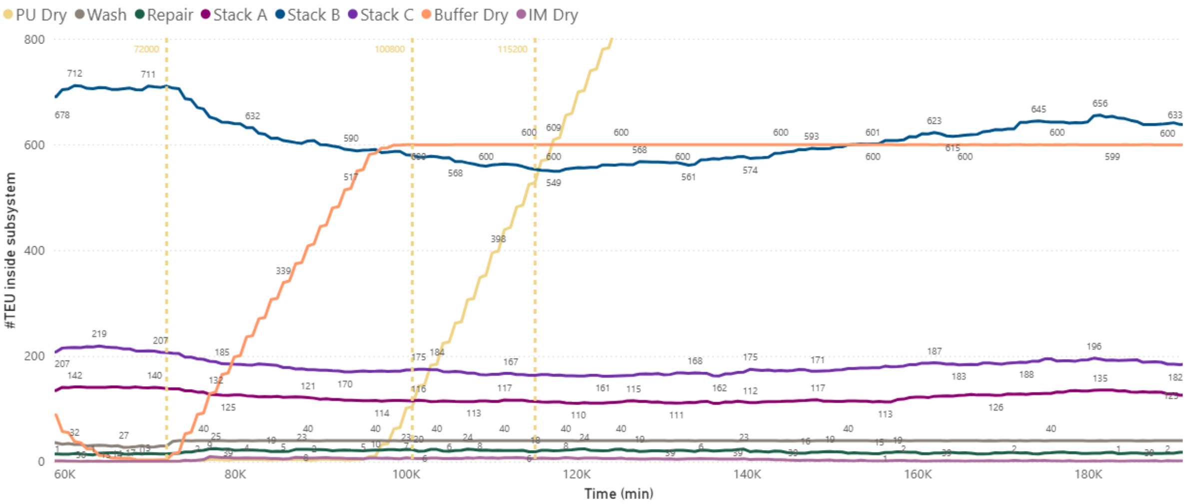

Figure D.9: Scenario 1: Occupation subsystems (dry) setting 2 C

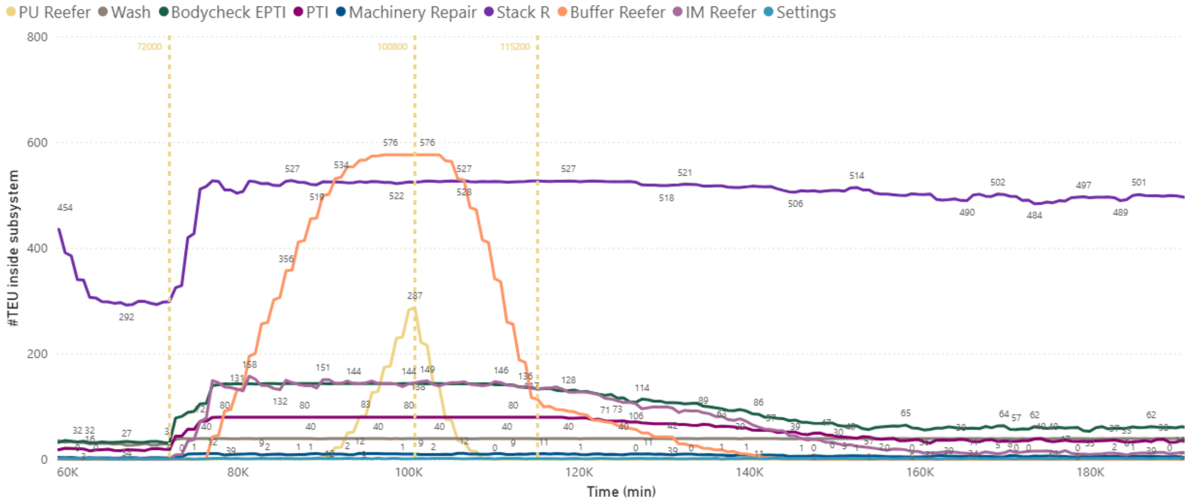

Figure D.10: Scenario 1: Occupation subsystems (reefer) setting 2 C

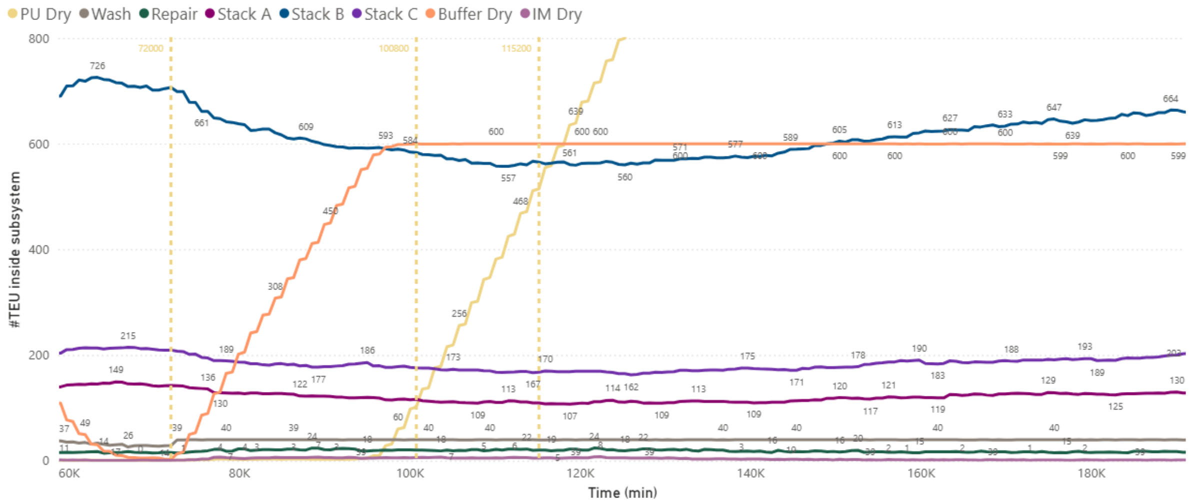

Figure D.11: Scenario 1: Occupation subsystems (dry) setting 3

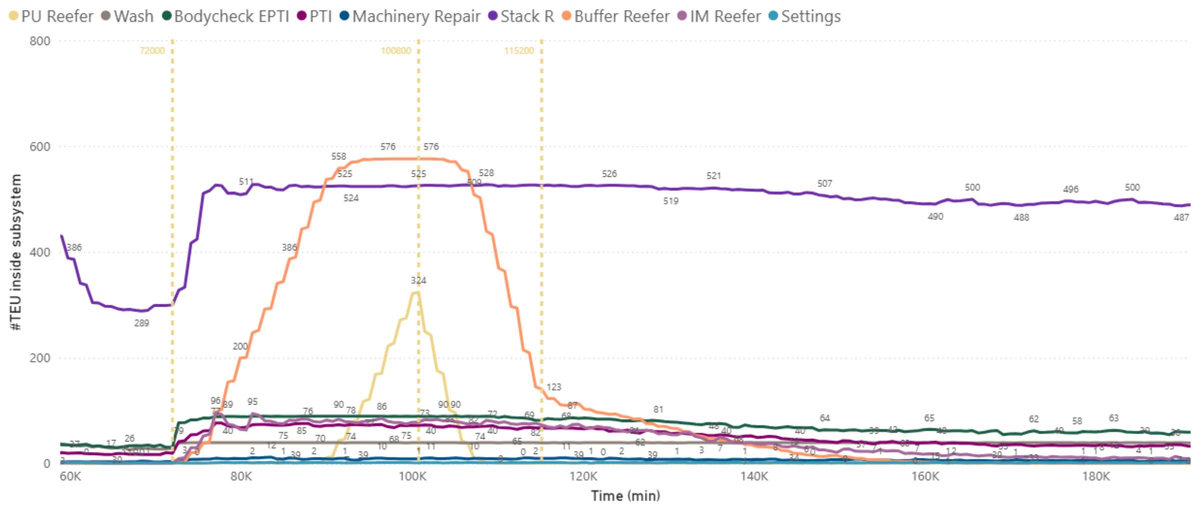

Figure D.12: Scenario 1: Occupation subsystems (reefer) setting 3

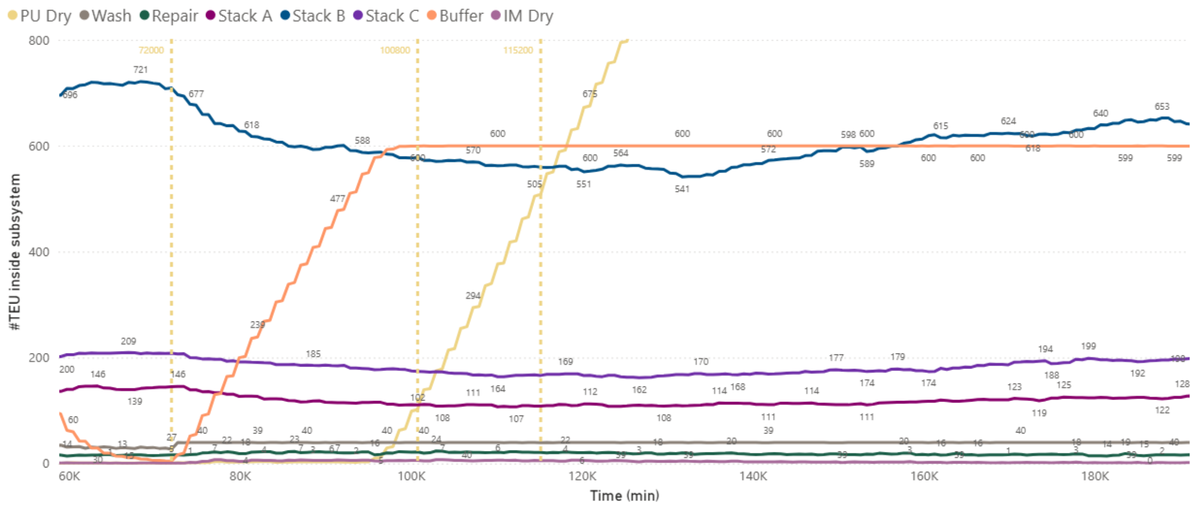

Figure D.13: Scenario 1: Occupation subsystems (dry) setting 4 OD

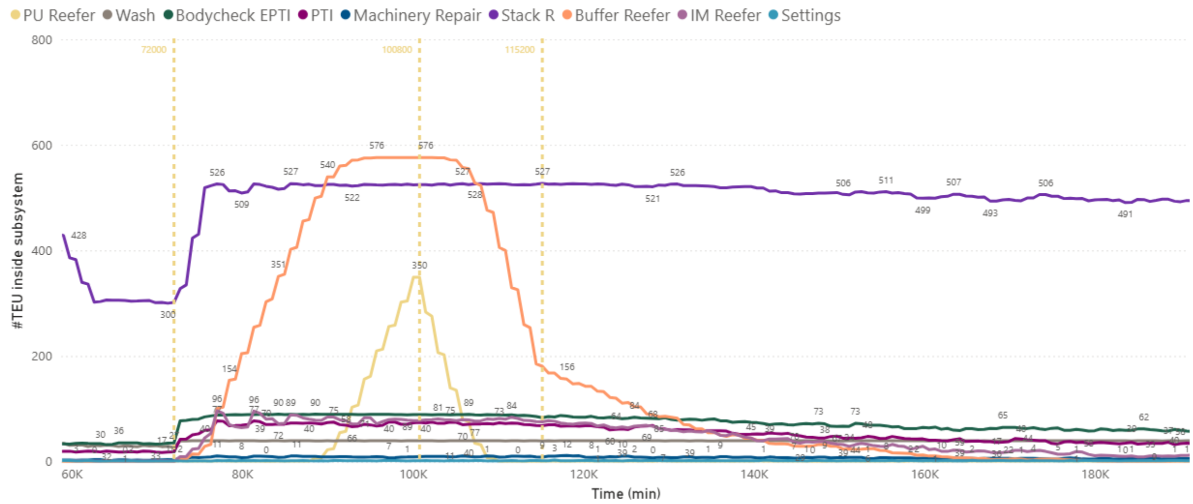

Figure D.14: Scenario 1: Occupation subsystems (reefer) setting 4 OD

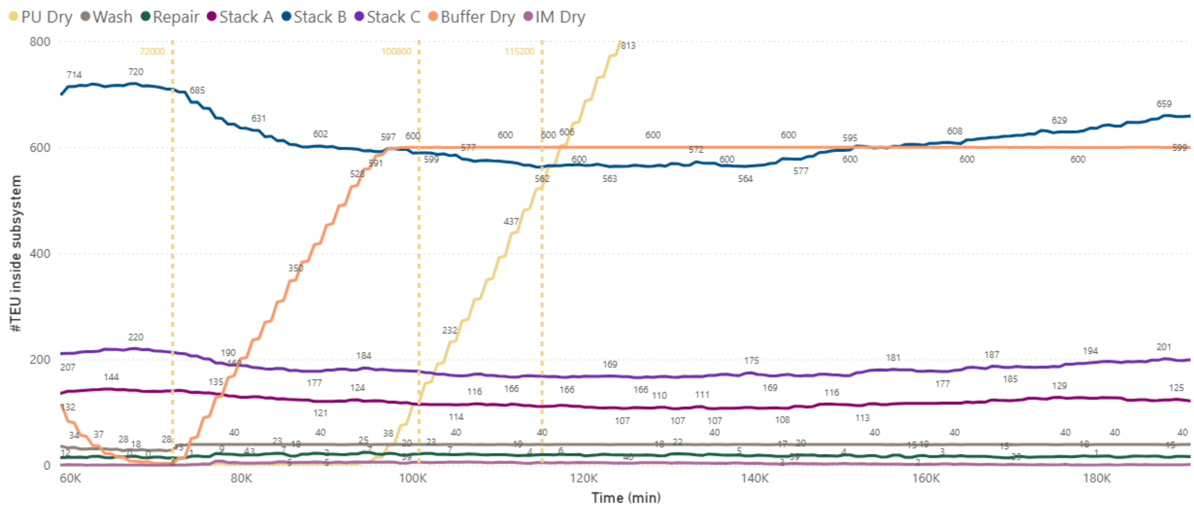

Figure D.15: Scenario 1: Occupation subsystems (dry) setting 4 C

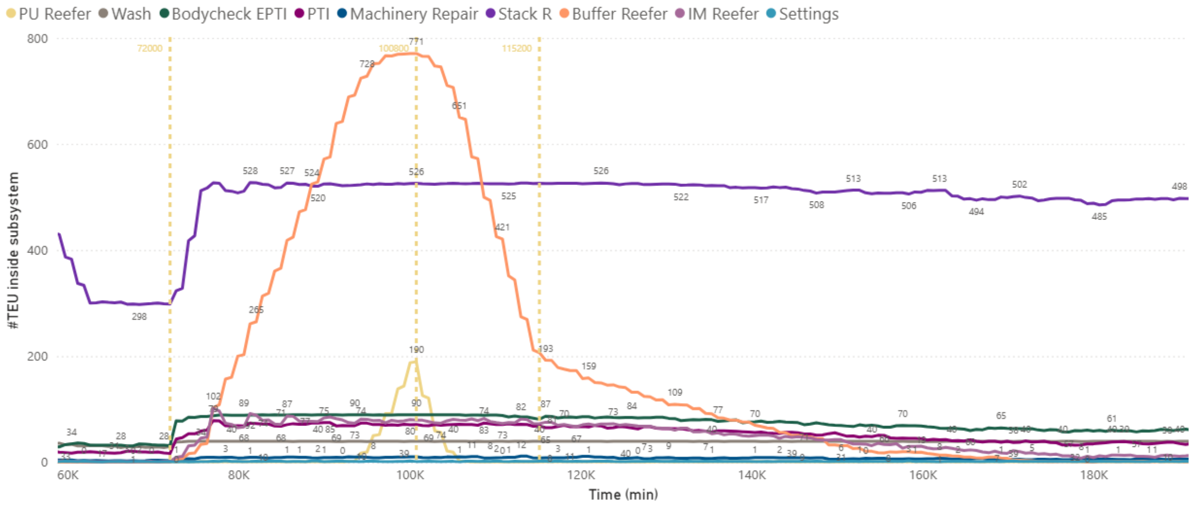

Figure D.16: Scenario 1: Occupation subsystems (reefer) setting 4 C

D.3. Scenario 2: Occupation visualisations

This section highlights all occupation graphs for the alternative settings that were not presented in the main report. Showing three different visualisations, which represent the occupation values of dry subsystems throughout the simulation.

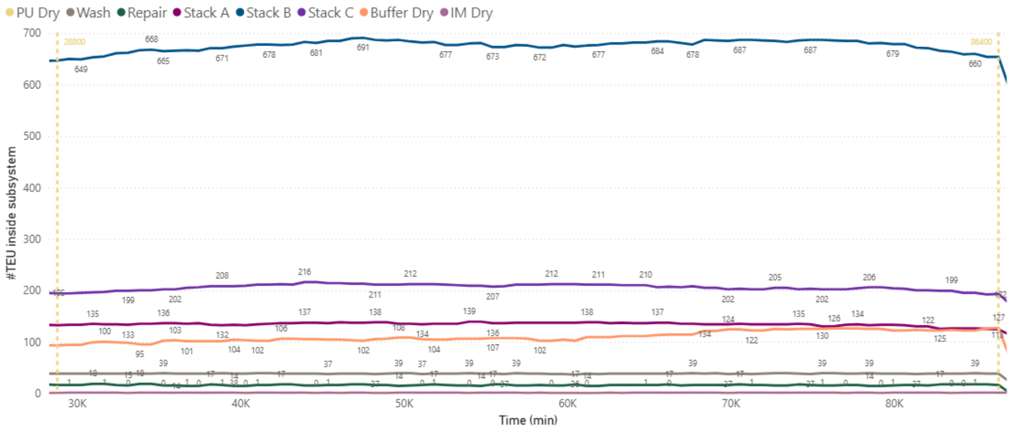

Figure D.17: Scenario 2: Occupation subsystems (dry) setting 2 C

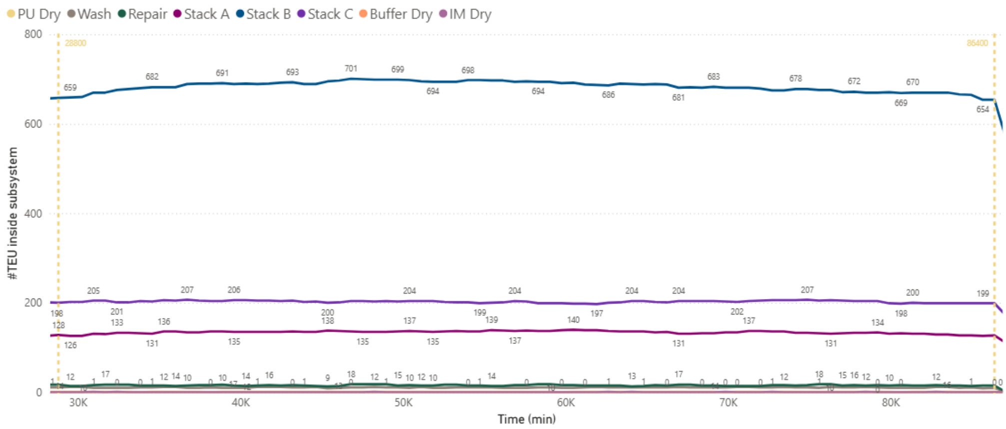

Figure D.18: Scenario 2: Occupation subsystems (dry) setting 5

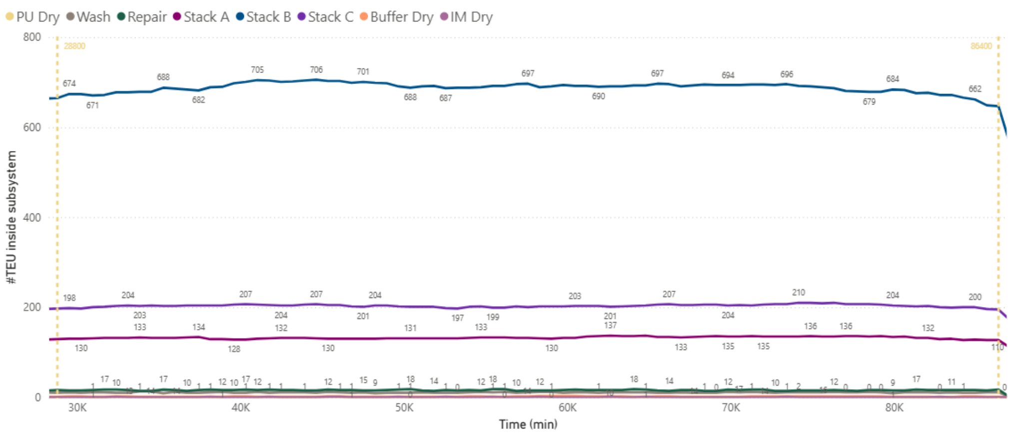

Figure D.19: Scenario 2: Occupation subsystems (dry) setting 6

D.4. Scenario 4: Occupation visualisations

This section highlights all occupation graphs which were not presented in the main report. Showing four different visualisations, which represent the occupation values of dry subsystems throughout the simulation.

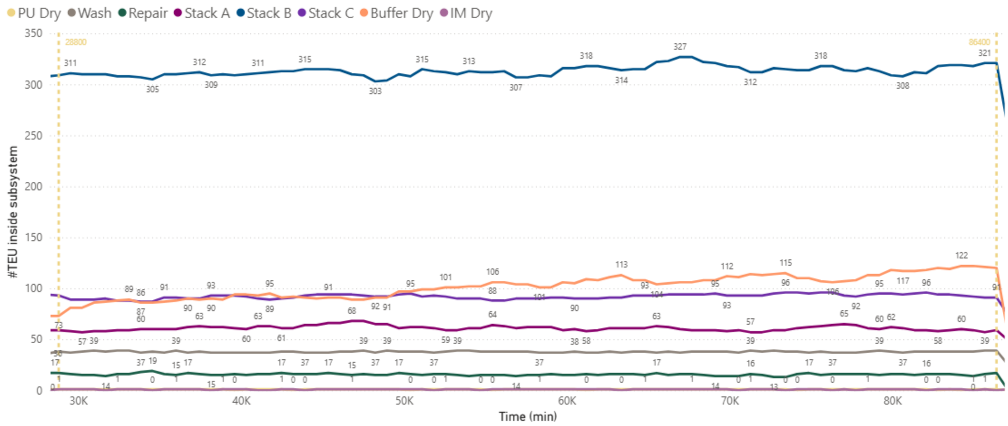

Figure D.20: Scenario 4: Occupation subsystems (dry) setting baseline

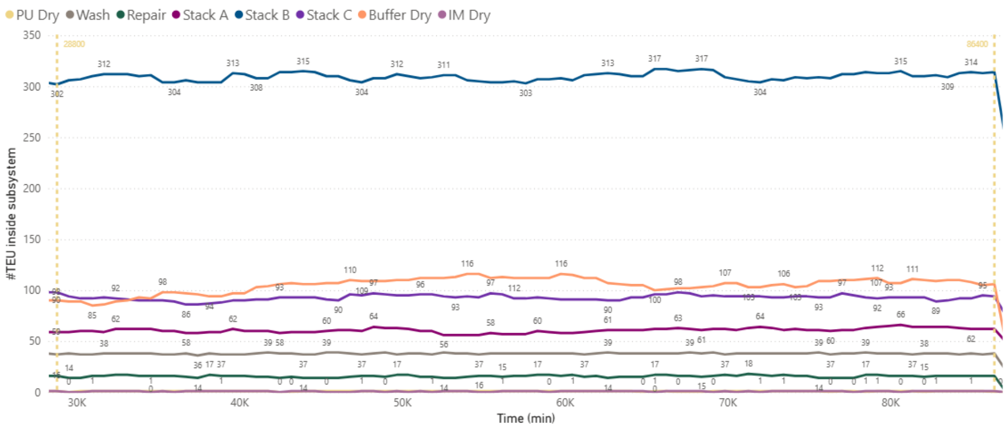

Figure D.21: Scenario 4: Occupation subsystems (dry) setting 2C

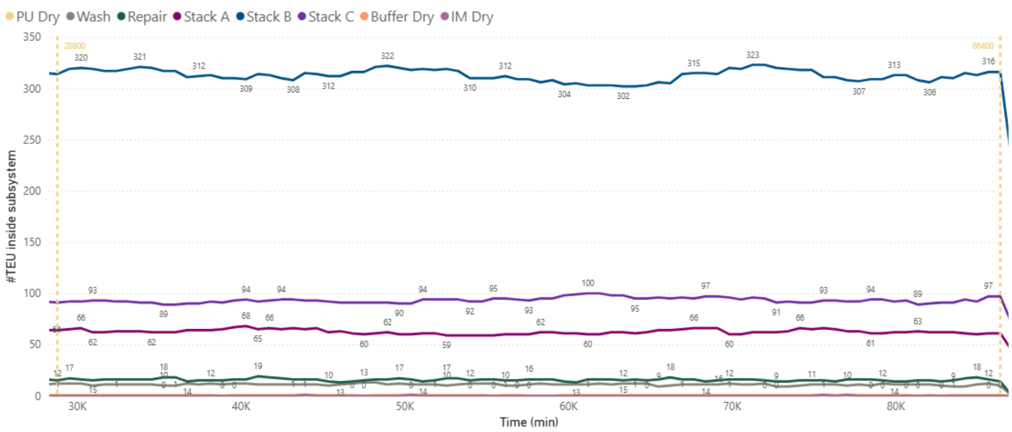

Figure D.22: Scenario 4: Occupation subsystems (dry) setting 5

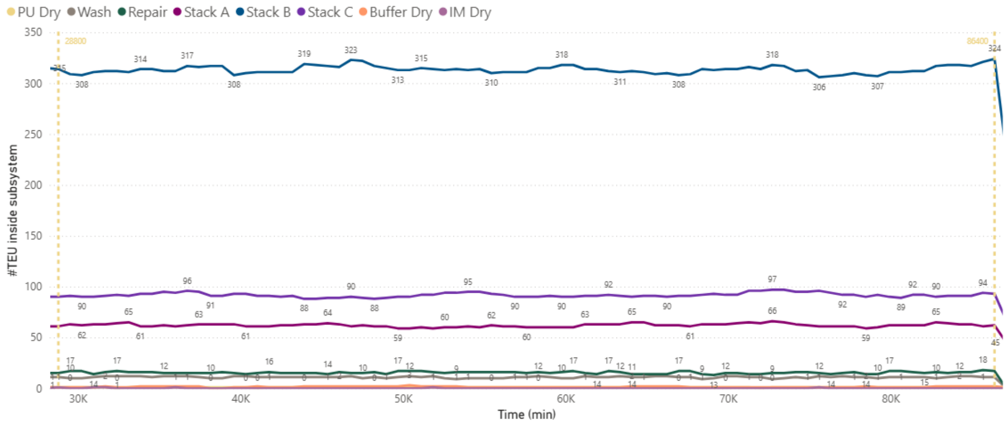

Figure D.23: Scenario 4: Occupation subsystems (dry) setting 6