POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Multi-criteria Analysis of Internal Cross-docking Operations

JOHNNY ALBERTO PAREDES SEMINARIO
Département de mathématiques et de génie industriel

Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise en sciences appliquées*
Génie industriel

Août 2020

POLYTECHNIQUE MONTRÉAL
affiliée à l'Université de Montréal

Ce mémoire intitulé :

Multi-criteria Analysis of Internal Cross-docking Operations

présenté par **Johnny Alberto PAREDES SEMINARIO**
en vue de l'obtention du diplôme de *Maîtrise en sciences appliquées*
a été dûment accepté par le jury d'examen constitué de :

Martin TRÉPANIER, président
Jean-Marc FRAYRET, membre et directeur de recherche
Luc ADJENGUE, membre et codirecteur de recherche
Maha BEN ALI, membre

DEDICATION

This paper is dedicated to forklift operators around the globe,
may the general public value your relentless efforts
in enabling global supply chains to succeed.

ACKNOWLEDGEMENTS

Special thanks to the **CILCAD** and **Laval University** for being instrumental in the development of this research project, to **CIRRELT** and its associates for providing ongoing inspiration, to **Groupe Robert** for their open-mindedness, collaboration and support, to my research directors, **Jean-Marc and Luc** for their patience and coherence, and to my favourite coffee shop, *Expressions du Monde*, for providing me a roof under which creativity could flow.

RÉSUMÉ

Cette étude vise à améliorer la performance environnementale et logistique des opérations de manutention dans un centre de transbordement (soit *cross-dock*). L'évaluation des opérations internes considère ainsi plusieurs mesures de performance, d'où s'explique la désignation *multicritère*. L'installation étudiée appartient à une organisation qui fournit des services de transport en charge partielle (LTL), desservant un vaste réseau d'approvisionnement. À l'intérieur du centre de transbordement, toute la manutention est accomplie par des caristes en utilisant des chariots élévateurs à gaz naturel comprimé (GNC).

Premièrement, une revue de littérature a été complétée dans l'intention de déterminer une façon systématique de caractériser et d'étudier des centres de transbordement. En conséquence, une grille de caractérisation fondée sur six critères a été dévelopée pour décrire qualitativement une installation de transbordement. Quoi que la plupart des études en transbordement optent pour des modèles de recherche opérationnelle, la recherche scientifique propose que les modèles de simulation à évènements discrets soient aussi des outils appropriés et propices pour l'analyse de ce type d'installation - malgré leur faible popularité dans le domaine. À la suite de ces repères, un modèle de simulation par agents a été développé pour cette étude, inspiré par des modèles existants d'entreposage, ainsi que par des techniques de modélisation traditionnelles adaptées au milieu industriel. Également, une analyse de l'état initial des opérations de transbordement fut complétée avec l'intention de définir les limites du modèle, ses entrants et les interactions entre ses agents. Finalement, une validation statistique du modèle de simulation fut effectuée afin de déterminer le nombre approprié de réplications.

Ensuite, le modèle final fut utilisé pour l'expérimentation des différentes stratégies d'affectation des portes du centre de transbordement. Ces expériences avaient deux variables de réponse: la consommation de GNC (en mètres cubiques) et la distance couverte par la flotte de chariots élévateurs (en pieds). De plus, les émissions équivalentes de CO_2 furent aussi calculées (en kilogrammes équivalents de CO_2). Quant aux facteurs expérimentaux, les expériences se basent sur des variations dans l'affectation des portes de l'installation aux activités de manutention (chargement, déchargement) et aux zones de distribution. Dans d'autres termes, chaque expérience est axée sur une combinaison unique d'affectation des portes, désignée comme *solution d'affectation*. Puisqu'une quantité incommensurable de solutions sont possibles, une heuristique fut créée dans le but de générer des solutions d'affection d'après la distance minimale entre les portes et les flots de palettes par zones d'origine et de destina-

tion. En outre, des affectations aléatoires et un scénario sans aucune affectation furent aussi considérés.

Les résultats expérimentaux confirment que des changements dans l'affectation de portes peuvent réduire la consommation totale de combustible et les déplacements des appareils de manutention, ainsi que les émissions de CO_2. En outre, cette étude met en évidence que l'empreinte environnementale des installations de distribution n'est point négligeable. L'approche multicritère et notamment la perspective environnementale deviennent ainsi pertinentes aux études en logistique interne. Or, une recherche plus approfondie serait nécessaire afin d'évaluer l'impact de l'affectation de portes dans tout le système de transbordement, au-delà des murs de l'installation.

Sommaire des résultats	Distance (ft)	GNC (m^3)	CO_2 (kg éq.)
Scénario sans aucune affectation	531 663	745	1 432
Performance initiale	514 656	702	1 349
Meilleure solution d'affectation	489 673	626	1 203

ABSTRACT

The performance of internal material handling operations in an existing cross-docking facility is sought to be improved from both a logistic and environmental perspective. The facility studied consists of a transportation terminal serving a vast less-than-truckload (LTL) supply chain. Inside the cross-dock, all material handling is performed by forklifts fuelled by compressed natural gas (CNG). A review of the state of the art is conducted, from which a cross-dock characterization approach is outlined. Similarly, the literature reveals that discrete-event simulation, while generally under-looked, is an appropriate tool for the study of such transportation facilities. Accordingly, an agent-based simulation (ABM) model is developed in order to study the cross-dock. The model is influenced by existing warehousing models, as well as by traditional discrete-event modelling in an industrial setting. Moreover, a comprehensive analysis of the current state of operations was completed in order to define model boundaries, inputs and agent interactions. Then, the model was used to conduct experiments based on distinct door-assignment strategies, having CNG consumption and forklift distance as response variables. The generation of door assignments, conversely, was achieved by a heuristic based on the minimum distance between dock doors and pallet flow. The experimental results indicate that such door assignments do lead to a reduction in both response variables. Further study is, howbeit, required to assess the full impact of door assignments in the system, beyond internal boundaries.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ACRONYMS

TL	Truck-Load
LTL	Less-Than-Truckload
CDAP	Cross-dock Door Assignment Problem
MILP	Mixed Integer Linear Programming
PN	Particle Number
LNG	Liquefied Natural Gas
CNG	Compressed Natural Gas
ABM	Agent-based Modelling
CAD	Computer-aided design
NHPP	Non-homogeneous Poisson process
DOE	Design of experiments
OFAT	One factor at a time
ERD	Entity relationship diagram
EPA	Environmental Protection Agency

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

The contemporary supply chain is constantly challenged by an ever-growing demand of expedited shipments. Whilst transportation requirements evolve in complexity, distribution networks develop intricate and dynamic relationships. Fortunately, there exists a number of successful distribution strategies that enable organisations worldwide to excel in delivering goods to customers. Cross-docking, despite being rather recent, has gained significant popularity across a wide array of industries as a cost-effective distribution approach within increasingly synchronised networks. The study presented in this paper revolves around a cross-docking facility serving a less-than-truckload (LTL) transportation network. More specifically, the internal material handling operations of this facility are sought to be improved. Such improvement, howbeit, will be scrutinized from an environmental perspective. Namely, the main focus is the impact of material handling on green-house gas emissions. The present section introduces the reader to the notion of cross-docking, as well as presenting the specific setting and problematic of the study. Lastly, the research objectives are outlined.

1.1 Defining Cross-docking

Cross-docking is a relatively recent practice in supply chain management [9], though its popularity as a distribution strategy has sky-rocketed in recent decades. When compared to traditional distribution approaches, such as warehousing or direct shipping, cross-docking has consistently proved to yield noticeable reductions in space utilisation, vehicle fuel consumption and overall operational spend [1] . As a consequence, a wide variety of industries rely on cross-docking to satisfy their transportation needs. In spite of being a well-established industry practice, distinct and sometimes conflicting definitions of cross-docking abound.

In general, cross-docking is the process through which incoming goods are consolidated based on common attributes in order to be shipped together. Such process utilizes one or various facilities, customarily referred to as cross-docks. The most defining attribute is the destination zone or route; that is, goods sharing the same delivery route are consolidated together into one shipment. A series of distinct handling activities allow cross-docking facilities (cross-docks) to achieve economic loads [10]. These activities include both material handling activities (internal) and trailer shunting (external), as well as a plethora of possible value-adding activities. The perception of cross-docking as a process is paramount yet somewhat neglected. On that account, many definitions tend to revolve around facility considerations, such as shape, layout, internal flow, amongst others. More contemporary definitions, however, refer to cross-docking as a supply-chain wide process wherein synchronization of inbound and outbound flows is attained on a supply-chain scale [5]. Following this perspective, cross-docking acquires operational, tactical and strategic relevance. Thus, the delineation of the cross-dock facility itself becomes only the starting point to a much broader problematic.

Hence, cross-docking can be perceived as a process requiring the coordination of inbound and outbound flows through one or more facilities. The incoming truck trailers are normally handled by shunting operations prior to entering the cross-dock, allowing for more control on the throughout within the facility. Controlling the inbound flow of material commonly entails upstream visibility so as to prepare in advance for the arrival of goods. Shunting is usually performed by means of shunting trucks that place incoming trailers in designated areas around the cross-dock, a trailer yard. The trailers are halted at the yard until their contents are ready to be unloaded into the facility. After unloading, staging is performed, which involves internal material handling. Unloaded goods are either directly loaded onto an outbound trailer or stored temporarily in the facility. Such temporary storage can be accomplished with pallet racks or on the floor if stacking is possible. Moreover, other value-adding activities may be performed during the staging process, such as labelling, weighing, wrapping, amongst others. Thanks to staging, goods are grouped based on their common attributes, which are most often dictated by common delivery routes. In other words, goods sharing a common destination are consolidated together in an *economic load* so as to be loaded into the same outbound trailer, though other considerations may influence such grouping, like weight, volume or type of commodity. Finally, loading is the last step to cross-docking, though the wider process effectively ends upon final delivery.

1.2 Specific Industrial Setting

The study hereby presented is the result of a collaboration with an industry partner, showcasing the integration of both industry and academia in a common-goal project. *Groupe Robert*, based in Quebec, Canada, is a family-owned company specialized in supply chain, namely in distribution, transportation and logistics. An overview of their services will be provided prior to a detailed explanation of the specific setting relevant to this project.

As a reputed Canadian supply-chain service provider, *Robert* offers quite a diverse portfolio of services, which can be grouped into three main divisions. First, logistic solutions comprise supply chain partnership, as well as consultation and training services. In both cases, customers benefit from Robert's expertise in logistics. These solutions may include anything from fleet management to distribution strategies; their implementation being tailored to the customer's specific requirements with a varying degree of integration. Secondly, transportation services are at the core of Robert's reputability. These consist of truck-load (TL) and less-than-truck-load (LTL) transportation throughout Canada and most of the United States. Moreover, specialized and inter-modal transportation solutions are also offered. Last but not least, distribution centres are the third main division of Robert's services. As part of their distribution portfolio, value-adding services and dedicated warehousing are made available to customers thanks to an extensive network consisting of various state-of-the-art facilities [11]. The organisation's focus on network-oriented solutions is of utter importance to all three service divisions.

This study focuses on LTL transportation services and, consequently, a well-rounded understanding of Robert's LTL transportation network is paramount. In the case of Robert, less-than-truckload merchandise is virtually all palletized and transported by trailer trucks. The vastness of the LTL network spans the whole Canadian territory, extending to the contiguous United States as well. In order to effectively serve customers throughout such an extensive expanse of land, Robert's LTL network is, in practice, divided in twain: a local network and an extended one. The former includes facilities and transportation lanes within southern Ontario and Quebec, while the latter is the result of close collaboration with other LTL transportation service providers. These strategic partnerships allow the organisation to serve a large geographic area without extending their infrastructure beyond their local network. While several transportations lanes are handed to transportation partners, most of the goods transit through at least one cross-dock within the local network. These facilities allow for the consolidation of orders, synchronizing both inbound and outbound flows so as to honour the promised transit times. Eight cross-docks are operational 24-hours, 5 to 6 days per week. The most important facility, the "T04", is located in Boucherville, Quebec, adjacent to the company's headquarters. A schematic plan of the facility and its shunting yard is shown in Figure 1.1.

With the above-described setting in mind, this study revolves around Robert's main cross-dock: the T04. More specifically, the purpose is to characterize, measure and improve the operational performance of such facility. The T04 is exclusively dedicated to the flow of LTL merchandise and its operations are representative of other facilities. Not only is this cross-dock suitable for a comprehensive analysis but it has central importance within the LTL distribution network. There exist, howbeit, a plethora of possibilities when it comes to the study of internal operations. It is thus imperative to delineate a more concrete problematic to be addressed. The following section describes the various issues related to the operations in the T04.

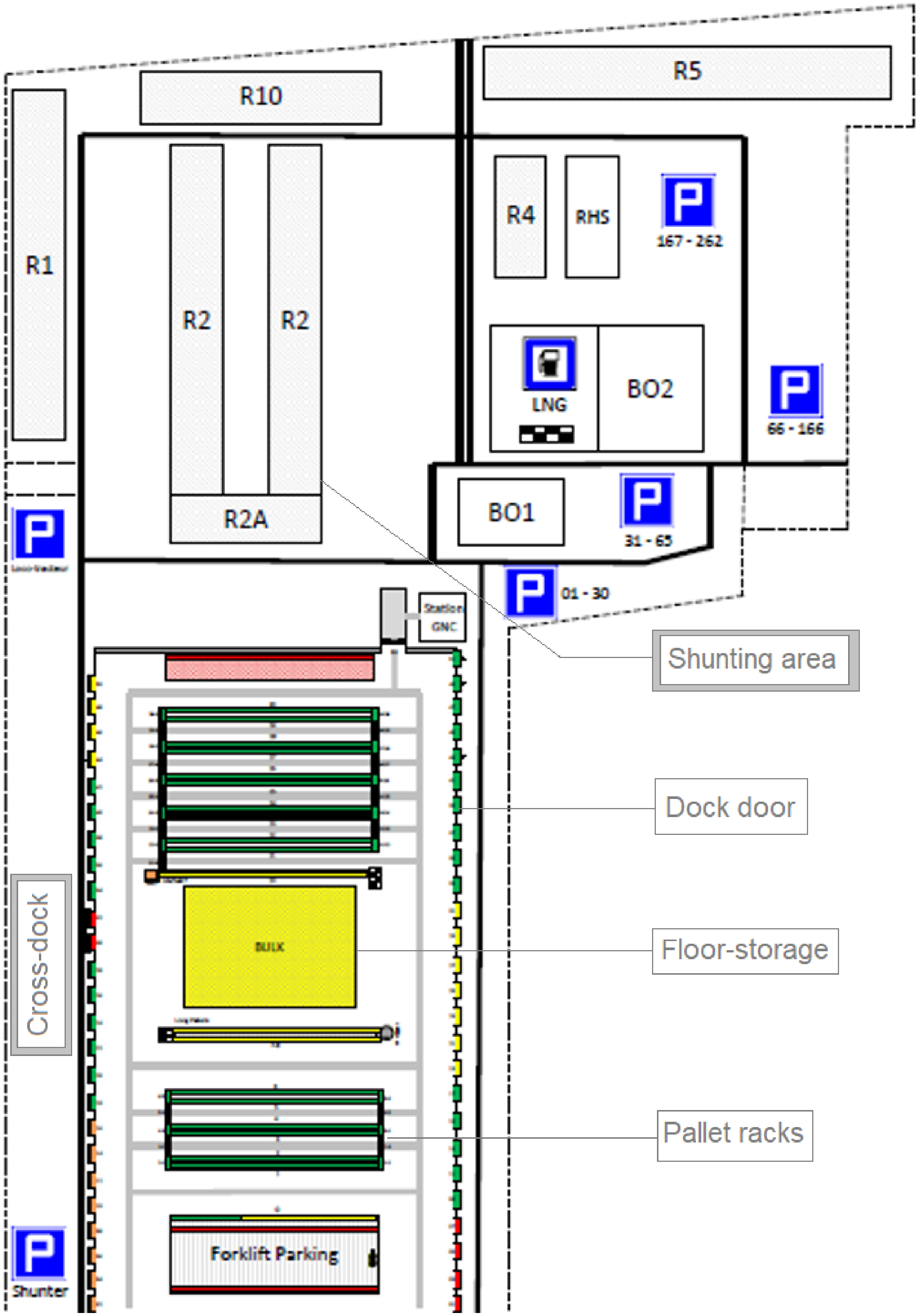


Figure 1.1 LTL-service Cross-dock and Shunting Yard (not to scale)

1.3 Problem Description

Generally speaking, cross-docking's main challenge is the coordination (or synchronisation) of both inbound and outbound flows of material within a facility of limited capacity. The facility or facilities wherein goods transit are constrained in terms of space available, layout, number of doors, workforce, amongst others. Time-related constraints also come into play. A successful cross-dock achieves such coordination while maximizing outbound trailer fill rate and minimizing handling time. Additional criteria include resource utilisation, cost and, in this case, environmental performance. How is the performance of Robert's facility limited by the aforementioned constraints?

Given the wide array of possibilities in terms of cross-docking problems, this project's focus is the result of close collaboration with the industry partner involved. At the initial stages, a series of issues were reported by the company itself. These were as exhaustive as they were ill-defined. Many of the reported issues stemmed from daily occupational interactions and were, in most cases, based on individual appreciations by workers having different roles within the organisation. These included forklift operators, floor managers, operations managers, amongst others. Through all levels of the organisation, though, recurrent themes appeared to be brought up. As previously outlined, cross-docking involves both shunting and internal material handling. At Robert, both activities take place in designated areas. Shunting, in particular, is executed based on loading priorities dictated by a third-party software. Through this specialized software, cross-dock managers determine the location and duration of inbound trailer shunting. Moreover, the shunting area is divided into zones used for priority management. While systematic shunting rules exist, they are not uniformly applied in the company and important variations in shunting practices prevail between facilities. Likewise, internal material handling tends to differ from cross-dock to cross-dock. The organisation has spent a considerable amount of resources in arranging the pallet racks, as well as in designating floor storage areas within the facility. Howbeit, the creation of material handling rules, together with the assignment of dock doors to zones and activities, has yet to be automated or supported by computer-based tools. The same applies to pallet rack configuration, forklift operator schedules and pallet loading. One important exception to this trend is the content of outbound trailers, which is decided via another software that assigns unloaded orders to outbound trailers based on compatible delivery routes. All pallets within the facility are handled by forklifts fuelled with compressed natural gas (CNG), chosen as a *greener* option to the diesel engines used in the past.

Furthermore, most of the operations workforce (forklift operators, floor managers and facility custodians) report a constant lack of space for the temporary storage of pallets in both possible staging options (rack or floor). Whether the lack of space is perceived or effective is difficult to determine without an extensive analysis of pallet flow and storage capacity. Additional reported problems include excessive forklift displacement during pallet staging, slow material retrieval from temporary storage and overall forklift congestion during peak hours. These issues appear to lead to delays in trailer loading, which are mostly observed during the morning work shift, between 6:00 AM and 9:00 AM. A distinct problematic seems to be pallet rack configuration. As previously explained, pallet racks and floor storage areas have been manually arranged to deal with the observed pallet flow. Unfortunately, these assignments are seldom respected and they rather serve as a guiding principle. Moreover, rack cells have variables dimensions (namely, height and width), which further burdens forklift operators when it comes to placing pallets in racks. Although the physical locations of the pallet racks are set, the rules for placing pallets in them are diffuse. Figure 1.2 displays the layout of pallet racks in the cross-dock, together with the designated floor storage areas. Of note, pallets tend to be stored in the alleyways between racks in spite of them not being assigned as floor storage zones. Last but not least, a more general issue is the use of separate software packages for different steps of the process: there are several computer-based tools utilised by the organisation. These software are used for different stages of the LTL service, ranging from order reception to the creation and modification of delivery routes. The main pitfall of this arrangement, however, is that separate computer tools result in distinct databases, with different parts of the cross-docking process being recorded independently. Not only does this lead to processes working in silo, but it makes it cumbersome to aggregate data and measure performance. The later has a organisation-wide impact since the generation and dissemination of performance indicators is deficient and limited to certain levels of the organisational hierarchy.

To sum up, the problematic surrounding the operations of the cross-dock is two-fold. On the one hand, the cross-docking processes and its associated activities have not been conceived in a unitary fashion, there being many exceptions and grey areas. This tendency is also reflected in the use of various separate software tools. On the other hand, the facility's layout seems to hinder both performance and responsiveness. Later in this paper, the validity of these problems will be scrutinized in order to determine how to improve the cross-docking operations while reducing the rate of green-house gas emissions associated to CNG consumption.

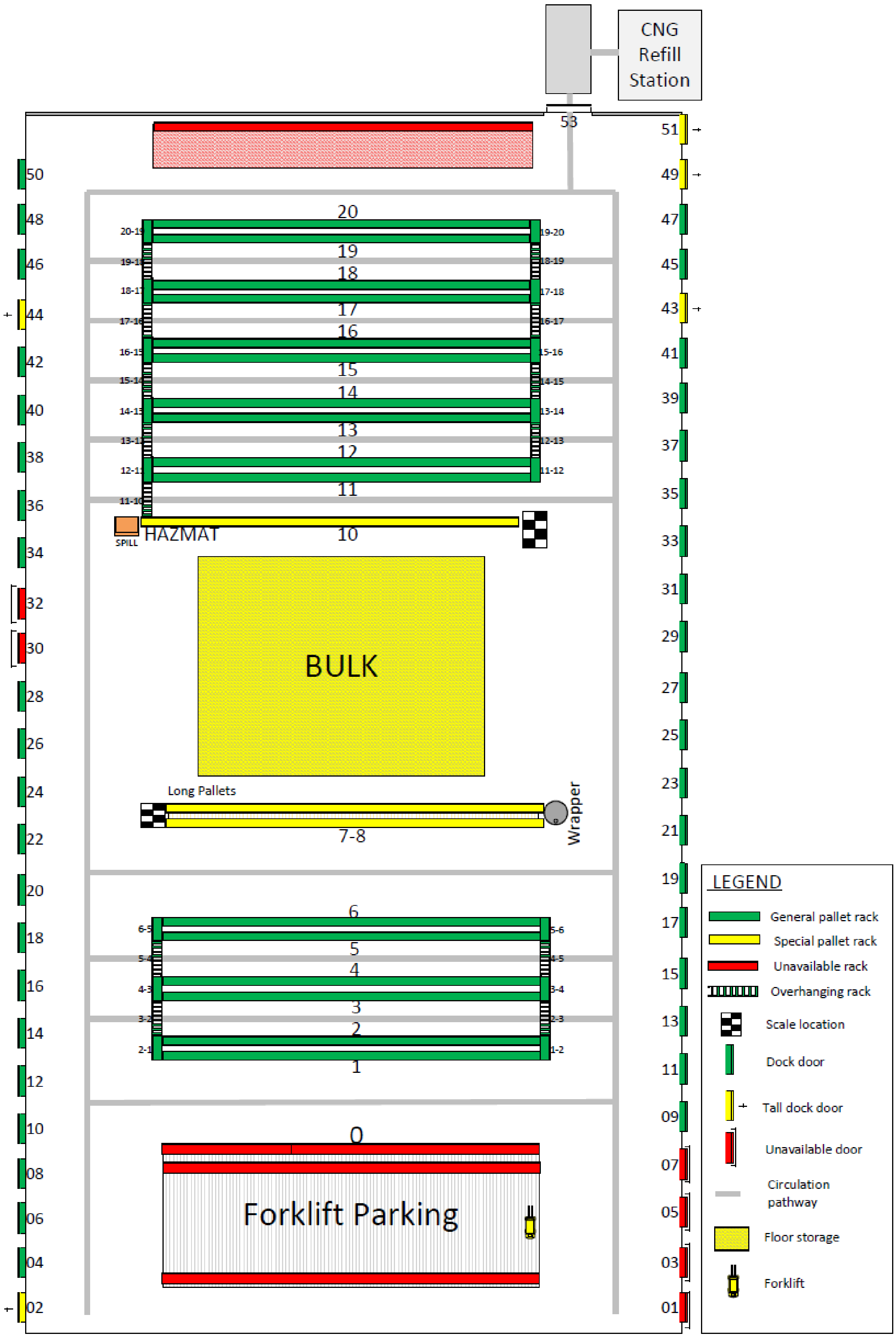


Figure 1.2 Cross-dock internal layout

1.4 Research Objectives

This study is concerned with the development and testing of a systematic multi-criteria method to improve the internal operations of a cross-dock. Such improvement effort is assessed from both a logistic and environmental viewpoint. Namely, its impact will be measured with respect to the consumption of CNG by forklifts; the associated average handling distance will also be examined.

1.4.1 General Objectives

The main objective of this research is to determine approaches to improve internal cross-docking operations. The assessment of such improvement strategies is also concerned with their impact on green-house gas emissions. Internal operations include all material handling activities from pallet unloading to loading onto outbound trailers, but exclude trailer shunting, which is executed in the shunting yard adjacent to studied cross-dock. As far as the environmental performance is regarded, this project focuses exclusively on the consumption of CNG by the forklift fleet utilised in the studied cross-dock. Trailer shunting, while potentially a bigger contributor to fuel consumption, is beyond the scope of this study. The internal focus of the project is based on the previously described problematic, though the company's business goals and the availability of process data have also delineated this focus. On that account, improvement of operations could be achieved by fine tuning the cross-docking process (e.g., storage areas, door assignment, priority management), proposing changes in resource allocation (e.g., forklift operators, forklift fleet, pallet racks, number of dock doors used) or modifying to the existing facility layout.

1.4.2 Specific Objectives

In order to improve internal cross-docking operations while reducing their environmental impact, three separate and sequential objectives have been defined. Firstly, a way to measure both the environmental and economic performance of the process needs to be established so that actual operations are not disturbed. Ergo, in order to take into account the intricate relationships between the various operational variables and constraints of a cross-dock, the use of discrete-event simulation appears to be the most convenient approach. Secondly, improvement alternatives need to be proposed to the organisation. These solutions should not only reduce CNG consumption but lead to an improved logistic performance within the facility. Moreover, they need not be prohibitively costly. Thirdly, the precise impact of material handling operations (and equipment) on green-house gas emissions is to be quantified.

This third objective is, potentially, the most challenging given that the organisation does not currently survey its fuel consumption in a systematic manner.

1.4.3 Contribution Impact

The internal operations of transportation terminals have been the subject of extensive research. Publications on the optimization of their operations abound, offering a myriad of different approaches and perspectives on material handling. The environmental impact of such operations is, in turn, rarely considered, as it will be elucidated in chapter 2. Thus, the main contribution of this project is the inclusion of environmental criteria in the study of internal logistics. Several kinds of material handling equipment run of fossil fuels, yet their emissions are rarely quantified. To date, most studies have been limited to fuel consumption by trucks or large industrial vehicles (such as shunting trucks). By veering the focus towards material handling equipment, an entirely new set of possibilities emerge. Has the environmental impact of transportation facilities been unfairly overlooked in the past? Both environmental and logistic performance could be enhanced by better utilising material handling equipment. While it is possible that the effect of material handling on green-house gas emissions is negligible, the originality of this project relies on assuming the opposite. In addition, the industry partner participating in the study will potentially benefit from an improved material flow and the associated reduction in fuel consumption, notwithstanding the savings in terms of time and workforce. Finally, the integration of environmental concerns into an industrial setting has social significance. Such an innovation may help guide further research towards environmental awareness, which is increasingly urgent, critical and relevant to all scientific initiatives.

1.5 Research Structure

The fulfilment of the above-described objectives relies on a specific methodological approach. The first stage entails the mapping of the current process behind cross-docking operations. Such mapping should follow a comprehensive analysis of both the LTL business and cross-docking practices throughout the organisation; that is, the mapping shall not be limited to the facility itself. The process must be mapped in detail so as to identify pitfalls, patterns and standard practices. Extensive analysis of available business data is also of utter importance to the mapping phase. Not only are there several databases readily available but data analysis will be key in narrowing down the scope of the problematic at the facility. The second stage of this project involves the development of a discrete-event simulation model that replicates the functioning of the studied facility. Given the plethora of complex and dynamic interactions that arise in a transportation terminal, the simulation model will be of mixed nature, both agent-based and triggered by discrete events. The resulting simulation model will then be validated through statistical analysis. Most importantly, its functioning will be confronted to the real system by means of the data extracted during mapping. Following model validation, cost-effective approaches to improving internal operations will be identified. Such solutions should ideally be systematic in nature and are, in this case, based on a customized heuristic. Subsequently, the simulation model will be used to experiment with different improvement alternatives. At this point, the environmental and logistic impact of different strategies will be measured and compared. Finally, the solution that leads to improvements in both CNG consumption and logistic performance will be selected and proposed to the company. At this last stage, potential extensions to this study will be discussed.

CHAPTER 2 LITERATURE REVIEW

From an industrial viewpoint, cross-docking is an established logistic strategy implemented in a myriad of different industries. Conceptually speaking though, the theory behind cross-docking is far from uniform and consistent. As such, the existing theoretical framework is as vast as it is diverse. Few academic textbooks focus exclusively on this strategy and the existing reference books tend to revolve around the potential of cross-docking or its associated cost-savings, as well as the requirements for its successful implementation [4, 10]. Such texts also discuss the distinctive attributes of cross-docking when compared to more traditional distribution strategies, namely: direct shipping, milk runs and warehousing [1]. The latter is arguably a suitable starting point for this discussion, given that warehousing and cross-docking are inherently intertwined, as shown in Figure 2.1. Both share the traditional functions of receiving and shipping, yet they differ in their approach to material handling. Warehouses customarily require long-term storage and subsequent order picking activities. Cross-docks, in turn, replace both activities by **staging**, which includes sorting, temporary storage (usually less than 24 hours) and order consolidation. The replacement of time-intensive warehousing functions yields considerable savings in time, resources and cost. A schematic representation of the cross-docking process and its unique attributes is included in Figure 2.2. On the account of its distinctive features, how have cross-docks been characterized and compared to one another by the existing literature?

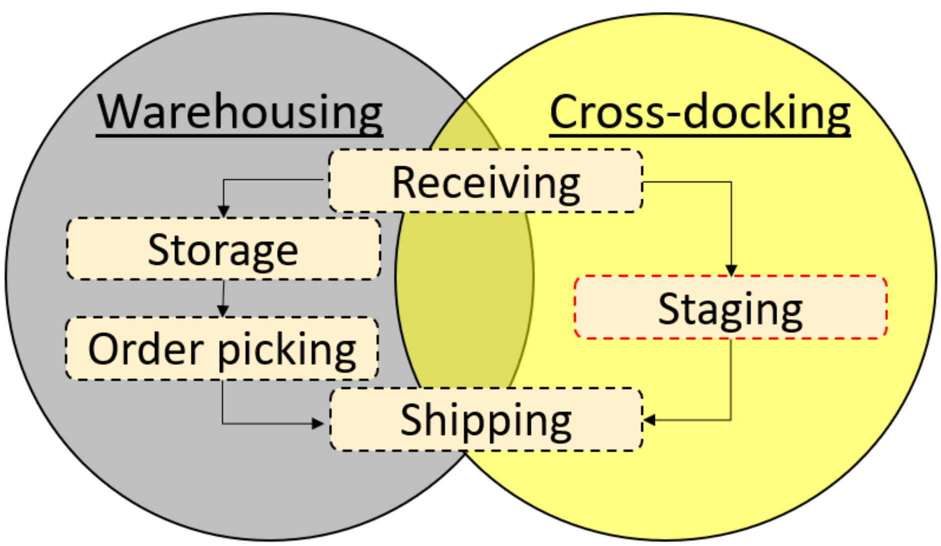


Figure 2.1 Warehousing and Cross-docking compared [1]

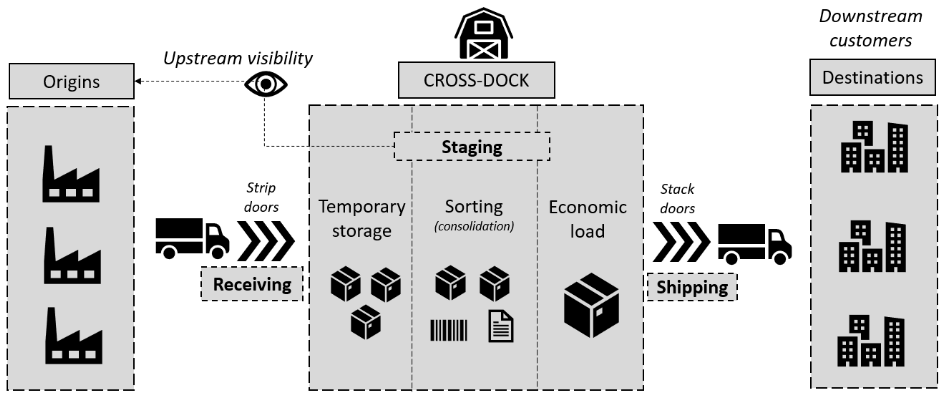


Figure 2.2 The cross-docking process [4, 5]

2.1 Characterization and Cross-docking Problems

As previously mentioned, research on cross-docking is quite diverse and widespread. Amongst the plethora of published studies, two of the most recurring themes are the characterization of cross-docking facilities and the classification of cross-docking problems. The former provides a valuable framework for the analysis, comparison and overall understanding of cross-docks, while the latter is related to performance measurement and improvement of operations. Both type of studies, howbeit, frequently overlap with an assessment of the state of the art, which on itself represents a great starting point for further research endeavours.

As far as cross-dock characterization is regarded, different and somewhat antithetical approaches exist. First and foremost, cross-docks have been customarily defined by their layout; that is, their *physical characteristics*. These usually refer to the number of doors, the shape of the facility and the internal transportation system (manual or automated). Another related criterion is the type of freight handled within the facility. In the past, cross docks used to be mainly defined by the kind of commodities they handled or the business they serviced. This orientation, however, has been largely abandoned in favour of a wider process-oriented perspective. Consequently, criteria such as the *number of stages* (distinct handling activities) performed or the *type of network* wherein a facility operates have gained popularity. Similarly, the type of *destination assignment* (i.e. the moment at which the freight's destination is set) has also been identified as a defining feature of cross-docking. Following this line of thought, additional characterization criteria include *operational constraints* and *flow considerations*. Operations are constrained by the service mode: exclusive when dock doors are dedicated to one activity (unloading or loading) or mixed, as well as pre-emption policies, which indicate whether the interruption of loading /unloading activities is possible. The inclusion of additional value-adding activities in the process is also an operational constraint. The facility's flow, in turn, is defined by both its arrival and departure pattern, together with the possibility of product interchangeability, the availability of temporary storage and the internal resource capacity [1–3, 5]. Whilst some researchers favour some of this criteria against other, the wide range of possibilities in terms of cross-docking processes and networks calls for a holistic approach. Cross-dock characterization shall thus encompass a large set of characteristics instead of one or a few defining features, so as to avoid a reductionist portrayal of a complex and dynamic setting. Accordingly, the aforementioned criteria have been grouped in table 2.1, which aims at serving as a basis for detailed cross-dock characterization. Furthermore, defining a facility with respect to all six criteria simplifies its comparison with other facilities, well beyond the type of freight they may handle.

Table 2.1 Cross-dock characterization [1–3]

Criterion		Possibilities
Number of stages		Pure cross-docking (one touch)
		Single-stage (two touches)
		Two-stage (multiple touches)
Destination assignment		Pre-distribution
		Post-distribution
Network type	Single facility	Few-to-many
		Many-to-few (JIT)
		Many-to-many (LTL)
	Multiple facilities	Single layer
		Hub and spoke
Physical characteristics	Shape	**I**, L, U, T, H, E
	Number of doors	ϵ [2, 6, 8, 40, **50**, 200, 500]
	Internal transportation	Manual (flow through)
		Automated (distributed)
		Combination
Operation	Service mode	Exclusive (inbound, outbound)
		Mixed
	Pre-emption	Enabled or not
	Value-adding services	Performed or not
Flow	Arrival pattern	Concentrated
		Scattered (per truck / trailer)
	Departure pattern	Restricted (deadline)
		Unrestricted
	Product interchangeability	Dedicated to destination
		Interchangeability allowed
	Temporary storage	Limited
		Not allowed
	Internal resource capacity	Limited
		Infinite

Unlike cross-dock characterization, the associated cross-docking problematic is definitely more consistent and structured throughout the literature. Hence, cross-docking problems are typically assessed with respect to their planning horizon or their relation to the wider transportation network; although both the impact of time and network may be contemplated. The smallest time frame is that of operational or day-to-day problems, which relate chiefly to *scheduling*. The daily assignment of trucks to doors is, for example, one of the most common scheduling problems. Others include truck sequencing or scheduling, and its extension: truck-to-door sequencing or scheduling. On a slightly larger temporal scale, tactical problems are concerned with the *planning* of resources on a monthly or quarterly basis, dealing with the assignment of dock doors to loading or unloading activities (i.e. service mode), as well as resource assignment (workforce, fleet, amongst others). The largest planning horizon, nonetheless, is that of strategic problems, which are mostly limited to facility layout and tend to precede the *design* of the cross-dock itself [2, 3]. While all these problems can be studied individually, there is a large degree of hierarchical dependency between operational, tactical and strategic concerns, with researchers establishing different set of hypotheses to either simplify or mitigate such dependencies. Furthermore, more recent research showcases lateral dependencies between cross-docking problems, which refer to the relationship between individual facilities and the network wherein they function, considering other facilities and material flows. Network synchronization has thus become a major component of cross-docking problems, with impacts on design, planning and scheduling [5]. Network-wide problems are also extensive to all three planning horizons. Strategic network design includes, for instance, facility location and the determination of the number of facilities required. Similarly, tactical network-wide planning deals with transport capacity (fleet size) and the creation of transportation routes. Last but not least, network scheduling tackles vehicle routing and flow alignment. Not only is the above-described framework for cross-docking problems useful for rapid classification, but it also enables the novel researcher to identify both temporal (hierarchical) and network (lateral) dependencies that may impact the problem definition itself. Figure 2.3 summarizes the classification framework of cross-docking problems.

The existing literature has achieved quite a detailed and well-rounded definition of both the type of cross-docks and the problematic surrounding them. How do researchers formulate and deal with these problems? Most importantly, which approaches are favoured when it comes to solving them? The following section discusses these questions in detail.

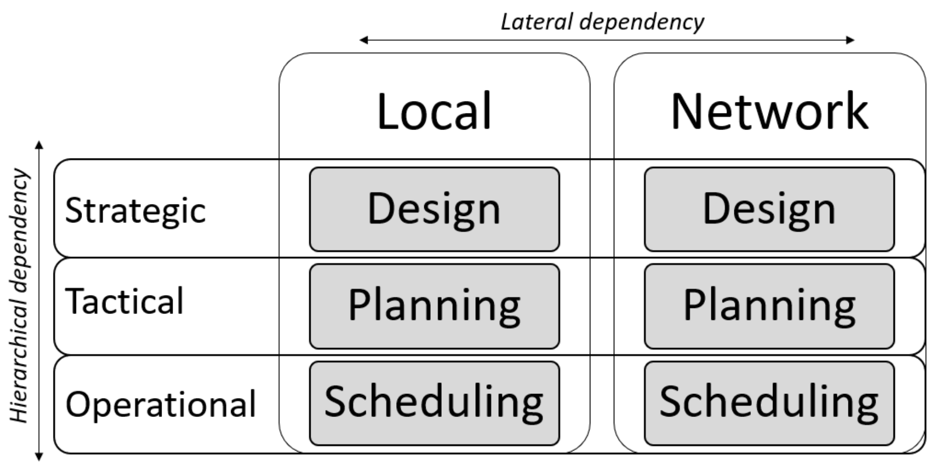


Figure 2.3 Classification of cross-docking problems [2, 3, 5]

2.2 Mathematical models

The preferred approach for the formulation and resolution of cross-docking problems is, by far, deterministic methods. Namely, most of the literature focuses on mathematical models aiming at the optimisation (maximization or minimization) of an objective function based on one or various decision variables, tied themselves to cross-dock performance. In spite of being optimisation-oriented, most models draw upon heuristics and constraint relaxation in order to yield feasible solutions, given the complexity of real-life cross-docking processes.

From the cross-docking problems described in the previous section, the vehicle (truck) scheduling problem and the door assignment problem are targeted most frequently, with the latter dominating the published research. These fall into both operational (scheduling) and tactical (planning) time horizons while being mostly local problems: applied to a single facility (refer to figure 2.3). Moreover, the cross-dock door assignment problem (CDAP) deals with service mode assignment, given that one of two activities (inbound loading or outbound loading) is assigned to a given dock door. Some authors perform door assignments in order to balance the overall workload with respect to capacity constraints, which is also described as the balancing of inbound and outbound flows [12, 13]. Others, conversely, assign trucks to doors with respect to performance-related decision variables, such as temporary holding cost [9, 14, 15] or distance travelled by material handling equipment (i.e. forklifts) [16, 17]. Of note, formulations differ in the how door assignment is defined: either inbound and outbound trucks (or trailers) are assigned to doors, or activities (loading or unloading) are assigned to them. The extent to which such formulations are used is a function of both the computational requirements of the model and the input data available. Different formulations are also compared in some publications [9,15]. Lastly, the great majority of the papers focus on a single optimisation problem. Nonetheless, some authors do propose an integrated resolution approach for both truck sequencing (scheduling) and door assignment [9].

All of the aforementioned deterministic models have been formulated as either integer or mixed-integer linear programming (MIP or MILP) models. While the authors do succeed in resolving the proposed mathematical formulations, they either reach sub-optimal solutions with heuristics or simplify the model through constraint relaxation. Whenever heuristics are explored, sub-optimality is reached without compromising the set of constraints proper to the model. Moreover, well-known algorithms, such as particle swarm, must be tailored to the specific problem on hand. Such resolution approaches are often unavoidable given the computational requirements of cross-docking models. Namely, a great number of binary or integer variables must be considered for individual door assignments. The average number of doors in a cross-dock is 50 [1] and most assignment algorithms have pair-wise exchange as a starting point. In the case of constraint relaxation, these are often based on hypotheses established prior to model formulation. For instance, product mix may be simplified to a single flow so as to ease the calculation of total distance or total holding cost. Similarly, seasonal or daily schedule variations are often omitted in order for inputs to be unique. While the existing cross-docking models are exceptional in terms of formulation, their applicability to real-life situations is limited. Only a fraction of the studied literature has been developed in an actual facility [13]. What's more, many of the models rely on generated data instead of drawing their inputs from industry databases.

Mathematical modelling provides a valuable outlook on the diversity of cross-docking problems. The published research is extensive in defining relevant performance measures and conceptualisations of inbound and outbound flows within a cross-dock. Unfortunately, the main shortcoming of deterministic methods is that they lead to infeasibly cumbersome models that require tailored heuristics. Their applicability is thus limited. The wide gap between academic research and industry is also addressed by papers discussing the current state of the art of cross-docking [3, 5]. Fortunately, there is an existing alternative to mathematical programming that allows for more realistic models: simulation.

2.3 Simulation models

An alternative to computationally cumbersome mathematical models and tailored heuristics is discrete-event simulation. While this technique has been gaining popularity in the recent decade, it is not yet the preferred orientation for research aiming at cross-dock improvement. Simulation models, nonetheless, are advantageous as they can capture the complexity and dynamic nature of interactions both around and within a transportation facility. The studied literature has been selected with respect to internal operations of transportation terminals, which are often neglected since studies on vehicle routing are favoured.

The earliest simulation study concerned with a transportation facility analogous to a modern cross-dock dates back to 1983. Although it might appear recent, contemporary data extraction, storage and analysis tools were neither developed not widespread at this time. In spite of these limitations, the proposed simulation model successfully replicates the functioning of a LTL general-commodity transportation terminal. Not only is the author an authentic pioneer in the field, but he is quite innovative as research thus far had disregarded internal operations in distribution terminals. Additional contributions include the generation and standardisation of shipment data, as well as the development of a heuristic for door assignment to minimize transit time [18]. Even though this particular simulation method may be outdated, its value lies in the applicability of this technique to systems hinged on material handling and temporary storage. A more recent publication tangential to cross-docking focuses on staging in particular. Three alternative configurations of staging queues are proposed and compared through a discrete-event simulation model so as to maximize throughput in a theoretical material handling and transportation system [19]. The staging phase is common to most distribution centres, warehouses and cross-docks alike. It takes capital importance in the latter case, though, as sorting, temporary storage and consolidation are pivotal to cross-docking operations.

Both of the above-described simulation models represent significant advancements in the applicability of simulation to transportation terminals, although both describe theoretical facilities. Simulations of real-life cross-docks are unfortunately uncommon as most researchers study either warehouses or distribution terminals with a varying degree of cross-docking taking place within them. Some studies also use simulation to scrutinize the validity and advantages of turning a facility into a formal cross-dock [20]. In this context, the gains associated with the consolidation of goods into an *economic load* through staging are measured with respect to various performance indicators, such as throughput time, capacity utilisation and fill rate of outbound loading units. Beyond isolated case studies, though, the development of a framework for the modelling of a generic cross-dock is ongoing [21]. The existing guidelines confirm that simulation is suitable, promising and largely unexplored for cross-dock modelling. Furthermore, the development of a specific framework for simulation of cross-docks is urgent as this type of terminals are distinct when compared to more traditional transportation facilities. Temporary storage is, for instance, time-constrained and handling activities are performed in a pre-defined sequence. Similarly, cross-docking performance measures differ from traditional warehousing indicators. Additional authors dwell more into these particularities, developing a simulation framework for LTL cross-docks [22]. Given that LTL terminals customarily handle heterogeneous commodities, an exhaustive account of model inputs is provided, together with the required resources, capacity limits and material handling specificities. Besides, a notable innovation is the introduction of a *logical entity* to replicate the functioning of the dock dispatcher. Such complex interactions, between dock staff and material flow, are yet to be integrated into existing simulation models.

All in all, simulation offers an important opportunity for the study and improvement of cross-docking operations. Theoretical studies have been preliminarily developed and guidelines have been outlined. The current literature thus serves as a framework for future research. Most remarkably, simulation models offer significant advantages when compared with deterministic methods.

2.4 Fuel Consumption

Throughout this literature review, a number of performance metrics relevant to cross-docking operations have been mentioned. Some pertain to time, others to distance, throughput or holding cost. None, unfortunately, consider the impact of cross-docking on fuel consumption or green-house gas emissions. The former, however, is a remarkably popular area of research, with fuel consumption of heavy-duty vehicles being reoccurring in research journals. Another recurrent theme in the published research is the comparison of different fuel alternatives, but mostly to minimize cost.

Prediction of fuel consumption is paramount to fleet managers. Accordingly, research is abundant when it comes to modelling the behaviour of heavy-duty vehicles, such as trailer trucks, together with the characteristics of the road and routes they transit. The result of such models is a speed profile that calculates different rates of fuel consumption with respect to vehicle parameters and road characteristics [23]. Determining the most cost-effective itineraries for a fleet of trucks has remained the main goal for this kind of studies. Researchers, howbeit, are increasingly veering their attention towards green-house gas emissions, which can be measured in several ways. Particle number (PN) has been used to measure and compare the emission rates of different types of fuel, such as gasoline, diesel, liquefied natural gas (LNG), compressed natural gas (CNG) or hybrid-electric light-duty engines. When comparing emission rates amongst fuel types, real-life driving conditions are derived from engine specifications and parameters, rather than from road characteristics. In general, CNG leads to the lowest emissions of green-house gases, particularly CO_2 [24]. Natural gas is well-known to be an environmentally friendlier alternative to traditional fuel, though the driving range associated to CNG is shorter to that of LNG. Following a technical and economic analysis of both fuel alternatives, CNG is more effective for shorter-distance transport [25]. On that account, it has been demonstrated that lighter two-wheeled vehicles are suitable candidates for CNG engines. For such vehicles, environmental performance can be defined in terms of the grams (or volume) of CO_2 emitted per distance (in m or km), usually as a function of the vehicle's speed or drive cycle [26]. Finally, guidelines for determining CNG consumption exist and are defined with respect to the cylinder storage efficiency. The latter depends on the cylinder's size and volume, the temperature and the pressure and can be used to extrapolate driving ranges [27].

All things considered, fuel consumption is a well researched subject. The impact of fuel consumption on green-house gas emissions has also become a significant area of study. The available literature is, nonetheless, mostly concerned with trucks, lighter vehicles tend to be given less attention. In spite of these shortcomings, the tools exist to extend fuel consumption studies to smaller vehicles and even to internal operations.

2.5 Conclusion

The literature provides a diverse assortment of approaches to cross-dock characterization. Similarly, the existing research deals with a wide array of problems, which have been clearly defined and classified. While some problems appear to be more prevailing than other (such as the CDAP), deterministic models have been predominantly favoured for their formulation and resolution. As previously stated, these entail the relaxation of real-life constraints. Moreover, they are computationally demanding and require custom-fit heuristics in order to yield feasible solutions. Another pitfall of mathematical models is that, by and large, they are not commonly developed in conjunction with the industry; that is, they are not applied to real-life facilities. Therefore, discrete-event simulation has emerged as a promising alternative and guidelines for cross-docking simulation models exist. Finally, the research discussed thus far blatantly neglects the environmental impact of cross-docking operations. Whilst the green-house gas emissions of trucks have been addressed by fuel-consumption studies, the environmental effect of internal facility operations (i.e. material handling) is yet to be quantified for a transportation facility.

CHAPTER 3 METHODOLOGY

In order to address the problems described in chapter 1, a simulation model has been developed to reproduce the internal operations of the studied cross-dock. Whilst simulation software has been established as an adequate and non-intrusive tool, the creation of a veracious model requires careful scrutiny and attention to detail. In this section, the theoretic framework used to develop such a model will be explained first. Secondly, the underlying cross-docking process will be made explicit through a comprehensive mapping of the current state of affairs. Following this analysis, the afore-described problematic will be questioned and confronted with real-life data. Thereafter, the model will be meticulously described in terms of general assumptions, system boundaries and, most importantly, data inputs. Similarly, the particularities behind its agent-based model (ABM) features will be outlined, together with the approach followed to calculate fuel consumption. Finally, the model will be statistically validated and an appropriate number of replications will be determined.

3.1 Simulation Framework

There are three main considerations surrounding the methodological approach followed. The implications of studying a real-life system are the most critical, as the application of simulation techniques to a real cross-dock is rather recent. Moreover, the peculiarities of cross-docks and the complex nature of such systems are key factors. Thirdly, the agent-based technique used to develop the model hereby described requires caution. In all three cases, existing frameworks have been consulted and adapted.

First and foremost, the cross-dock studied is a real facility with actual workers belonging to a large supply-chain organisation. Given this context, the simulation methodology followed must be suited to the industrial setting. Fortunately, a detailed framework exists [6] for the application and development of simulation models in industry. The former is comprised of a set of comprehensive guidelines adapted to the technical challenges of a real company. Most remarkably, eight phases for the successful deployment of a simulation model are defined, ranging from problem definition to the determination of the model life cycle. These steps are summarized in figure 3.1 and have been thoroughly pursued in this simulation endeavour. One key innovation of this approach is that a well-rounded study of the real system precedes the design of the conceptual model. Consequently, key data inputs, boundaries and assumptions are identified well before modelling begins. The clear delineation of a simulation project also serves as a bridge between the academic intent of this research and the company involved.

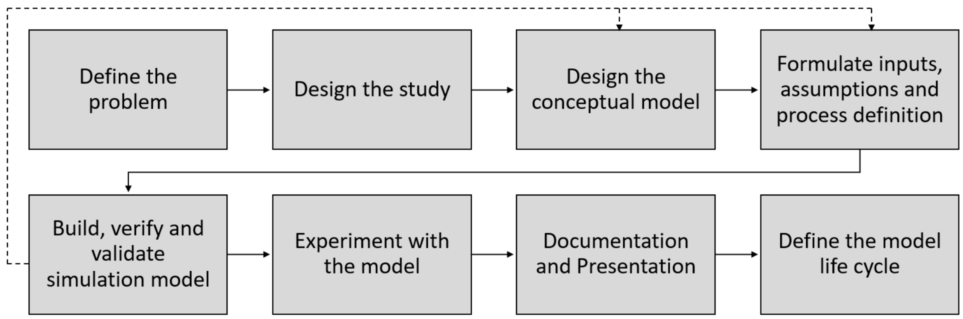


Figure 3.1 Phases of a simulation project in an industrial setting [6]

Once the various phases of the project have been defined, the particular features of a cross-docking facility must be evaluated, especially in regard to simulation. Fortunately, as explained in chapter 2, a general framework for simulating cross-docks exists [21, 22]. While the full extent of the cross-docking process encompasses pickup and delivery routes, as well as other facilities, there are eight moments relevant to the facility itself. First, the arrival of incoming vehicles (generally trucks) triggers the subsequent sub-process of shunting, which is customarily performed in the trailer yard adjacent to the cross-dock. Shunting may result in wait time: the goods (usually in trailers) are halted in the yard until the facility's capacity can accommodate them. After the wait, if any, trailers are docked in one of the available dock doors. At this moment, the assignment of doors to handling activities (loading or unloading) becomes a critical constraint. Other factors, such as specific attributes of the merchandise, may also influence door assignment. Once docked, the trailers are unloaded and internal cross-docking operations begin. The latter are referred to as *staging*, covering all movement of goods within the facility. Once the goods are ready and a compatible outbound trailer is docked, loading takes place. Finally, the outbound trailer is undocked and delivery ensues [22]. The simulation model would ideally include all of these moments, though the modeller may choose to exclude or under represent some of them. Shunting, for instance, should be meticulously modelled, though such a decision may prove cumbersome and time-prohibitive. If the specific movements of trucks in the yard are excluded, the model should still account for their influence on cross-dock performance [21]. Likewise, the workings of internal operations can be modelled in a simplified fashion, through a logical entity or *dispatcher*, instead of reproducing the various interactions between cross-dock directors, forklift employees and decision-support software [22]. Finally, the inclusion of appropriate data inputs is pivotal. The inputs listed below are considered indispensable for a functional cross-dock simulation model. Note that, in this case, the smallest load unit is an order; in other words, the orders are directly handled. In all cases, it is recommended to include randomness in these inputs by representing them with statistical distributions [21].

- Shipment (truck or trailer) arrival rate: based on actual shipping schedules
- Shipment origin
- Number of orders (load unit) in a shipment
- Order attributes: destination, weight and dimensions
- Time required for handling activities
- Velocity of material handling equipment, failure and downtime
- Resources and capacity: dock doors, workers, equipment
- Facility layout and internal distances

The above-described simulation framework considers a discrete-event model wherein the arrival of shipments trigger both shunting and staging. Although discrete events are essential in modelling transportation facilities and their complex system dynamics [22], ABM holds untapped potential in terms of reproducing such complex interactions. As explained before, cross-docking models often include a *dispatcher* or logical entity that deals with decision making. In an agent-based setting, howbeit, decisions can be made directly by agents that embody the distinct components of a cross-dock: forklifts, orders, trailers and doors. The resources and entities of the model thus become agents that interact with one another, as well as with the facility itself. The cornerstone of ABM is the specification of agents, environment and interactions [28]. Not only do these three aspects define the model, but they provide a greater degree of flexibility and customization. Accordingly, the simulation built as part of this study is a hybrid that integrates traditional discrete-event modelling with ABM.

There is an additional building block for this agent-based cross-docking simulation model. Many of the agent types are inspired from AnyLogic's reference model of a distribution center warehouse [29], though they have been significantly modified to reflect cross-docking. Using a warehousing model as a reference point is appropriate given the similarities between warehouses and cross-docks (refer to figure 2.1 in chapter 2). On the one hand, the reference model includes operations akin to cross-docking, such as unloading and loading. Order assembly, a traditional warehousing activity, is however replaced by staging. On the other hand, the source model simulates truck arrival and movements around the facility, which do not necessarily reflect shunting operations. These parts of the model have thus been omitted.

All in all, the methodological approach of this project combines discrete-event simulation and ABM to reproduce cross-docking operations. The project is also developed in collaboration with an industrial partner, with the framework being adapted to this circumstance. The creation and validation of the model will allow for the evaluation and comparison of different strategies aiming at improving environmental and logistic performance in the facility. These strategies may relate to door assignment, workforce allocation, internal layout, amongst others. Based on the steps shown in figure 3.1, mapping of the current state of the cross-dock has been carried out prior to modelling, focusing on current layout, activities and performance. The following section describes the current process in a top-down approach, starting with the larger LTL business process.

3.2 Current Process

The cross-docking process is vast, it reaches upstream up to pick-up and downstream into final delivery, spanning the whole distribution network. Although the importance of supply-chain synchronization cannot be understated, the entirety of the cross-docking process does not pertain to this study of a single facility. Throughout this section, the current state of operations in the studied cross-dock will be detailed.

At Groupe Robert, the LTL business represents one of the key logistic services, involving various departments within the organisation. Customer-service representatives, upon receiving a request, start the LTL process by scheduling a pick-up. Subsequently, the dispatch team, together with the cross-dock employees and truck drivers, execute the pick-up, cross-docking and final delivery. The coordination of pick-up and delivery routes is also performed. The process, thus, can be split in three distinct phases: pick-up, cross-docking (shunting and internal operations) and delivery. Virtually all goods handled are palletized and most pallets transit at least one cross-dock. That being said, a minority of pallets transit through more than one facility. Likewise, direct pick-up and delivery (without cross-docking) are rare. The LTL business process is portrayed in figure 3.2. The simulation model is concerned with the cross-docking phase, though the participation of truck drivers is not considered. Being familiar with the wider process allows the modeller to comprehend critical factors and hurdles. In this case, several software interfaces are used throughout the process, depending on the department involved. Consequently, communication between the various business functions is not smooth and operations tend to function in-silo. Thus, the integration of the different databases should be addressed by the organisation. In spite of such hindrance, the current business process succeeds in delivering goods within restricted deadlines. Following this look at the big picture, the T04 cross-dock itself will be examined.

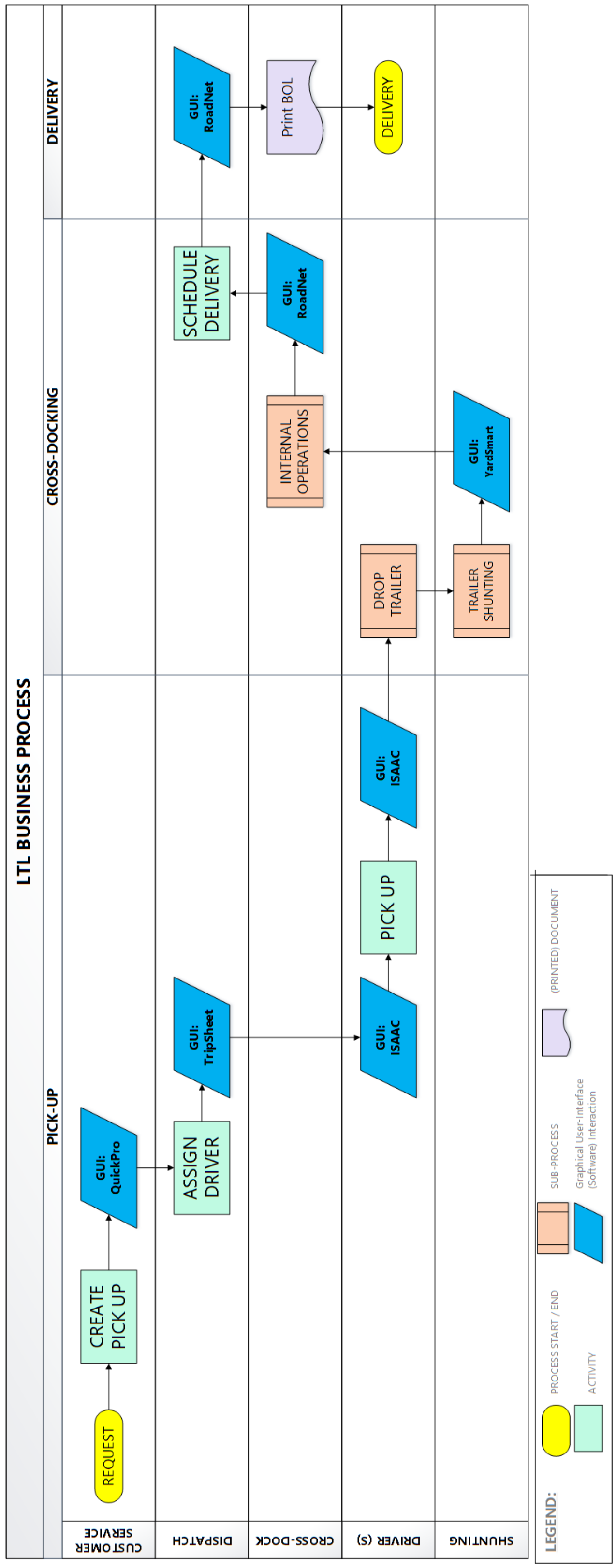


Figure 3.2 LTL business process flow chart

In chapter 2, a systematic approach to cross-dock characterization was laid out and summarized in table 2.1. Based on the criteria considered, the set of features defining the facility studied have been outlined in table 3.1. Not only do this set of characteristics define the facility, but they provide insightful information about its layout, operations and flow. Some of the latter include the destination assignment of pallets, which is predefined (pre-distribution) and restricts the consolidation of pallets into outbound trailers. Additional constraints are the limited storage capacity (either on defined floor sections or on pallet racks) and the limited internal resource capacity (fleet of forklifts). Furthermore, the multi-stage nature of material handling within the cross-dock means that the simulation model must combine loading, unloading, direct loading (transfer), temporary storage and value-adding activities (such as weighing). The diversity of handling activities is a source of complex interactions. Another critical factor is the service mode, or the door assignment mode, which significantly constricts operations. In the case of the studied cross-dock, doors can be assigned to any handling activity, resulting in a rather complicated system wherein forklifts move freely from door to door. Additionally, the scattered pattern of inbound and outbound trailer arrival further complicates internal operations. Given these conditions, ABM becomes an advantageous tool to reproduce such a dynamic and intricate system.

Table 3.1 Characterization of the studied cross-dock [1–3]

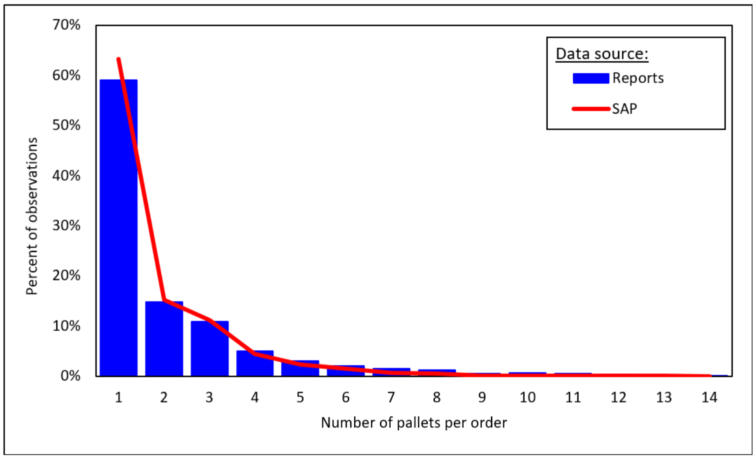
#	Criterion		Type
1	**Number of stages**		Two-stage (multiple touches)
2	**Destination assignment**		Pre-distribution
3	**Network Type**	Multiple facilities	Hub & spoke network
4	**Physical characteristics**	Shape	I
		Number of doors	~50
		Internal transportation	Manual (flow-through): forklift
5	**Operation**	Service mode	Mixed
		Pre-emption	Not allowed
		Value-adding services	Yes: weighing and labelling
6	**Flow**	Arrival pattern	Scattered
		Departure pattern	Restricted
		Product interchangeability	Dedicated to destination
		Temporary storage	Limited: floor and pallet racks
		Internal resource capacity	Limited: forklifts and workers

Following the characterization of the facility, how could its performance be measured? Measuring the current-state of internal cross-docking operations requires understanding the load unit, or the smallest entity transported and handled. In this case, data about orders and pallets is available in various databases. For the purposes of this project, two main data sources where consulted. First, internal dock reports where used for a three-month period spanning the months of June, July and August 2018. This time period is the busiest for the LTL business. A secondary source of data was the company's enterprise resource system (ERP), SAP. The ERP system proved difficult to access and data for only one month, July 2018, could be extracted. In spite of there being different data sources, the content of both agreed and figures were generally similar. All data analyses were thus based in either or both of these sources. With that in mind, the load unit will be typified in terms of quantity, physical attributes, frequency and handling time.

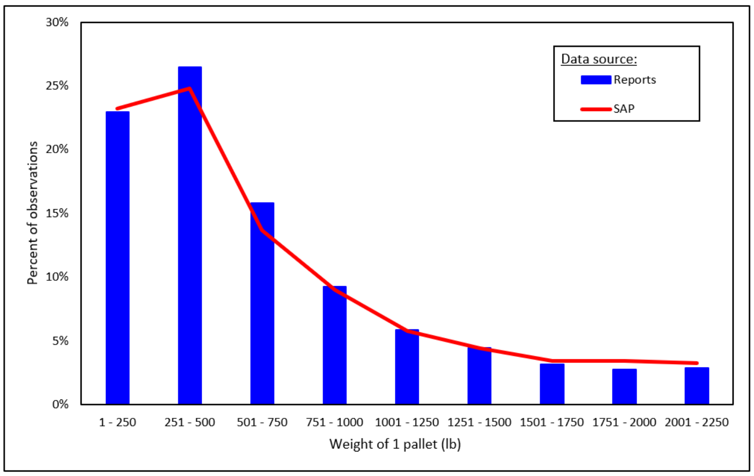
Table 3.2 Origin and destination zone codes

Zone Code	Zone description
DB	Boucherville and Monteregie
DH	Hull, Gatineau and Outaouais
DL	Lac-Megantic
DM	Greater Montreal
DQ	Quebec (Capitale National region)
DR	Toronto, Mississauga and Southern Ontario
DS	Sherbrooke and Estrie
DT	Trois-Rivieres and Mauricie
US	United States
CAW	Canadian West
CAM	Canadian Maritimes
NL	Newfoundland

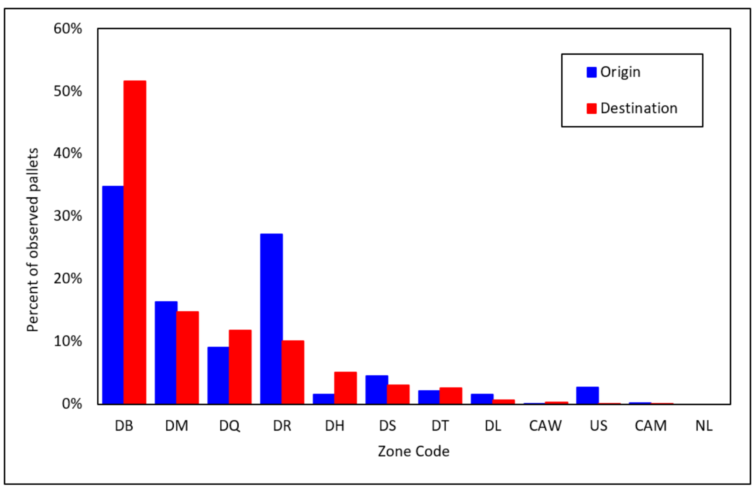
In the interest of understanding the load unit, the quantity of pallets handled at a time must be defined, together with their physical attributes. A LTL order may contain one or several pallets. The number of pallets per order is shown in figure 3.3a. Over 60% of orders consist of no more than two pallets. In spite of the relatively small number of pallets per order, the individual load units are heavy, as depicted in figure 3.3b. Therefore, the handling of pallets requires mechanic aid. During pick-up and delivery, truck drivers utilise an electric pallet truck, which is charged overnight at the cross-dock and carried in the trailers at all times. Within the facility, all pallet handling is done with forklifts, given an average pallet weight of around 1,120 lb. While extreme weights are possible - reaching over 2,000 lb, the pallet racks' weight limit is between 2,200 and 2,500. Most pallets can thus be temporarily stored on the existing racks. Additional characteristics of the load unit are its origin and its destination. Within the company, the distribution network has been split into 12 general zones designed by two or three-letter codes. Table 3.2 contains a list of these zone codes. Based on this coding, the distribution of origin and destination zones per pallet is portrayed in figure 3.3c. From this graph, we can imply that there is an imbalance between origins and destinations. For instance, less pallets arrive from the region of Monteregie (DB) (where the facility is located) than those delivered to that region. The opposite is true for the region of Southern Ontario (DR), with more inbound than outbound pallets. These imbalances may result in truck loads with low fill rates: trailers coming from Ontario (DR) may arrive full but must depart will less of their volume filled. This apparent problem, though, must be confronted with another dimension of the load unit: the frequency of shipments.



(a) Number of pallets per order



(b) Pallet weight (lb)



(c) Pallet origin and destination

Figure 3.3 Load unit (pallet) attributes

A second dimension to defining the load unit is the frequency at which pallets arrive in the facility. On a weekly basis, around 7,500 pallets transit through the cross-dock. Whereas seasonal variations do occur, this figure is rather stable during the busy summer months, with the weekly pallet throughput not fluctuating far from this average - as depicted in figure 3.4. Daily and hourly frequencies must then be observed. At the beginning of the project, the cross-dock operated non-stop: 24 hours and seven days per week. At that moment, hourly pallet reception during the day varied greatly between weekdays and the weekend. Figure 3.5 depicts the different pallet-reception profiles per hour and day of the week. During weekdays (figure 3.5b), there are two peak periods of operation: between 5 and 7 AM and between 6 and 9 PM. During the weekends (figure 3.5c), in turn, less pallets are unloaded and noticeably busy periods do not occur as such. As a consequence of this analysis, the organisation decided to no longer operate on Sundays and to restrict the work schedule to 12 hours on Saturdays. For the purposes of this project, the main focus is thus modelling a typical day of the week where the pallet reception profile matches that shown in figure 3.5d. While this graph represents the average number of pallets received in a weekday, it it also an indicator of throughput, though the number of pallets in temporary storage is not included.

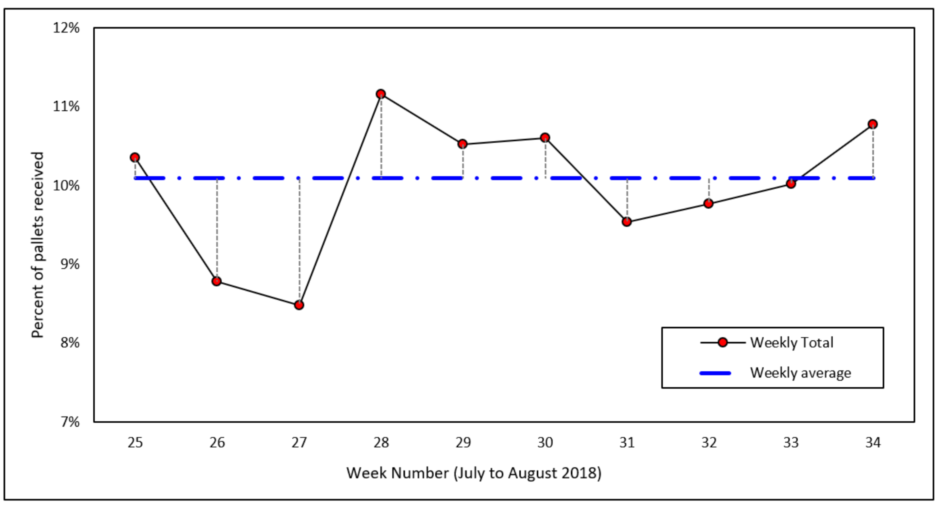
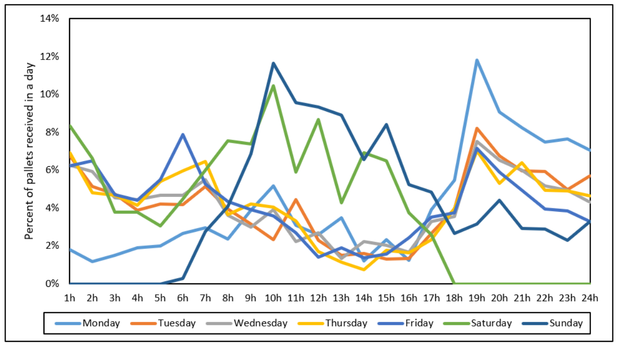
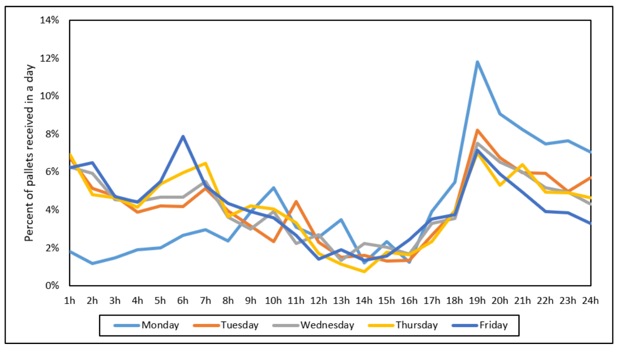


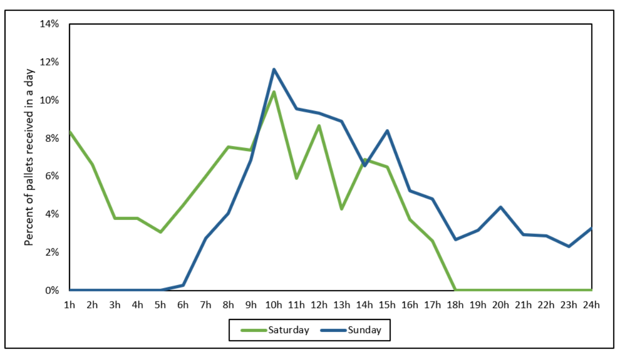
Figure 3.4 Pallets received per week



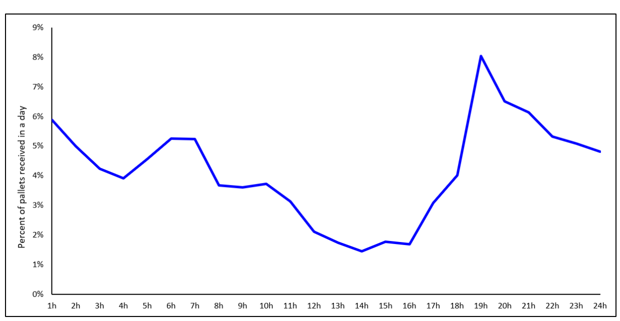
(a) Whole week



(b) Weekdays



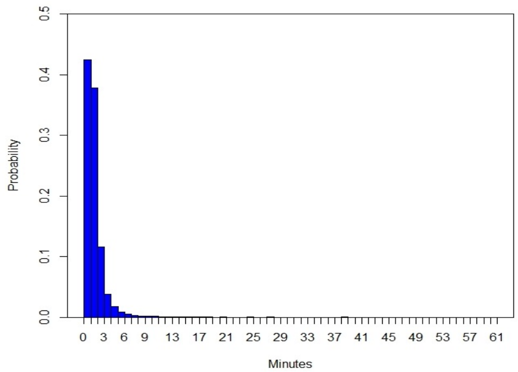
(c) Weekends



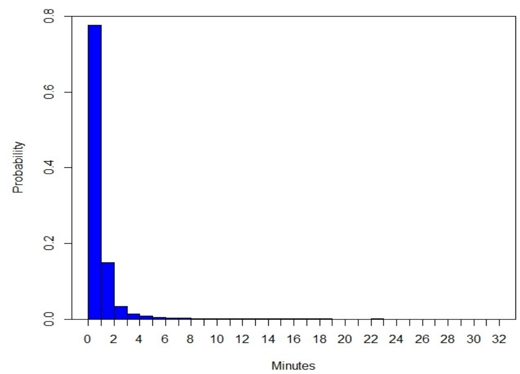
(d) Weekday average

Figure 3.5 Load unit daily frequency: pallets received hourly

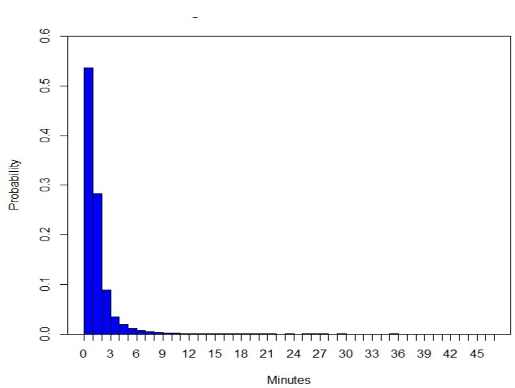
Studying the load unit in detail, from its physical attributes to its frequency, offers a good insight on how operations happen in the cross-dock. The busy hours of operations can be implied from this study, together with the weight requirements of the pallet racks. A missing piece to a broader understanding of the facility, nonetheless, is the handling activities and, most importantly, the time they take. During staging, the cross-dock workers must scan the pallet's bar-code label every time an order is moved. The resulting time stamps are stored in the aforementioned databases and have been used to determine handling activities and measure their duration. What's more, these time calculations were validated through a time study performed on site during non-busy hours. This validation confirmed the reliability of time measurements while shedding light on the specifics of the staging process. There are three main handling activities: stripping or unloading, stacking or loading and transfer. An order is either stripped, temporarily stored and stacked at a later time or it is directly transferred from an inbound to an outbound trailer. The distributions of handling times are shown in figure 3.6. Strip, Stack and Transfer times are measured in minutes given their short duration, even though extreme values (such as half an hour) may arise. These three time measurements also include pallet weighing time. While temporary storage is not directly measured, it can be implied from the time stamps. Figure 3.6d thus shows the distribution of total time in dock per pallet. On average, pallets do not spend more than 2.5 hours in the facility, but some exceptions are possible. The average time calculated confirms that our facility is, indeed, a cross-dock, since temporary storage does not exceed 24 hours [1].



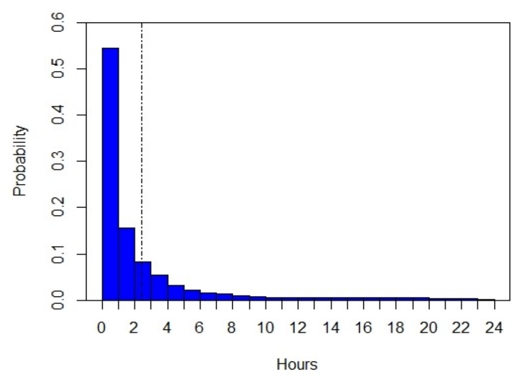
(a) Strip (unload)



(b) Stack (load)



(c) Transfer (direct loading)



(d) Total time in dock with mean

Figure 3.6 Handling times per pallet

Having defined the load unit and the handling activities associated with it, there remains an important question to address: can the facility accommodate the existing pallet throughput? Measuring the storage capacity of the cross-dock was not a menial endeavour, but it held utter importance in determining the current state of operations. There are two alternatives for pallet storage: the pallet racks or the floor. The latter is rather ambiguous, as there are many options. Pallets can be stored in the center of the facility, in a designated area named *bulk storage*, or they can be placed in the alleyways between pallet racks so long as space is available. Thus, floor storage capacity was determined by calculating the ratio between the available floor surface and the area of a standard pallet (48 x 40 inches). For the purposes of this study, a 80% space utilisation rate was assumed because there are not set rules for the use of alleyways and pallet stacking is often impossible. Moreover, having the pallets placed on the floor in a disorganized manner may hinder the efficient use of the available space. As far as the pallet racks are concerned, the length, width and height of each and every pallet cell was measured with a laser meter. In total, the facility contains 48 pallet racks: 19 are principal, 16 are secondary (on the side) and 13 are overhanging (top racks), suspended between principal racks and over the circulation alleyways. Principal racks are comprised of between 2 and 4 sections, with each section containing between 2 and 3 pallet spaces. Side and top racks all have one section only. Consequently, principal pallet racks have lengths of either 8 or 12 feet and fit two or three 4-inch-wide pallets, respectively. All side racks fit only two pallets and are 8-ft long. Top racks, in turn, are slightly longer at 13 ft to accommodate irregular pallets. All pallet racks have a constant width of 4 ft or 48 inches, which corresponds to the longest side of a standard pallet. Finally, principal and side pallet racks may contain between two to three levels, each with highly variable heights. Figure 3.7 shows the designated storage spaces in the facility layout. Of note, floor storage between pallet racks is not formally designated but rather informally enforced. Furthermore, principal rack 7-8 consists of two pallets racks merged together to accommodate abnormally long pallets. All things considered, it was estimated that the facility has a storage capacity of approximatedly **900 standard pallets**.

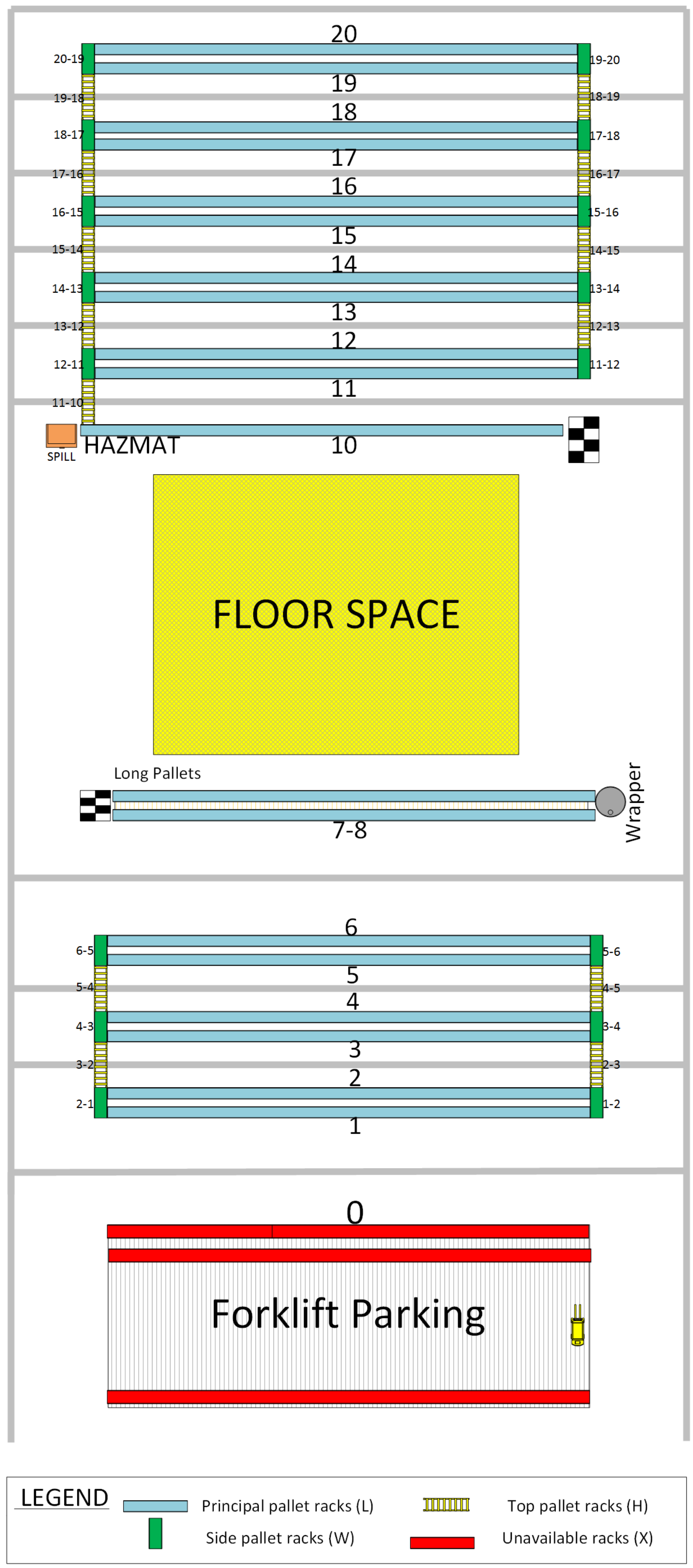
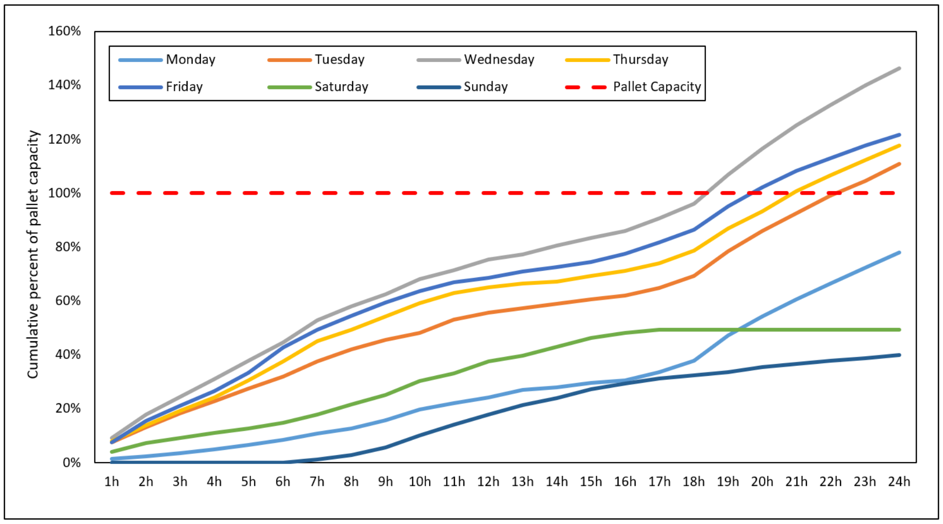


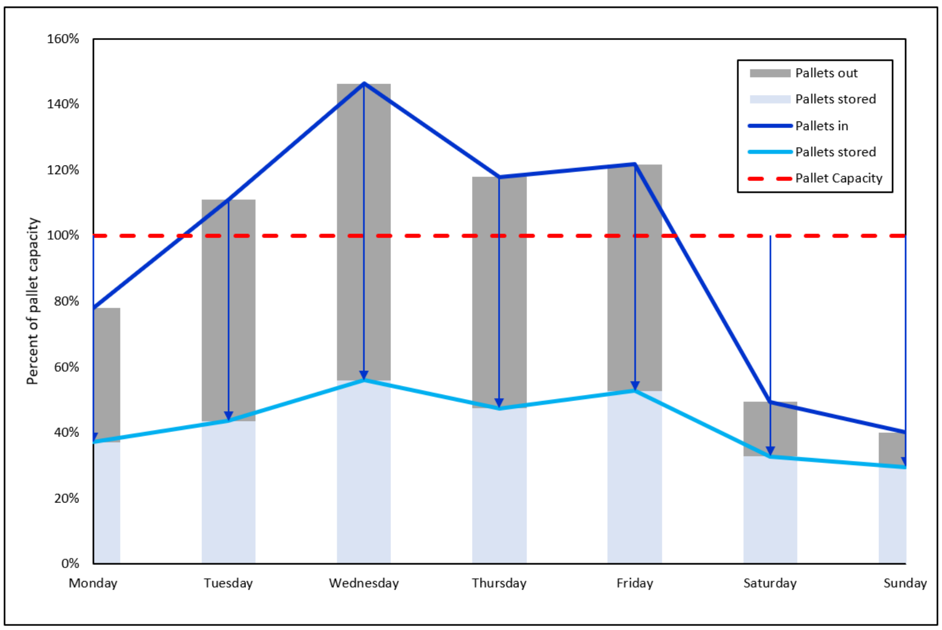
Figure 3.7 Cross-dock temporary storage locations

3.3 Targeted Problems

Having estimated the storage capacity of the cross-dock, the problematic previously presented (chapter 1) will be re-evaluated. The cross-dock employees repeatedly reported missing space for the temporary storage of pallets, which led to excessive forklift displacement and, in some cases, delays in outbound trailer loading. If the hourly arrival of pallets in a given day (shown in figure 3.5a) is observed in a cumulative fashion and compared to the estimated pallet storage capacity, it may appear that indeed the cross-dock lacks sufficient space for temporary storage. Figure 3.8a illustrates this idea: the amount of pallets received during a 24-hour day exceeds the estimated storage capacity in most weekdays. It must be noted, howbeit, that not all pallets transiting through the facility remain in storage; many are directly loaded onto outbound trailers. Moreover, the average time in dock per pallet does not exceed 3 hours. On that account, a more accurate portrayal of pallet throughout requires consideration of both inbound and outbound pallet flow during the day. Figure 3.8b exhibits the changes in daily pallet throughput: from all pallets being unloaded, a significant amount of them leave the facility in the same day. The effective number of pallets that remain in storage is well below the storage capacity of around 900 standard pallets. On average, between 400 and 500 pallets remain in storage. The issue of excessive forklift displacement is, consequently, symptomatic of organisational shortcomings. In other words, material handling equipment is not being used as efficiently as possible, which results in poor pallet placement in the facility. A careful revision of dock door assignments or even the disposition of pallet racks are possible resolution avenues. Having established this problematic, the conceptual model will be explained next.



(a) Cumulative average number of pallets received in a day



(b) Average inbound and outbound flow per day

Figure 3.8 Pallet flow

3.4 Conceptual Model

The conceptual model is an abstraction of the real cross-docking system and the facility where it takes place. It is defined by its boundaries, the general assumptions behind its functioning and the exclusions from the real system. These three elements will be explained.

As previously stated, the cross-docking process extends well beyond the facility. The model developed, conversely, focuses exclusively on the cross-dock, having the facility's walls as external boundaries. Inside these boundaries, the internal material handling network is comprised of circulation paths and nodes, where handling activities take place. Such activities have been described before as strip, stack and transfer. There are, nonetheless, secondary handling operations such as weighing the pallets, placing them on racks or dropping them on the floor. A more comprehensive understanding of the system and its boundaries can be obtained though a reproduction of the facility to scale. Figure 3.9 is a two-dimensional CAD plan of the cross-dock's layout, developed with AutoCad [7] and inspired by the architectural blueprints of the company. In the CAD drawing, each of the dock doors is identified, together with all pallet racks and circulation paths. Pallet racks are divided into three areas by the organisation: A, B and C. The exact distances between these elements have also been validated with real measurements. From the total of 50 available dock doors, only 45 are currently in use and 5 are taller than the rest to accommodate for abnormally large freight. A few of the pallet racks are also unused (refer to figure 3.7). Whilst the facility's walls define the physical boundaries of the model, its temporary boundaries are defined by a working schedule of 24 continuous hours, from midnight to midnight. That is, the model covers a one-day period that represents a busy summer (June to August) weekday.

Adding to the definition of boundaries, a set of general assumptions has been defined for the model. First, it is assumed that only pallets are handled. While on occasion some non-palletized freight might transit through the facility, an overwhelming majority of freight (over 98%) is palletized. Upon unloading, pallets are weighed in one of two scales in the facility, the choice of scale being entirely random. Then, pallets are either temporarily stored or transferred directly to a docked outbound trailer. In terms of temporary storage, only three options are conceived: the alleyways between pallet racks, the designated floor storage zone at the center of the cross-dock, or the pallet racks. Whenever pallets are placed on racks, the placement is based on available space, favouring area A first, then area B and finally area C. There are two especial pallet racks, one designated to dangerous goods and another one for abnormally long pallets (rack 7-8). Finally, pallets are consolidated into economic loads based on common destination zones. Consequently, an outbound trailer destined to a given zone will only contain pallets headed to that destination (assigned pre-distribution).

Attributes such as weight or dimensions do not restrict consolidation or loading, unless the trailer's volumetric capacity is exceeded. There are nevertheless two additional limits to trailer loading based on management directives:

1. At least 80% of the truck's volumetric capacity must be filled to consider the loading complete.
2. Otherwise, if an outbound trailer has waited for over an hour, it may depart with at least one order loaded.

No other loading restrictions are contemplated.

Elements from the real system excluded in the conceptual model are its final defining feature. First, the shunting process is not modelled but the impact of trailer wait on internal flow will be accounted for. Weekends are also not considered because the model reflects weekday operations. Moreover, pallets halted in temporary storage due to customs or other bureaucratic delays are not modelled, mostly because data for these isolated events is unavailable. Similarly, atypical shipments not part of the LTL business that might occasionally transit through the dock are not included since their volume is negligible. As far as the material handling equipment is concerned, the refuelling of forklifts is excluded, since this activity is customarily performed whenever the vehicles are not operational, having no impact on uptime. A final exclusion is related to pallet racks: instead of modelling the individual heights of each section in a rack, general heights will be assumed per rack. This decision is due to limitations of the modelling software, which does not allow for modelling of individual pallet cell heights in racks. Fortunately, height is not a critical factor in pallet storage because the diversity in rack height offers a high degree of flexibility, as shown in figure 3.10.

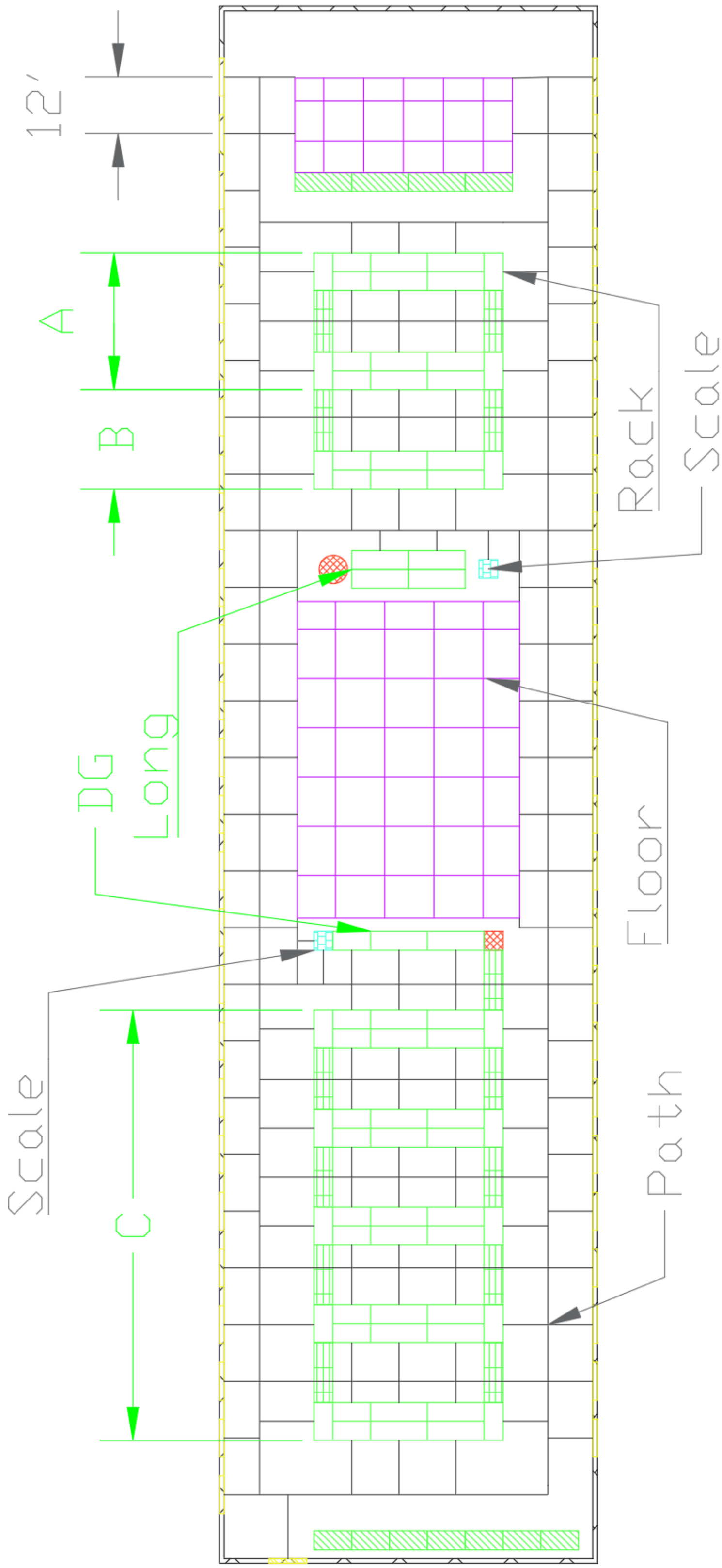


Figure 3.9 Architectural layout of the cross-dock [7]

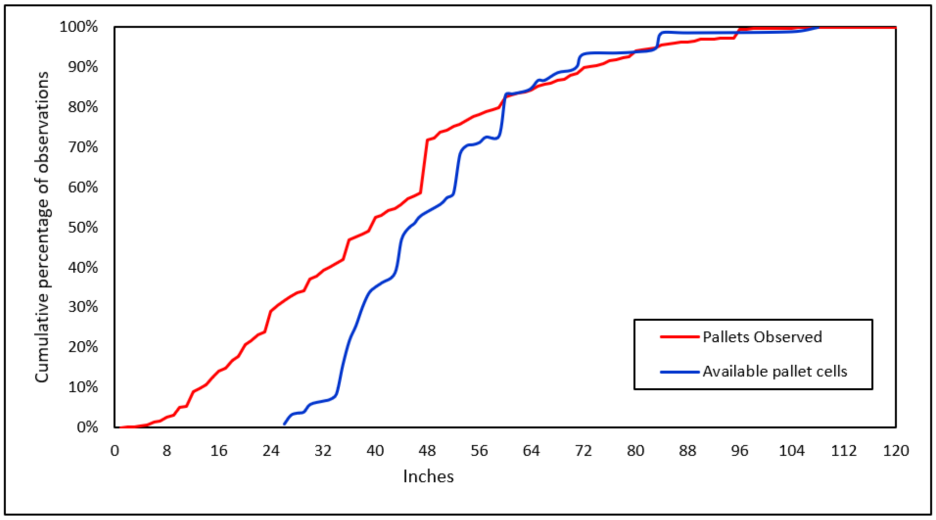


Figure 3.10 Pallet height distribution vs. available rack spaces

3.5 Simulation Model

There are several layers of complexity to the simulation model developed to replicate the internal operations of the studied cross-dock. The purpose of this section is to offer the reader a detailed explanation of the workings of such model, from input definition to output analysis. A screen-shot of the final model on the AnyLogic user interface [8] is shown in figure 3.11. Outbound trailers are depicted as blue rectangles, whereas red designates inbound trailers. The architectural blueprint detailed in figure 3.9 was used to reproduce the layout to scale. The distance travelled by forklifts can thus be calculated by the model.

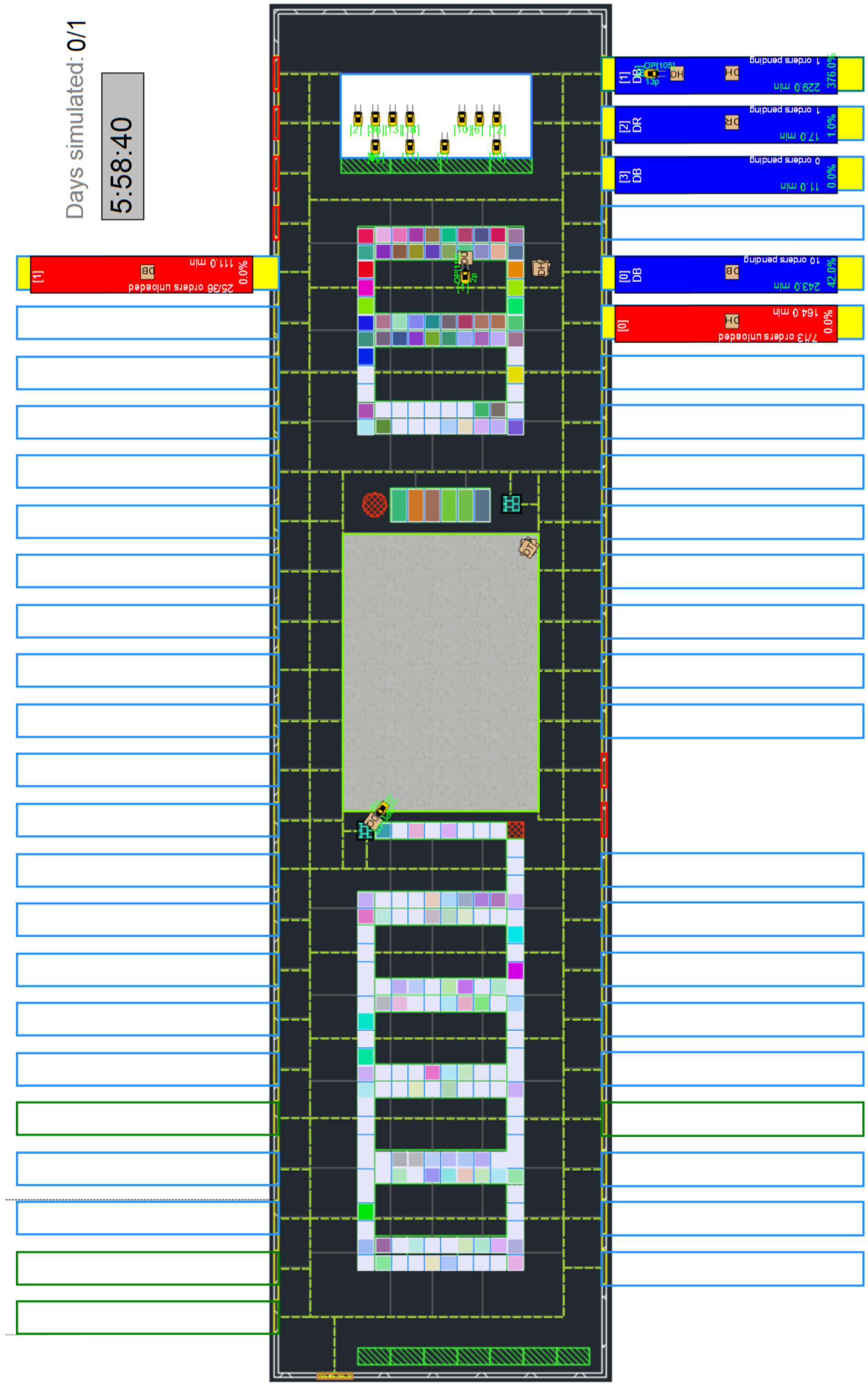


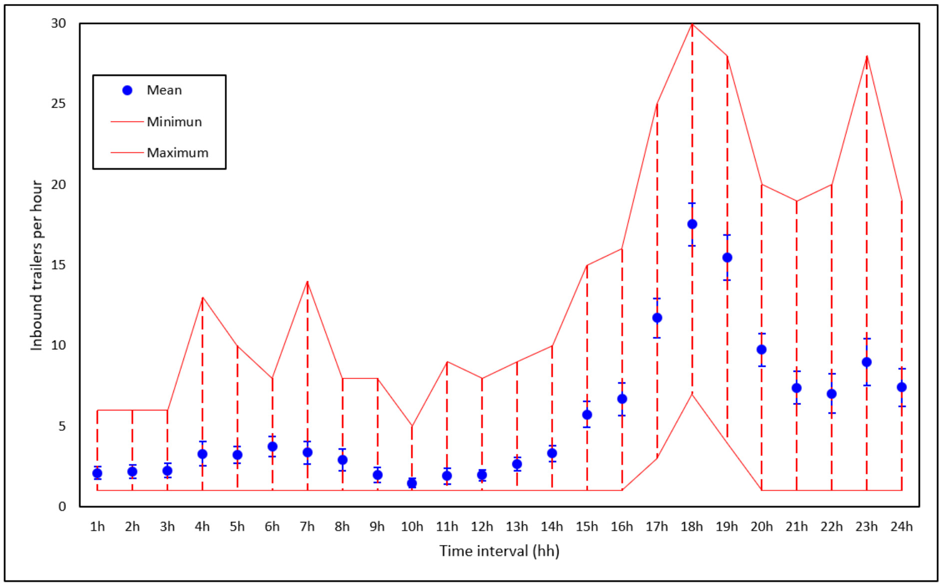
Figure 3.11 Final simulation model's visual representation [8]

3.5.1 Model Inputs

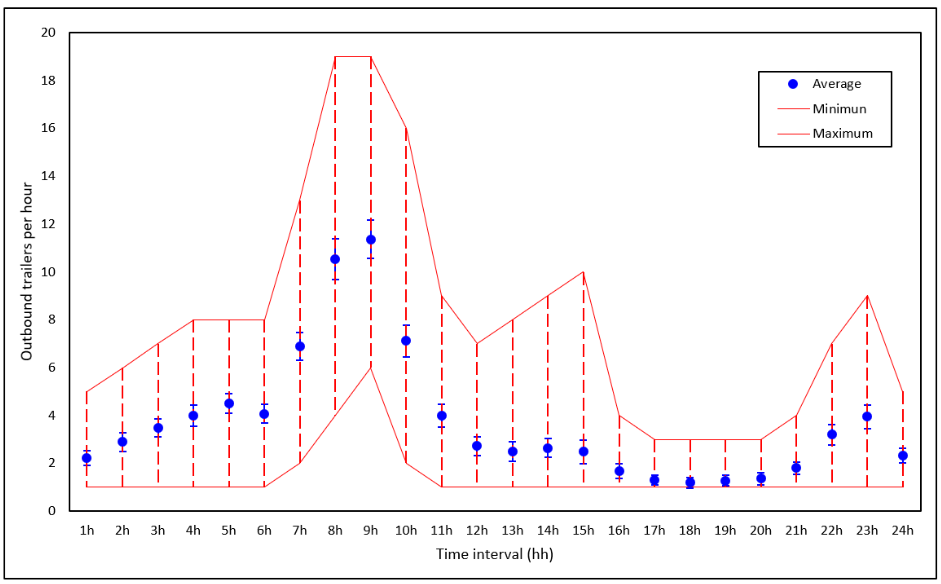
The first input of this model is the facility layout previously described. It specifies the storage rack layout, the internal material handling network and the distances within them. There are, nonetheless, a myriad of data inputs required for the model to function. Most of these were outlined at the beginning of this chapter. A more concrete description of these inputs follows, together with the probability distributions determined for them. These distributions were used to generate randomized values in the simulation model.

Arrival Rates

One of the major inputs of the model is the rate at which trailers arrive at the facility. Trailer arrival is the utmost discrete-event that triggers cross-docking. Besides, there is a distinction in the type of trailer being docked on a door: either inbound or outbound trailers are docked for unloading or loading, respectively. Modelling the arrival of trailers requires revisiting the time-stamped data previously used for pallet handling times. The data also shows gate-in and gate-out time stamps for all orders, referring to the moment when trailers entered or exited the facility. The earliest recorded gate-in time for a group of pallets inside the same trailer was used for inbound-trailer arrival. As for outbound trailers, the earliest gate-out time of an order was used. Using order time scans to determine trailer arrival is an indirect approach, yet it is the only one available. Unfortunately, the resulting arrival times are shifted by an unknown amount of time because wait time prior to loading/unloading cannot be deducted from them. In both cases, howbeit, the number of trailers docked per hour seemed to fluctuate considerably throughout the day and a single hourly arrival rate failed to reflect the real process. In such cases, modelling the arrival of trailers through a non-homogeneous Poisson process (NHPP) is a sensible option, given that the arrival rate need not be constant but can vary over time [30]. Not only is this approach widespread in simulating real systems [31, 32], but its application to transportation facilities is not uncommon [33]. Consequently, the arrival of trailers into the modelled cross-dock is defined by a Poisson process with an arrival rate (λ) that varies every hour in a 24-hour period, such that: $\lambda = \lambda(t), t = [1, 24], t\epsilon N$. The hourly rates for the NHPP of inbound and outbound trailer arrival is shown in figure 3.12, together with confidence intervals and ranges of variation. The busy periods of operations previously defined between 5 and 7 AM and between 6 and 9 PM correspond with the highest rates of outbound trailer and inbound trailer arrival, respectively.



(a) Inbound trailer hourly arrival rate

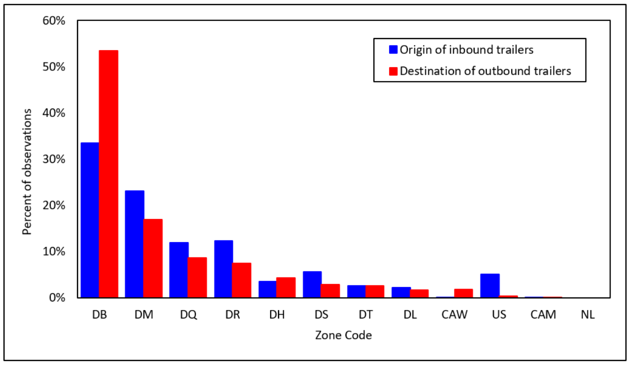


(b) Outbound trailer hourly arrival rate

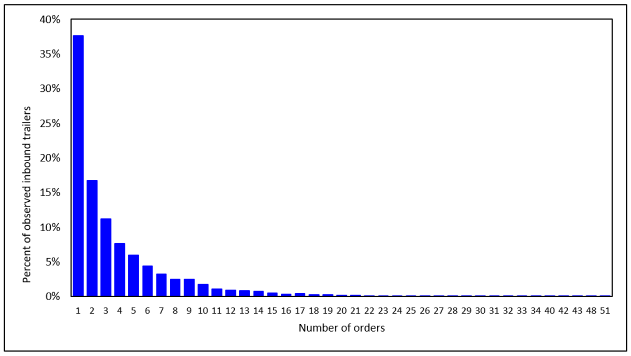
Figure 3.12 Non-homogeneous Poisson processes of trailer arrival

Trailer and Order Attributes

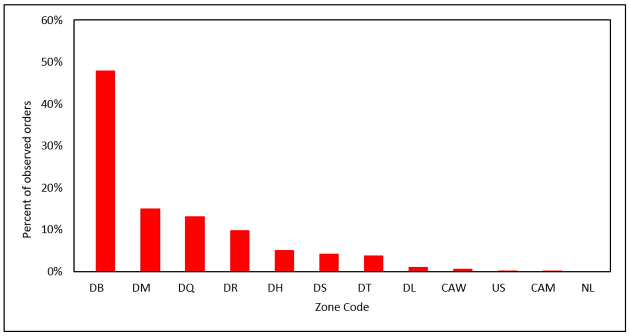
Although arrival rates are the defining feature of both inbound and outbound trailers, another set of attributes must be determined. First, trailer capacity is delimited by its length, width and height: 630.25, 109.69 and 98.38 inches. Furthermore, trailers contain orders, which are composed of pallets. Given that some of these pallets are oversized, trailers may require the use of one of the dock's five tall doors. It was estimated that around 10% of all trailers require the use of a tall door for over-sized pallets. Similarly, the origin of inbound trailers and the destination of outbound trailers follow distinct distributions, as shown in figure 3.13a. In terms of inbound trailers, the number of orders per trailer has also been determined in figure 3.13b. Whereas all the orders contained in an inbound trailer share the same origin zone, they have varying destinations following the distribution shown in figure 3.13c. The number of pallets per order has already been determined (refer to figure 3.3a). A final defining feature is the probability of an order containing dangerous goods (or hazardous material), estimated at 3.98% of all orders. All of this information allows the model to reproduce the random arrival of trailers, together with their contents in terms of orders and pallets. The attributes of both are inherited from their inbound trailer.



(a) Trailer origins and destinations



(b) Number of orders per inbound trailer



(c) Order destination

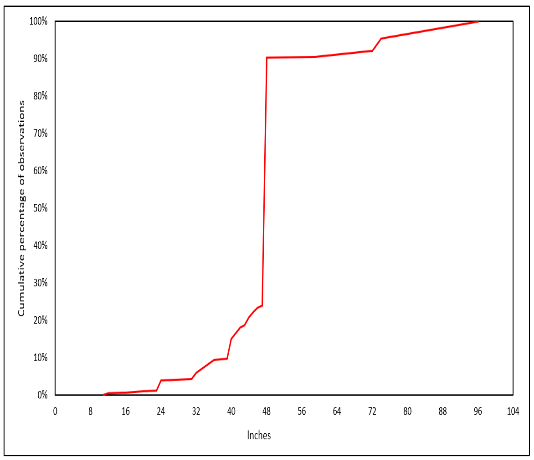
Figure 3.13 Trailer attributes

Pallet Attributes

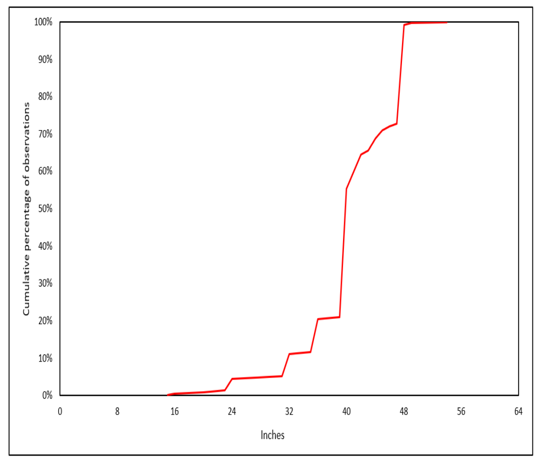
The pallets' origin and destination are inherited from the order they belong to. As formerly explained, the orders share their origin zone with the trailer wherein they arrived. Other attributes, however, are intrinsic to the pallet: length, width, height and weight. These physical attributes are an integral input to the simulation model.

In the records retrieved from the company's databases, not all pallets in an order were measured directly. That is, weight and dimensions were not always recorded pallet by pallet. For a specific order, there were a number of measurements (i.e. observations) that not necessarily agreed with the number of pallets in that order. For example, an order consisting of 3 pallets may have either three measurements, two or only one. If only one measurement was recorded, the 3 pallets might have had the same cube and weight. For the purposes of statistical analysis, each available measurement was taken as an observation. On that account, it was not assumed that an order of several pallets with one recorded measurement contained all identical pallets. Instead, the recorded measurement was taken as one single observation. Based on this logic, representative values for pallet dimensions (cube) and weight have been obtained in the form of statistical distributions.

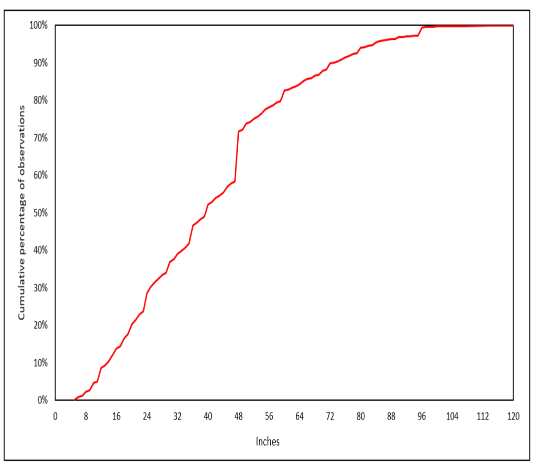
Accordingly, extensive statistical analysis confirmed that pallet weight followed a log-normal distribution. This fit was validated through a Kolmogorov-Smirnov test [34]. In the case of pallet dimensions, the recorded data proved difficult to fit to any known distribution. One common feature of the probability distributions of length, width and height was a high kurtosis and a positive skewness. Hence, the distributions display a significant tail to the right with high deviations from the mean. Not only is the presence of outliers evident but these extreme values prevent any normality tests from being applied. In spite of seeming erroneous, many of these *outliers* represent actual occurrences. Extreme pallet dimensions, howbeit rare, appear to be an inherent reality of the LTL business. Initially, the standard ISO specifications (ISO 6780:2003) were used as a basis for filtering out odd values for the length, width and height of pallets. Unfortunately, the ISO standard consists of no more than six pallet sizes [35]. These sizes fail to encompass the pallet diversity in LTL transportation. Pallets vary from customer to customer and custom sizes abound. As a consequence, commercially available customized pallets were also used as a reference for eliminating actual outliers. The resulting data sets for length and width contain around 80 percent of the recorded measurements, while covering a great deal of standard and commercially available pallet sizes. As for pallet height, a minimum possible height of 5 inches was taken as the smallest possible value, barely above the height of an empty pallet. The final cumulative statistical distributions of pallet attributes are displayed in figure 3.14, together with the log-normal fit for the weight.



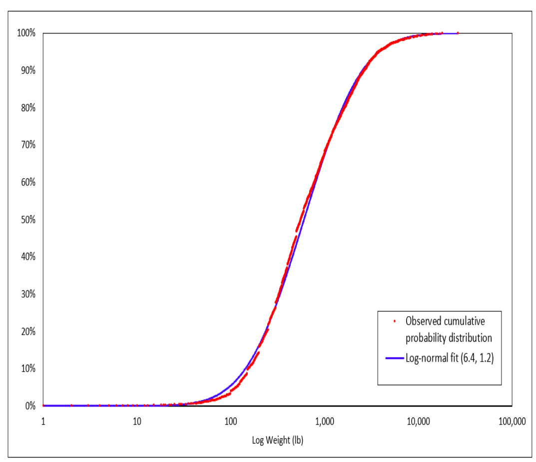
(a) Length (in)



(b) Width (in)



(c) Height (in)



(d) Weight (lb), log-normal fit

Figure 3.14 Pallet attributes: cumulative probability distributions

Door Assignment

Door assignment at the cross-dock is of mixed-service type. In other words, all 45 functioning dock doors can *serve* both inbound and outbound trailers. While this approach might seem quite unrestricted, it actually poses a great challenge when it comes to efficient assignment of doors to handling activities and zones. The current door assignments are enforced per eight-hour shift, with the workday consisting of three successive shifts. During each shift, each door may be assigned to a given activity - loading or unloading - or open to any of them. Likewise, a given door may be assigned to a specific zone or to a group of zones. This type of door assignments require a profound knowledge of the flow within the facility and the decisions are usually made by cross-dock managers. Table 3.3 summarizes the door assignments used by the organisation, together with the specific doors identified as *tall*.

Table 3.3 Dock door assignment to activities and zones

Door	Tall	Handling activity			Dedicated zones		
index	door	00h - 08h	08h - 16h	16h - 00h	00h - 08h	08h - 16h	16h - 00h
02	Yes	ANY	ANY	ANY	ALL	ALL	ALL
04		ANY	ANY	ANY	ALL	ALL	ALL
06		LOAD	ANY	ANY	DB	ALL	ALL
08		LOAD	ANY	ANY	DB	ALL	ALL
09		UNLOAD	ANY	LOAD	QC	ALL	QC
10		LOAD	ANY	ANY	ALL	ALL	ALL
11		UNLOAD	ANY	LOAD	QC	ALL	QC
12		ANY	ANY	ANY	ALL	ALL	ALL
13		UNLOAD	ANY	LOAD	QC	ALL	QC
14		ANY	ANY	ANY	ALL	US	ALL
15		UNLOAD	ANY	LOAD	QC	ALL	QC
16		ANY	ANY	ANY	ALL	US	ALL
17		UNLOAD	ANY	LOAD	QC	ALL	QC
18		LOAD	ANY	UNLOAD	DB	ALL	DB
19		LOAD	ANY	UNLOAD	DB	ALL	DB
20		LOAD	ANY	UNLOAD	DB	ALL	DB
21		LOAD	ANY	UNLOAD	DB	ALL	DB
22		LOAD	ANY	UNLOAD	DB	ALL	DB
23		LOAD	ANY	UNLOAD	DB	ALL	DB
24		LOAD	ANY	UNLOAD	DB	ALL	DB
25		LOAD	ANY	UNLOAD	DB	ALL	DB
26		LOAD	ANY	UNLOAD	DB	ALL	DB
27		LOAD	ANY	UNLOAD	DB	ALL	DB
28		LOAD	ANY	UNLOAD	DB	ALL	DB
29		LOAD	ANY	UNLOAD	DB	ALL	DB
31		LOAD	ANY	UNLOAD	DB	ALL	DB
33		ANY	ANY	UNLOAD	ALL	ALL	DB
34		LOAD	ANY	UNLOAD	ALL	ALL	ALL
35		ANY	ANY	UNLOAD	ALL	ALL	DB
36		LOAD	ANY	UNLOAD	ALL	ALL	ALL
37		ANY	ANY	UNLOAD	ALL	ALL	DB
38		LOAD	ANY	UNLOAD	ALL	ALL	ALL
39		ANY	ANY	UNLOAD	ALL	ALL	DB
40		LOAD	ANY	UNLOAD	ALL	ALL	ALL
41		ANY	ANY	UNLOAD	ALL	ALL	DB
42		LOAD	ANY	UNLOAD	ALL	ALL	ALL
43	Yes	ANY	UNLOAD	UNLOAD	ALL	ALL	DB
44	Yes	ANY	ANY	LOAD	ALL	ALL	DR
45		ANY	ANY	UNLOAD	ALL	ALL	DB
46		ANY	ANY	LOAD	ALL	ALL	DR
47		ANY	ANY	UNLOAD	ALL	ALL	DB
48		ANY	ANY	LOAD	ALL	ALL	DR
49	Yes	ANY	UNLOAD	UNLOAD	ALL	ALL	DB
50		ANY	ANY	LOAD	ALL	ALL	DR
51	Yes	ANY	UNLOAD	UNLOAD	ALL	ALL	DB

Forklift Fleet

The forklift fleet is at the core of the model, as the main resource within the facility and the main focus of the project. The cross-dock utilises a fleet of 20 forklifts fuelled by CNG. The CNG cylinders used are custom-made as the forklifts formerly run on diesel engines. The dock also has its own adjacent refuelling station, where cylinders can be refilled in a few minutes. In addition, the forklift operators have a set weekly schedule which results in a fixed capacity per hour of the day, as depicted in figure 3.15. Moreover, workers are required to keep a constant speed of 14 km/h so as to comply with the legal requirements concerning occupational safety. This constant speed will be used in the simulation model. As for the fuel consumption rate, it will be addressed in a later section of this chapter.

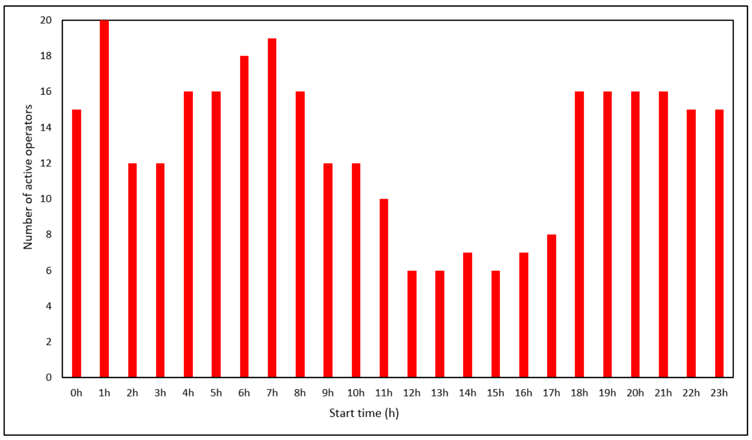


Figure 3.15 Forklift operator schedule

Missing Inputs

Other than the CNG consumption rate, an input that could not be estimated from the available data was the time it took forklift operators to weigh the pallets after unloading them. This value-adding activity holds great importance as it allows the organisation to bill its customers correctly. In order to estimate pallet weighing time, the AnyLogic built-in calibration tool [8] was used to calculate the most appropriate weighing time so that the total time pallets spent in dock matched the distribution shown in figure 3.6d. The calibrated weighing time was calculated at 1.31 minutes. Following this exercise, it was concluded that calibration could be used to target more critical missing inputs: fuel consumption rate and the impact of shunting on internal operations. These issues will be explained in later sections of this chapter.

3.5.2 Agent Definition and Interaction

The above-mentioned data inputs represent discrete events or attributes, which would suffice to define a model in traditional discrete-event simulation. In this case, howbeit, the ABM requires further specification. Namely, the roles of agents, the environment wherein they exist and the interactions defining their behaviours will now be specified.

To begin with, agents are the basic building block of the ABM, representing both physical and abstract entities. The level of granularity chosen for the agents is their first defining feature. For the purposes of this model, the smallest scale is the load unit or pallet. At this scale, the model can reproduce the individual movements of forklifts throughout the facility. A second feature of agents is their level of cognition, which dictates their decision-making process. Most agents in this model are reflexive or responsive, built around rather simple rules to react to inputs and take actions. For example, dock doors react to the time of day in order to change their assignment. Some agents, however, are utility-based and act in order to either maximize or minimize a given utility function. This is the case of outbound trailers, which decide to extend their loading time in order to maximize fill rates. Two agents, in particular, are goal-based with all of their actions dictated by an end-goal or final state. This applies to forklifts and order processes. The former are assigned tasks one at a time and fulfil them by moving around the internal network. The latter, in turn, exist to ensure that a given order (or group of pallets) is eventually loaded, moment at which the order process reaches the completion state. Most of the agents in the model belong to a collection (population) of agents: forklifts, orders, pallets, inbound and outbound trailers. On the other hand, there are special agents beyond these categories. For instance, orders are meta-agents, composed of other agents (pallets). There are also proto-agents, which are not fully specified but are used as place-holders to future agents [28]. Trailers are thus proto-agents that can either become inbound or outbound trailers, with a different set of attributes in each case. Order processes are also proto-agents that, while being completely abstract, guarantee the cohesion of the model. Both proto and meta agents behave as parent agents from which other agents inherit attributes, not unlike class inheritance in object-oriented programming. Finally, forklifts, pallets and trailers move with respect to the network environment, whereas doors remain stationary in nodes and orders (together with order processes) lack network mobility.

The second piece of the ABM is the environment or interaction topology [28]. In this case, a discrete-space network-based environment was defined from the CAD layout previously examined (refer to figure 3.9). The topology includes nodes and links. In the former, activities can take place and moving agents can remain at rest. Therefore, scales, pallet racks, floor storage spaces and dock doors are represented by nodes. Links, conversely, represent pathways and define the internal network wherein mobile agents move. Most of the attributes of the network relate to either layout or pallet-storage capacity.

Interactions are the final component of the ABM, with five distinct types defined [28]. Agent-self interactions entail the agent evaluating its own current state and making a decision, which happens whenever outbound and inbound trailers evaluate their fill rate to undock. In a similar fashion, environment-self interactions involve areas of the topology altering their own state, which occurs with pallets racks as their availability changes. The most important interactions, though, happen between agents and entail competition (trailers and doors), consumption (pallets and outbound trailers) or communication (order processes and forklifts). Correspondingly, agent-environment exchanges result in the agent manipulating or examining part of the topology, as with forklifts and balances when weighing pallets. The fifth type of interaction involves two or more disparate environments, which does not apply to this specific model but could be pertinent if the shunting ground is ever included. In a way, most of the aforementioned interactions are dictated by agent attribute defined by the data inputs covered. An entity relationship diagram (ERD) is shown in figure 3.16 in order to illustrate these interactions. The ERD depicts the information exchange with respect to specific agent attributes, as well as the responses between agents, which reflect availability constraints. The diagram also displays the cardinality between agents, defined by both one-to-many and many-to-one relationships. One forklift, for example, interacts with many pallets, whilst the trailers and doors interact one-to-one.

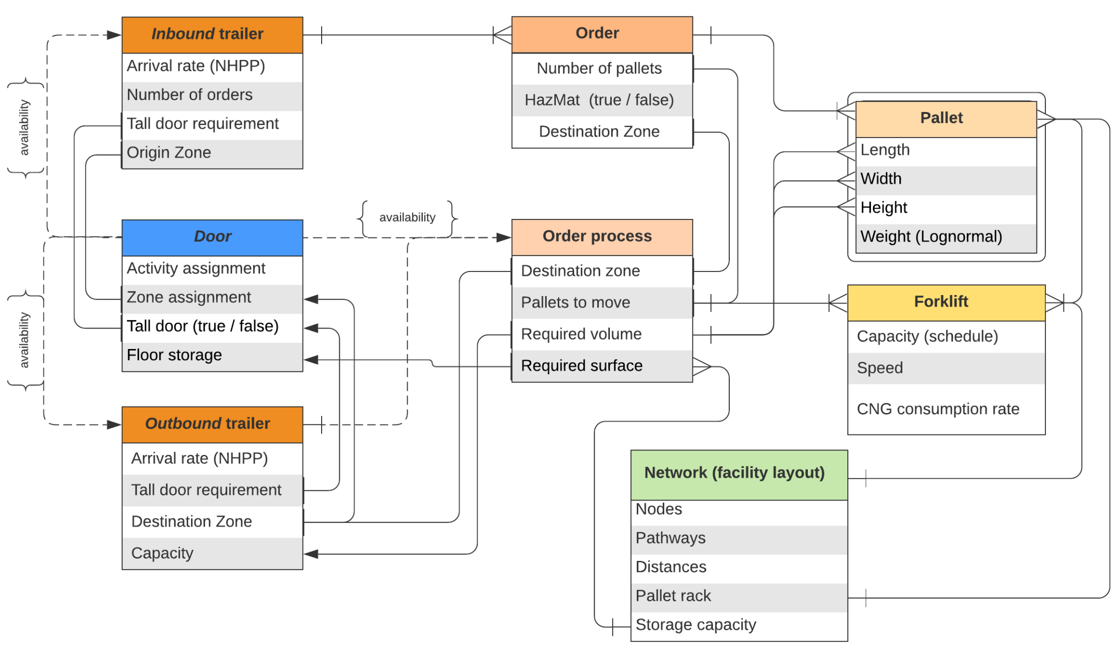


Figure 3.16 ERD of agents, environment and interaction

3.5.3 Modelling Fuel Consumption

Fuel consumption is directly associated with environmental impact. Consequently, modelling forklift fuel consumption correctly has chief importance to the objectives of this project. Sadly, the company does not keep any records with respect to CNG consumption beyond monthly bills. Rough monthly totals are measured by the CNG provider and used for billing purposes. These totals lack any level of detail that pertain to daily or vehicle-specific consumption. Being the only figures available, they were used to estimate daily consumption profiles for the fleet of 20 forklifts. It was estimated that between 470 and 569 m^3 of CNG were used per day, with a daily average of 524 m^3. These values were estimated from 12 months worth of data. Subsequently, a formula was developed to calculate daily consumption per forklift using the CNG cylinder's standard volume and pressure. Thus, daily fuel consumption is based on the hours of activity (t_o), the cylinders user per hour (C) and the volume per cylinder (V). The latter input could be calculated in a precise fashion from the existing patent of the CNG cylinders used by the forklifts [36]. Thence, each cylinder contains 12.41 m^3 of CNG. As for the number of cylinders used per hour (C), they were estimated through the calibration tool of AnyLogic [8]. The model was used to test different values of C until daily CNG consumption reached totals within the range of 470 to 570 m^3, favouring the mean value of 524 m^3. The calibrated value of C was estimated at 1.20 cylinders per hour of activity. Having determined both inputs, the simulation model could calculate the fuel consumption of a forklift based on the time said agent was active. Of note, *hours of activity* refer to the time a forklift spends executing tasks, either while moving a pallet or while waiting. The hours of activity are usually less than the duration of the work-shift, yet they include both possible drive-cycles: movement and rest. The time a forklift spends stationary but with the engine running is then included as part of the fuel consumption function. While equation 3.1 provides a general sense of the CNG consumption profile at the facility, it is far from being the best possible calculation approach. Ideally, daily fuel consumption should be measured and analysed. For this reason, the analysis of simulation results will focus on the daily utilisation of the entire forklift fleet rather than individual vehicle's consumption. Notwithstanding this hindrance, the simulated consumption, together with the daily distance travelled by forklifts, should aid to evaluate the environmental performance of the facility.

$$CNG \equiv t_o \times C \times V \qquad [m^3] \tag{3.1}$$

Where

t_o : hours of activity (movement and rest)		$[h]$
$C = 1.20$: cylinders per hour		$[h^{-1}]$
$V = 12.41$: volume per cylinder		$[m^3]$

3.5.4 Impact of Trailer Shunting on Internal Operations

As stated at the beginning of this chapter, trailer shunting has been excluded from the simulation model. The impact of shunting, nonetheless, cannot be completely disregarded [21]. Thanks to shunting, the unloading of inbound trailers is sufficiently delayed so that the capacity of internal operations is not exceeded. This delay allows the organisation to better handle the inbound flow of pallets and must be accounted for. How could the effects of shunting be considered without modelling the actual process? The main focus is the halting of inbound trailers in the yard. By delaying the docking and unloading of trailers, the cross-dock can better deal with busy periods of operation. Thus, a definition of *busy period* is required, together with the amount of time that trailers should wait in the yard. Moreover, the percentage of trailers to be halted should also be contemplated, given that not all trailers are delayed even at peak hours. The organisation uses specialized software for shunting operations but does not store data about trailer shunting per se. Therefore, the built-in calibration tool from AnyLogic [8] was used once more to estimate three parameters:

- Minimum number of pallets in the cross-dock to consider the system busy
- Shunting time for an inbound trailer
- Percentage of inbound trailers to be delayed during busy times

The calculation of these parameters was made with respect to the hourly pallet throughput measured in the actual facility, analogous to the reception profile shown in figure 3.5d. It was determined that the current pallet throughput (pallets in the cross-dock) had to reach 491 pallets for the system to be considered busy. This figure makes sense when compared to daily values calculated for pallets stored in the dock (figure 3.8b). Whenever the simulation system reaches said pallet throughput, 95% of inbound trailers would be halted for 0.85 hours or 51.24 minutes. For shunted trailers, docking and unloading would thus be delayed. Figure 3.17 illustrates the significance of the inclusion and calibration of shunting parameters. Therein, two graphs show the measured throughput (in blue) and the simulated throughout before and after the inclusion of shunting. After calibration, extreme deviations from the measured throughput disappeared, meaning that the simulation model could spread the inbound flow of pallets throughout the day, just like the real system. Moreover, the post-calibration model better reflected the busy hours of operations.

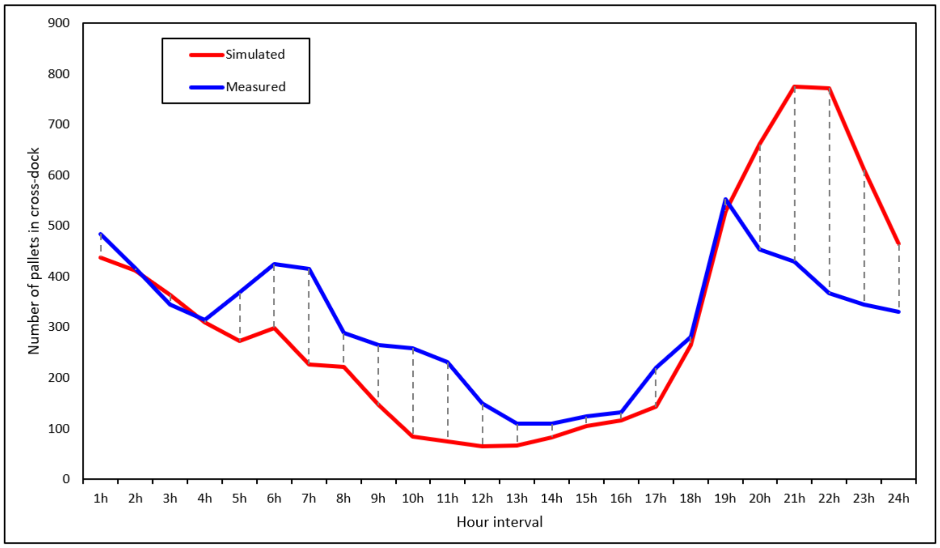


Figure 3.17 Pallet throughput during the workday after model calibration

3.5.5 Warm-up Period

It has thus far been established that the cross-dock is considered busy so long as there are at least 491 pallets being handled, either temporarily stored or in movement. Furthermore, between 400 and 500 pallets remain in storage after a full day of operations. The simulation itself, as a consequence, cannot begin with the facility being empty; that is, the model should not start without an existing pallet throughput. Another consideration is that the model starts to run at midnight, which is between the two peak periods of operation (6-9 PM and 5-7 AM). All things considered, the model requires a sensible warm-up period before statistics collection begins. During this warm-up period, only inbound trailers would arrive until a given pallet throughput triggers the simulation model to begin and operations to run normally. A complementary study of pallet throughput was then conducted, bearing in mind the above-mentioned figures. It was concluded that the model required a pallet throughput of 591 pallets for the simulation to start. This result is clearly an upper-limit, when compared to previously calculated storage and throughput figures. The duration of the resulting warm-up period was variable, between 7 and 17 hours. There are two reasons behind this: the arrival of inbound trailers follows a NHPP, and both the number of orders per inbound trailer and the number of pallets per order follow custom statistical distributions. The definition of the warm-up period is the last building block of the model. The next step is its validation through statistical analysis.

3.6 Output Analysis and Model Validation

One of the main advantages of simulation is the capacity to measure the system directly, there being endless possibilities in terms of statistics collection. That being said, which output variables would be appropriate to assess based on the objectives of this project?

3.6.1 Choice of Output Variables

Even prior to approaching an output analysis, performance measures were already an integral part of the simulation model. Fill rates are used by trailer agents, whilst daily distances and CNG consumption are calculated by forklift agents. Similarly, handling times and pallet throughput were a central component of the calibration process. Which of these measures should be chosen for model validation?

The choice of output variables is influenced by three main factors. The first limitation is the availability of real measurements that allow for the comparison of the simulation model with current operations in the facility. A second dimension to output analysis is delineated by the objectives of the project (refer to chapter 1). Namely, environmental and logistic performance should both be covered by output variables. Finally, a third consideration is the statistical significance of model validation, which should offer consistency and reproducibility. In terms of real measurements, the total time pallets spent in the facility or **total time in dock** will be used as the main output variable. Not only is this variable present in the company's data, but its real probability distribution has already been determined (refer to figure 3.6d). Moreover, deviations from the real distribution of total time in dock would indicate that the model does not deal with pallet throughput correctly. In spite of its importance, time-based performance does not fully embody the objectives of this project. To comply with the environmental perspective, both the distance travelled and the fuel consumed by forklifts will be considered as principal output variables. Distance (in feet) and CNG (in m^3) will be measured on a daily basis (24 hours) for all the forklift fleet. Although real measurements are not available for these indicators, statistical analysis will be used to scrutinize the simulation results. Last but not least, other performance indicators could be analysed since they are already a part of the model, such as pallet throughput, trailer fill rates, amongst others. The in-depth study of these variables, however, extends beyond the scope of this study.

3.6.2 Number of Replications

Output analysis enables the modeller to confirm that the model produces statistically significant data, while aiding to determine the number of simulation runs required [37]. Given the time horizon of one day (24 continuous hours), how many simulation days are enough? In order to assess the impact of simulation runs, three approaches have been followed, all with a confidence level of 90% ($\alpha = 10\%$). In all cases, independent simulation runs have been used due to the presence of a warm-up period.

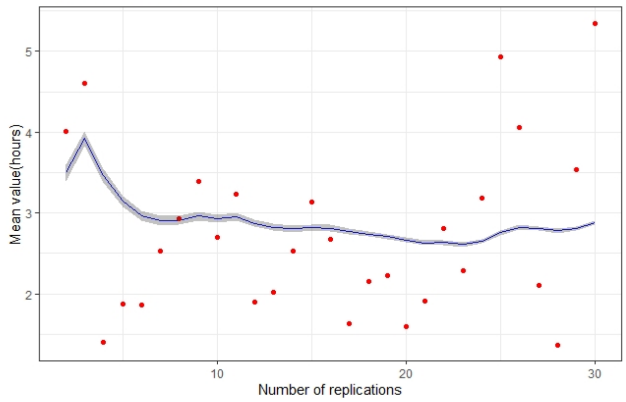
First, the mean value of output variables has been evaluated. Each simulation run (day) produces a local mean value ($\bar{X}$), whereas the successive aggregation of local means leads to a global mean ($\bar{\bar{X}}$). This statistical assessment revolves around the standard error of the mean (SE), shown in equation 3.2. It was calculated that after 15 replications, the global mean and its SE stabilized in all three cases. Figure 3.18 illustrates the evolution of the global means as the number of replications increases.

$$SE = \frac{\sigma}{\sqrt{n}} \tag{3.2}$$

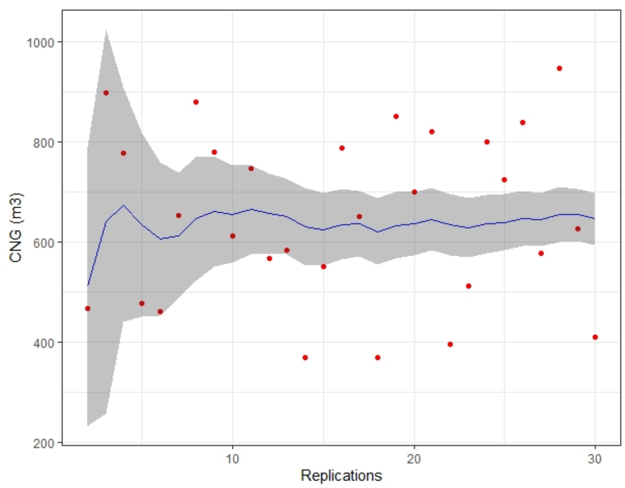
Where:

σ : standard deviation

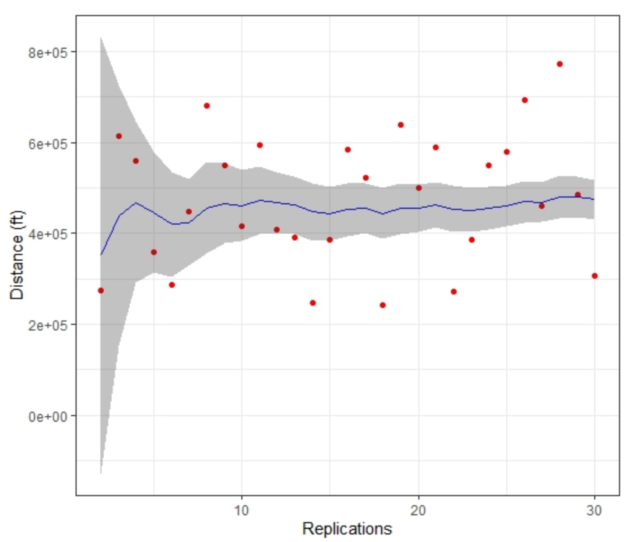
n : number of observations



(a) Total time in dock



(b) CNG consumption



(c) Distance travelled

Figure 3.18 Global mean and replications

The second approach to statistical validation also evaluates the mean value of output variables, but focusing on the half-width of the mean, defined in equation 3.3. The evolution of the half-width for all three output variables is shown in figure 3.19. This approach is similar to the standard error (SE) from a numerical viewpoint, but it provides a more understandable measure of margin of error. What's more, the half-width is also indicative of confidence intervals. The results in this case indicate that between 12 and 15 replications are needed. After that many simulation days, the value of the half-width is undoubtedly stable.

$$h = z_{\alpha/2} \times \frac{\sigma}{\sqrt{n}} \tag{3.3}$$

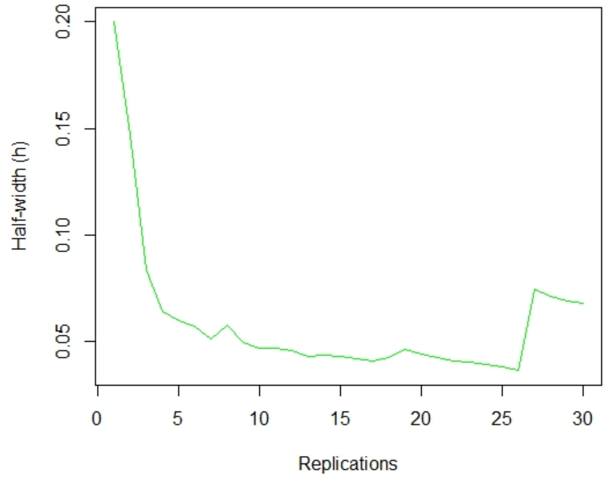
Where:

σ : standard deviation

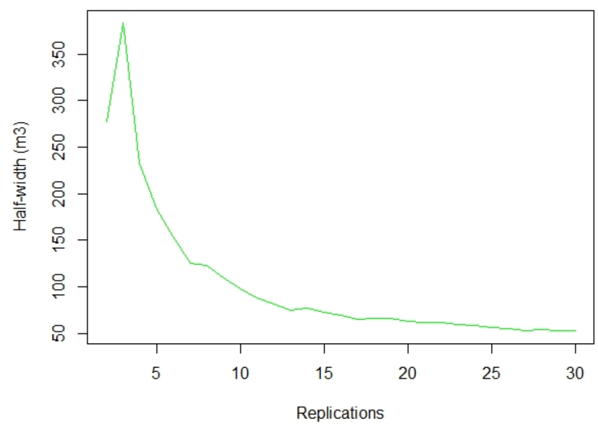
n : number of observations

$z_{\alpha/2}$: $100 \times (1 - \alpha/2)$ percentile of the standard normal distribution

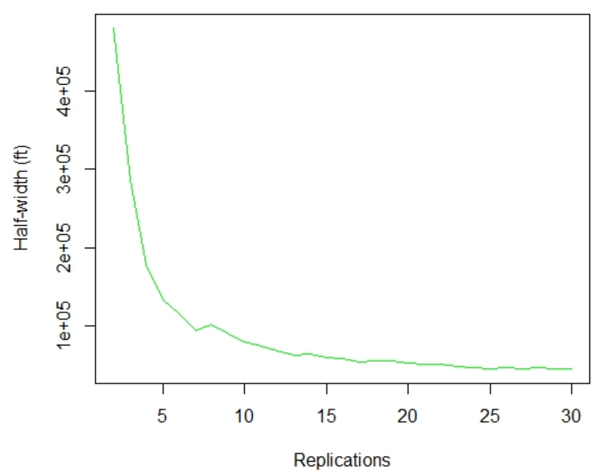
$(1 - \alpha)$: confidence level



(a) Total time in dock



(b) CNG consumption



(c) Distance travelled

Figure 3.19 Half-width of the mean and replications

Finally, the last method for output analysis consists on comparing the real probability distribution of an output variable with its simulated distribution. Consequently, only the variable of total time in dock can be assessed through this technique. Prior to executing the statistical test of comparison, both distributions are compared in figure 3.20, where the impact of replications on the simulated distribution can be seen. A two-sample test examines whether two samples belong to the same theoretical statistical distribution, which may be standard (normal, lognormal, binomial, etc.) or undetermined. In addition, several options for this test were considered. The Kolmogorov-Smirnov test is unfit for large data sets, so it was ruled out. Similarly, the Wilcoxon two-sample test requires paired samples. On that account, the Mann-Whitney U Test was selected, being the unpaired version of the Wilcoxon signed-rank test [34]. In addition, two measures of stochastic equality were chosen to complement the test: Vargha & Delaney's A and Cliff's delta. These indicators served as a confirmation that the test results where consistent. After performing the test, both samples were concluded to belong to the same underlying distribution; that is, they are stochastically identical, but with a shift of 0.45 hours. Upon further study, it was determined that this shift between real and simulated probability distributions is related to the trailer arrival rates discussed previously. Since these input values were estimated from pallet handling times, they did not reflect precise trailer arrival but rather trailer docking times. Nonetheless, this test confirms that the simulated system behaves akin to the actual facility. Furthermore, the test was performed with varying number of replications, leading to consistent results after only 5 replications. These results are summarized in figure 3.21.

The three methods for output analysis indicate that it takes between 5 to 15 replications for the model to produce statistically significant results. Howbeit, 5 replications suffice only for the variable of total time in dock, for which many more observations are recorded per simulated day. To be on safe side, 30 independent replications will be used for the experiments performed with the model. The nature, design and results of these experiments are described in depth throughout the next chapter.

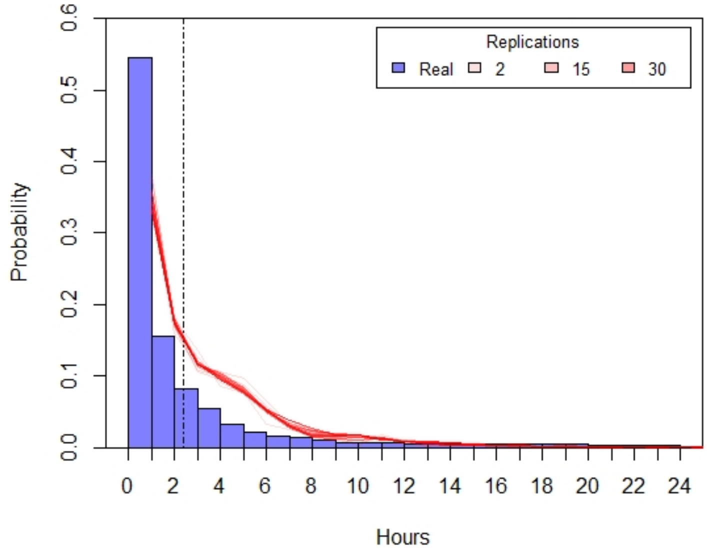
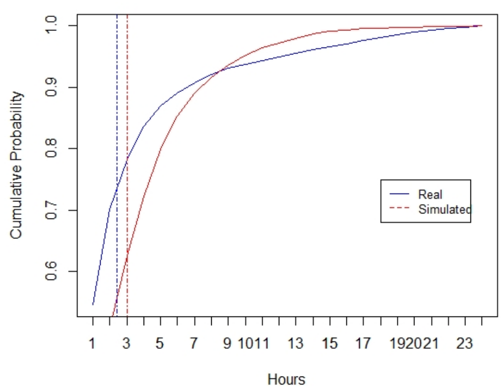
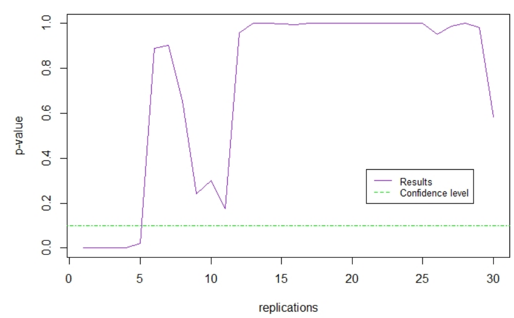


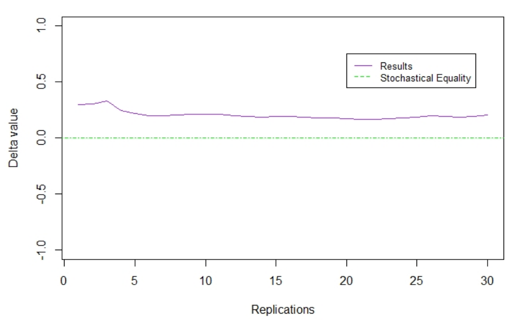
Figure 3.20 Total time in dock: distribution and mean



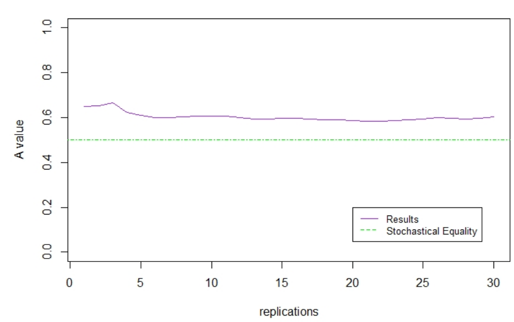
(a) Distribution and mean



(b) P-value



(c) Cliff's Delta



(d) Vargha and Delaney's A

Figure 3.21 Mann-Whitney U-test: total time in dock

CHAPTER 4 EXPERIMENTS

Generally speaking, an experiment can be defined as a series of test runs through which the input variables of a system are purposefully modified so as to observe changes in output variables. The reasons behind a given output response can also be analysed [38]. In the context of this project, experimenting with the simulation model facilitates the study of the cross-dock's performance from both a logistic and environmental perspective. Throughout this chapter, the experimental set-up will be defined in terms of input parameters (factors) and output variables (response), followed by the experimental results, in alignment with the research objectives stated in chapter 1.

4.1 Parameters

A diagnosis of the problematic hindering cross-docking operations in the studied facility was presented in chapter 3. The excessive displacement of forklifts to move pallets around the cross-dock was identified as a symptom, rather than a constitutional flaw of the process. Instead, there are two potential root causes, either the facility layout or the door assignments. As far as layout is regarded, the disposition of pallets racks could easily explain the problematic. Changes in layout are, unfortunately, cost prohibitive and require major modifications to the simulation model. Consequently, layout will not be assessed as part of the experiments. Other possibilities, such as the installation of balances on forklifts and other handling equipment upgrades, were discussed with the company but were discarded for being financially burdensome. Instead, door assignments are considered as the chief experimental parameter. The assignment of dock doors to activities and zones was explained in chapter 3 and summarized in table 3.3. While door assignment problems arise in all transportation facilities, cross-docks introduce additional levels of complexity to such problematic, namely in terms of service mode and time restrictions. Most research deals with door assignment through novel formulations and resolutions of the Cross-dock Door Assignment Problem (CDAP). These are usually developed around specific settings, though generic deterministic models do exist [9, 15–17]. Nonetheless, these problems often require customized heuristics to yield solutions. As discussed in chapter 2, computationally cumbersome solutions are difficult to implement in a real company, especially with regards to operational problems. Thus, the main challenge for experimenting with the model is the generation of door assignments that lead to reductions in distance and fuel consumption. Prior to creating potential assignment solutions though, the design of experiments must be addressed.

4.2 Design of Experiments

Statistical design of experiments (DOE) consists of a plan of the experiments that ensures data collection and analysis in a statistically meaningful manner, yielding valid and objective conclusions. DOE is built upon three main principles [38]:

1. **Randomization**: both the allocation of experimental material and the order of runs are randomly determined.

2. **Replication**: the aggregation of replicates, defined as independent repeat runs of each factor combination, leads to an estimate of experimental error and a more precise estimate of the response.

3. **Blocking**: design technique that boosts precision by creating a *block* or a set of relatively homogeneous experimental conditions.

Even though complete randomization is difficult, replication enhances the experimental procedure by targeting sources of variability both between runs and within runs. Moreover, blocking further reduces the variability from nuisance factors that may have not been addressed directly. In addition to the tripartite basis of DOE, the **factorial principle** is also foundational as it pertains to input parameters or *factors*. In this project, factors are defined as the individual door assignments to activities (load or unload) and zones (12 zone codes as shown in table 3.2). Factor variation will be described next.

4.2.1 Factor Variation

Experimental input variables or factors are usually modified within a range of values. The scope of this variation, in turn, can be determined through different approaches depending on the number of inputs. Adjusting one factor at a time (OFAT) is the simplest technique, though it may prove tedious for a high number of factors. The most statistically sound alternative is factorial design, which requires all factors to be varied together, making the most efficient use of experimental data by evaluating all possible factor combinations. The total number of experiments (N_E) is thus a function of the number of factors (f) and the number of levels (n) or possible values for each factor, so that $N_E = n^f$. Often times, howbeit, a fractional factorial experiment is performed given that not all factor variations are relevant to the experimental objectives [38]. In this specific case, door assignments (refer to table 3.3) can be considered as a set of 270 variables: 45 doors $\times$ 3 shifts $\times$ 2 assignment types (activity and zone). Furthermore, the two assignment types are different in nature, with activity assignments having three levels (load, unload or any) and there being 13 possible zone assignments (12 zones plus *all zones*). The total number of distinct experiments, based exclusively on door assignments, is then: $3^{135} + 13^{135}$, which an incommensurately large figure. Therefore, the experimental approach followed mirrors closely a fractional factorial experiment, given that evaluating all the experimental possibilities would be computationally infeasible. Having established the fractional factorial approach, a more pressing concern arises: how to find pertinent combination of experimental factors? An heuristic has been developed in order to create complete assignment tables, designated as *assignment solutions*. The innards of this algorithm are detailed next.

4.2.2 Door-assignment Heuristic

The custom-built procedure developed to assign doors to activities and zones is based on generalizable data inputs related to material flow and internal distances. In other words, although this heuristic has been developed with the studied facility in mind, it may be applied to door assignments in other transportation terminals, especially cross-docks. Its objective is the assignment of handling activities and zones to dock doors. Both assignment types are mostly influenced by the flow of pallets, whereas the choice of door is predominantly constrained by the distance between doors. Of note, deterministic models and notably mixed-integer programming remain a superior alternative as far as optimality is regarded. Their applicability is unfortunately beyond the scope of this project. With that in mind, one last caveat with respect to the heuristic is that a number of doors is expected to remain unassigned, with their activity as ANY and their zone as ALL.

Data Inputs

Staging is the core phase of cross-docking, spanning from the unloading of goods from inbound trailers to their loading onto outbound trailers. In the studied facility, forklifts are entirely in charge of pallet handling, moving through an internal network wherein distances are constant. On that account, three data inputs for the algorithm have been defined: the dominant handling activity, the pallet flow between origin and destination zones, and the distances between doors. The first two inputs are defined per work shift of eight hours, with a 24-hour simulation day consisting of three consecutive shifts labelled as:

- 00-08h: from midnight to 8 AM.
- 08-16h: from 8 AM to 4 PM.

- 16-00h: from 4 PM to midnight.

The importance of pallet flow stems from the imbalance between pallet origin and destinations zones. As discussed in chapter 3, the volume of pallets per origin zone does not match the volume for the same destination zone. Such an asymmetry was further illustrated by figures 3.3c and 3.13a. As a consequence, more pallets are either loaded or unloaded at a given time, with the trend varying per shift. During a given work shift, the inbound and outbound flow of pallets requires unloading and loading, respectively. Outbound pallets, in addition, may have been unloaded in the same shift or in a previous one. Moreover, part of the pallets unloaded in a given shift are temporarily stored and remain in the facility until a later shift. The percentage of daily pallet flow that enters and exits the cross-dock in the same shift is highlighted in yellow in table 4.1. Whilst most pallets unloaded are loaded within the same shift, an important proportion of pallets do remain in temporary storage. Based on the particularities of pallet flow, a dominant activity per shift has been determined and summarized in table 4.2. The purpose of determining the dominant handling activity is the assignment of a higher number of doors to that activity. Another component of pallet flow is the relationship between origin and destination zones, which relates to unloading and loading, respectively. Appendix A contains a table specifying the pallet flow between origins and destinations, with flow being defined as the quantity of pallets having a given origin-destination pair. The origin-destination flow is, just like the dominant activity, defined per work shift.

Table 4.1 Inbound and outbound pallet flow per work shift

(percent of pallets)		Outbound			
	Shift	00-08h	08-16h	16-00h	Unloaded
Inbound	00-08h	29%	8%	1%	38%
	08-16h	3%	9%	3%	14%
	16-00h	13%	3%	31%	47%
	Loaded	46%	19%	35%	100%

Despite the internal network being fixed, the distance between two doors varies given that all pallets are weighed after unloading and that there are two scales in the facility. Therefore, a forklift has two options when moving a pallet from an inbound to an outbound door, as exemplified in figure 4.1. Given that at least two different handling distances are possible between a pair of doors, two separate distance matrices were calculated based on the CAD drawing of the facility (refer to figure 3.9) - both are included in appendix B. Between a unique pair of doors, the minimum of these two possible distances has been used as an input to the assignment heuristic. It is thus supposed that the assignment of origin and destination zones will be performed giving preference to door pairs that are closer to one another. The resulting input is a table with each unique door pair (from - to) and the (minimum) distance between them.

Table 4.2 Dominant handling activity per shift

Shift	Activity		Dominant activity
	UNLOAD	LOAD	
00-08h	38%	46%	LOAD
08-16h	14%	19%	LOAD
16-00h	47%	35%	UNLOAD
	100%	100%	

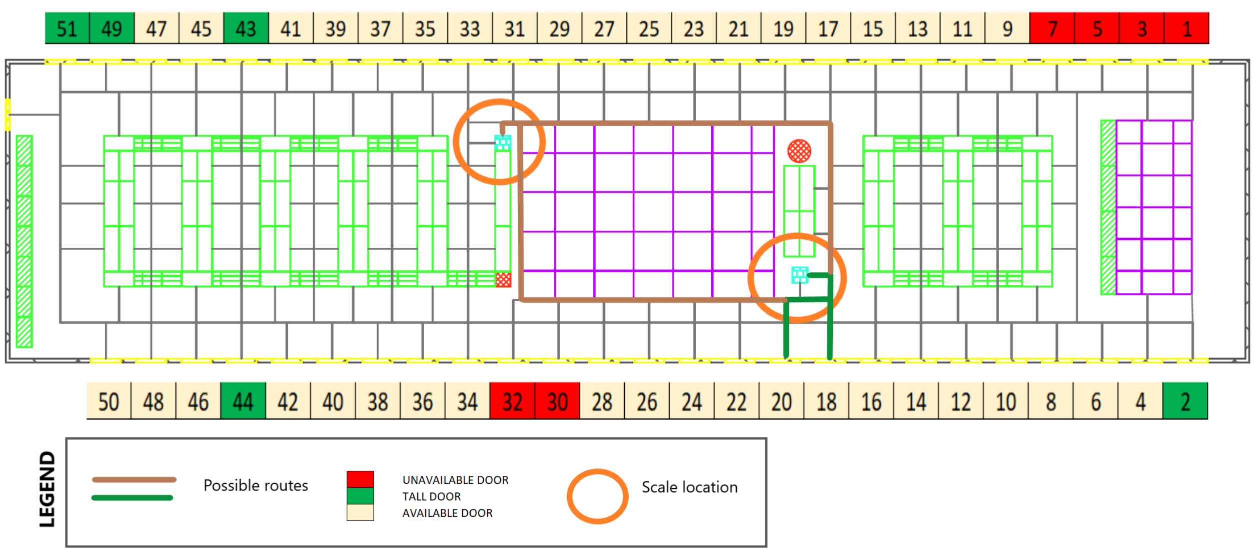


Figure 4.1 Possible distances between doors #18 and 20

The Heuristic

While the minimum distance between doors is the same regardless of the time of the day, door assignments change thrice a day. Therefore, the heuristic creates an assignment table valid for an eight-hour shift and the procedure must be repeated three time to yield a complete *assignment solution* for a 24-hour workday. As previously stated, the heuristic is inspired by fractional factorial experiments and favours proximity between doors, as well as origin-destination (O-D) pairs with a heavy flow of pallets between them. Moreover, the procedure assigns at least two doors to a given origin-destination pair: one is assigned to the origin and to unloading, whereas the other is assigned to the destination and to loading. Besides, origin-destination pairs that have a low pallet flow between them and hence require less than two doors will not be assigned to any door. Likewise, the five *tall* doors are left unassigned, as they might become a bottleneck otherwise (10% of inbound trailers require a tall door). In total, 40 dock doors require activity and zone assignments. Whenever an O-D pair requires an uneven number of doors, the unpaired door is assigned to the dominant activity of the shift and to its respective zone. One major pitfall of the heuristic is that it fails to target the difference of door assignments between shifts. Conceiving door assignment for each shift separately may pose operational hurdles if the assignments between two successive work shifts differ considerably. That being said, the specifics of the heuristic are explained next; the whole procedure has been carried out in RStudio [39].

Prior to running the heuristic, further modification of the inputs is necessary. Data preparation begins with the afore-described distance table. First, all door pairs (from - to) containing a tall door are removed, as tall doors are not to be assigned. The distance table is then sorted by increasing distance in order to keep door pairs with the smallest distance between them at the top. The logic behind this arrangement is to have the procedure loop through the distance table starting with the doors closest to one another. As far as the pallet-flow table is regarded, it initially contains three fields: origin zone, destination zone and pallets (quantity). The table is first sorted by descending number of pallets, so that the O-D pairs with the heaviest flow are at the top. Subsequently, the percentage of pallet flow is calculated for each O-D pair, together with the number of doors required per pair. The latter is the product of the total number of doors to assign (40) and the percentage of pallet flow for a given O-D pair. Next, the O-D pairs requiring less than 1.5 doors are removed from the flow table. Not all O-D pairs can be assigned to doors because some are negligible in terms of flow. Therefore, only origin-destination pairs requiring over 1.5 doors will be considered. The cumulative percentage of pallet flow after which O-D pairs are excluded usually ranges from 70 to 80%. This percent limit also influences the number of doors to assign, which is recalculated by multiplying the limit by 40. In this manner, it is ensured that the 40 doors will cover the entire pallet flow although some remain unassigned. Once the flow table has been reduced, the percentages of pallet flow for each O-D pair are re-tallied based on the new total of pallets. Similarly, the number of doors required per pair is recalculated. The required number of doors per O-D pairs are finally rounded to integer numbers, favouring the largest integer. The choice of rounding up the number of doors required is valid because less than 40 doors will be assigned in any case. Finally, an assignment table is created containing all 40 doors indexes and two columns: activity and zone, with all assignments being initialized to *ANY* and *ALL*, respectively. After data preparation is complete, the heuristic iterates through the flow table first, assigning an origin and a destination to two doors at a time by looping through the distance table and recording the allocations in the assignment table. Having sorted the distances by ascending values and the flow by descending values allows the procedure to assign the most important O-D pairs and the closest door pairs. Pseudo-code for this procedure is shown on page 70.

Adding Randomness

Randomization is one of the foundational pillars of DOE and it should be considered when it comes to factor variation. Unfortunately, the heuristic described always produces the same result for invariable inputs, preventing the generation of different assignment solutions. Instead of modifying the procedure to include randomness, data preparation was slightly altered. Namely, randomness was introduced by modifying the distance table. More specifically, the distances were rounded up to the unit, leading to groups of door pairs having the exact same distance. Then, when sorting the table by increasing distance, door pairs having the same values were randomly sorted. Consequently, whenever the distance table was sorted, a different and randomized input table was obtained. In this manner, closest distances were still of utmost importance yet the algorithm could generate unique results depending on the random sorting of some door pairs - all without requiring any changes to the heuristic itself. This larger range of manoeuvre enabled the creation of 10 different solutions based on the minimum possible distance between doors. Moreover, 10 completely random solutions where obtained by mixing the distance table around without any regards to distance values. These assignment solutions were used to run experiments labelled in the following fashion:

- Exp. 0: designates the current assignment or baseline
- Exp. 1 to 10: assignment solutions based on the minimum distance between doors
- Exp. 11 to 20: assignments solutions based on the randomly mixed distance table
- Exp. 21: entirely unassigned solution (activity: ANY and zone: ALL, for all doors in the three shifts)

Door assignment heuristic

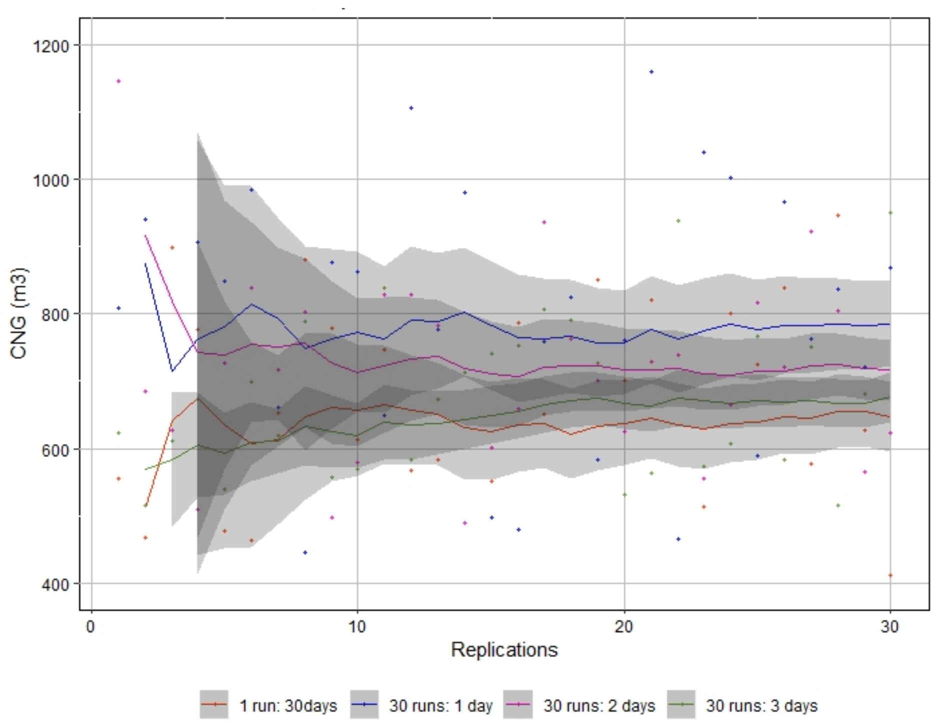
```
Result: Assign activity and zone to each door
Initialization: [dominant activity], [flow table], [distance table], [assignment table];
for each origin-destination zone (O-D) pair in [flow table] do
    [origin] = origin zone code in O-D pair;
    [destination] = destination zone code in O-D pair;
    d : integer number of doors to assign;
    a : integer number of doors assigned = 0;
    if d is uneven then
        d = d − 1;
        d_0 : unpaired door = 1;
    while a < d do
        for each door pair in [distance table] do
            if both doors in a pair are unassigned in [assignment table] then
                Assign lowest-index door to: UNLOAD, [origin];
                Assign other door to: LOAD, [destination];
                Record assignments in [assignment table];
                a = a + 2
        end
    end
    if d_0 > 0 then
        for each door pair in [distance table] do
            if [dominant activity] = LOAD then
                if one door in a door pair is assigned to [origin] and the other is
                 unassigned in [assignment table] then
                    Assign unassigned door to: LOAD, [destination];
            else if [dominant activity] = UNLOAD then
                if one door in a door pair is assigned to [destination] and the other is
                 unassigned in [assignment table] then
                    Assign unassigned door to: UNLOAD, [origin];
        end
end
```

4.2.3 Performance Indicators

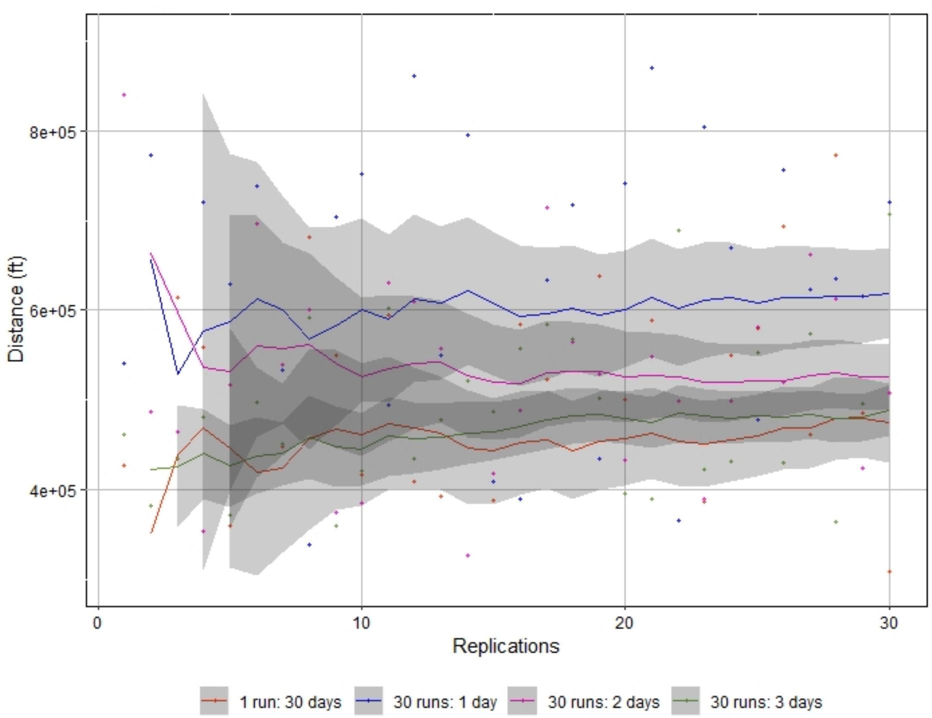
The final component of DOE is the choice of output variables or the **response**. The simulation model of the cross-dock has three main output variables: total time in dock, CNG consumption and distance travelled by all forklifts. The last two are measured for a whole simulation day (24 continuous hours) and reflect environmental and logistic performance, respectively. Given that they are comparable and related, they will be used to evaluate the experimental results. Furthermore, the validation of the experimental set-up is also based on these two indicators.

4.3 Validation

Replication and blocking are core principles in DOE. The former requires each simulation run to be independent because variations in the response are expected both between experiments and within an experiment. Blocking, in turn, calls for the experimental conditions not to vary between experiments. The statistical validity of the experimental response therefore relies upon an appropriate number of replications and the level consistency between them. Following the output analysis performed in chapter 3, a total of 30 replications were determined to suffice from a statistical viewpoint. The duration of each individual run, nonetheless, was not scrutinized. Further analysis revealed that the duration of an individual simulation run should be extended to three 24-hour days, instead of one. Extending the time horizon to three days allows the simulation model to better overcome the variability associated with the warm-up period. In one single day, the model was unable to absorb the statistical effects of warm-up. Three days, in turn, reflected a considerably steadier state, as depicted in figure 4.2. In these graphs, both response variables have been tallied for a replication time of one, two and three days. In other words, the individual duration of a replication varied from one to three days, with 30 total replications. These results were compared with a single simulation run of 30 continuous days (each day being a *replication*). The results of the single run of 30 continuous days reflect a steady-state, which is only comparable with 30 independent runs of 3-days each. Having defined the time horizon and replications, the experimental framework is finalized and complies with the three aforementioned principles. Figure 4.3 portrays the validity of the experiments, demonstrating the variability between individual experimental runs (experimental error), together with the mean value towards which they converge.

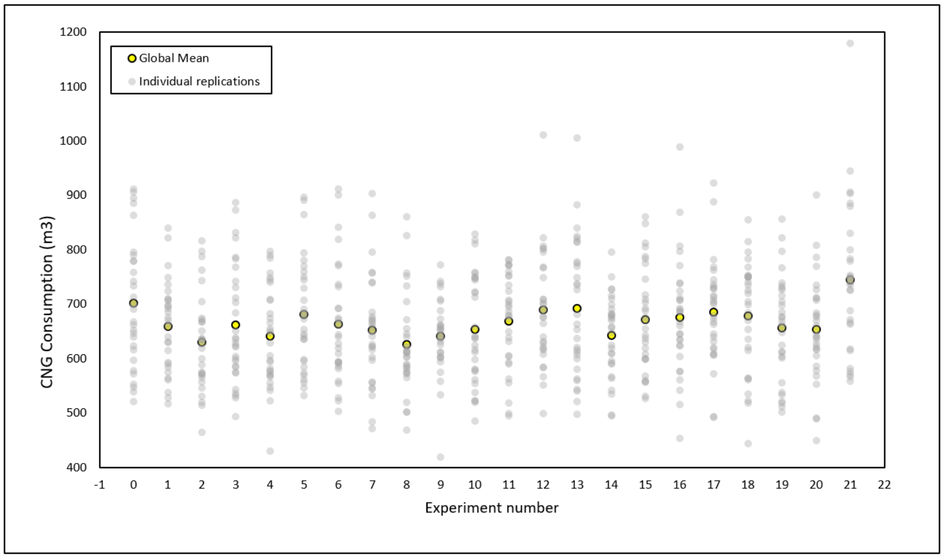


(a) CNG Consumption (m^3)

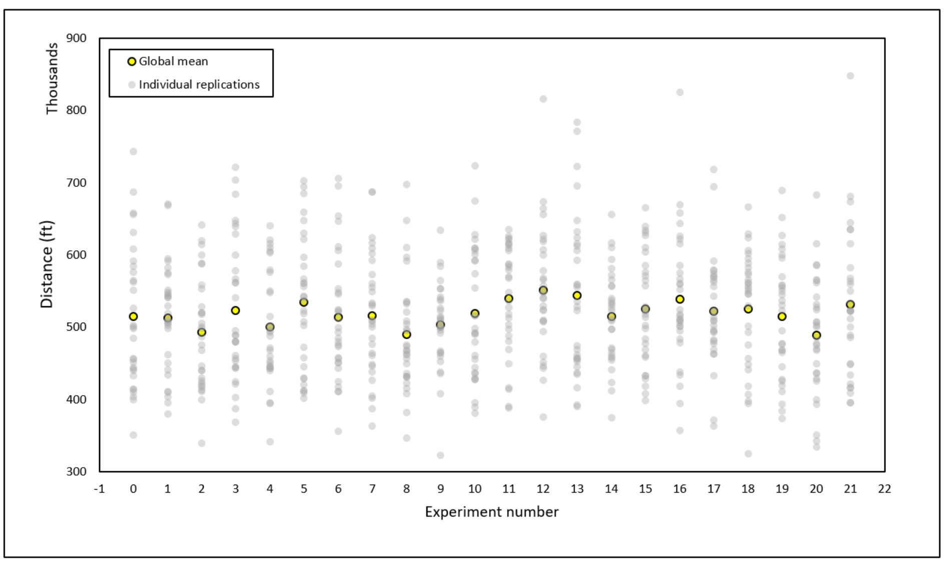


(b) Distance (ft)

Figure 4.2 Simulated results based on the number of replication days



(a) CNG Consumption (m^3)



(b) Distance (ft)

Figure 4.3 Variability of experimental results

4.4 Experimental Results

To sum-up, the experiments performed follow three conditions:

1. Each experiment utilizes a different door-assignment solution, the only experimental parameter.
2. Each experiment was repeated through 30 independent replications, used to calculate experimental results.
3. Each replication consists of a simulation run of three consecutive 24-hour days, excluding the warm-up time.

The experimental results are summarized in figure 4.4. In general, the assignment solutions based on the minimum distance between doors are superior than those randomly assigned, though a few random solutions may outperform them. In addition, the baseline assignment (#0) shows a better performance than the unassigned solution (#21), proving that the current practices at the facility are reasonable, especially in terms of distance. Conversely, all random solutions lead to less CNG consumption than the baseline, implying that current door assignments entail considerable forklift wait times (fuel consumption without distance). Last but not least, all ten heuristic-generated assignment solutions (#1 to 10) are better than the baseline as far as CNG is concerned. Only five out of these, howbeit, generate a better overall response than the baseline (#1, 2, 4, 8 and 9), considering both CNG consumption and distance. The assignment solution #8 is undoubtedly the most performing option, but its feasibility and pertinence must be further examined. The conclusion undertakes this discussion.

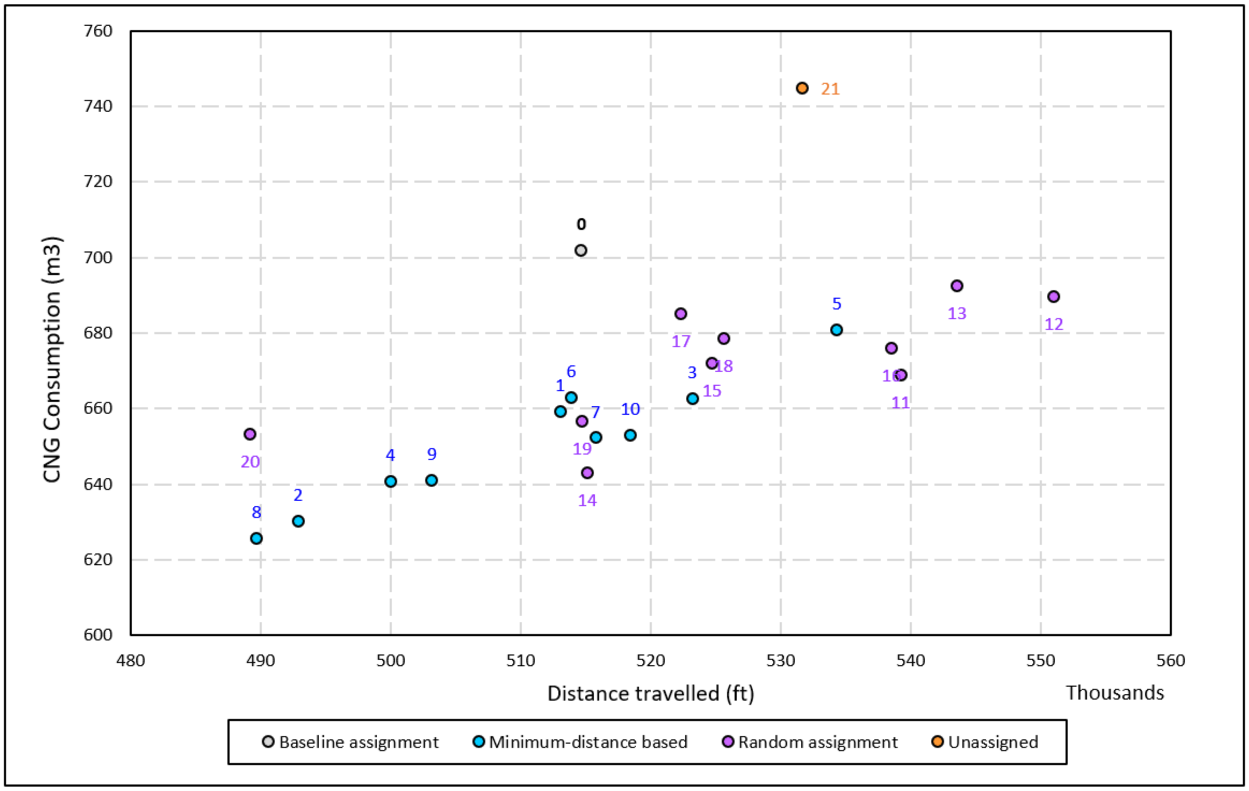


Figure 4.4 Experimental results (24-hour average for all forklifts)

4.5 Environmental Impact

Thus far, fuel consumption has been used to assess environmental impact. Given that the company is billed by their consumption of CNG (in cubic meters), this orientation facilitated conveying experimental results to the organisation. Despite this choice of metric, the environmental focus of the project calls for a more relevant indicator: CO_2 emissions.

The equivalent CO_2 emissions associated to fuel consumption can be expressed either in kilograms or in metric tons. While different approaches exist for such conversion depending on the country and vehicle, standard conversion factors from the United States Environmental Protection Agency (EPA) have been used in this case [40]. The experimental results previously presented have been converted to equivalent Kg of CO_2, as shown in figure 4.5. Based on these results, it can be inferred that current operations (solution labelled as #0) emit less CO_2 than the case of an entirely unassigned setting (solution #21). Nonetheless, there is ample room for improvement and additional efforts could be made to reduce the environmental impact of internal cross-docking operations. To further explore the potential reduction of CO_2 emissions, an alternative emission metric can be used: the equivalent emissions by a typical passenger vehicle's gasoline engine. According to the EPA, a typical gasoline engine emits 8.89 Kg of CO_2 per gallon [40]. Consequently, current material handling activities in the cross-dock pollute as much as 152 gallons of gasoline per day. This daily emission figure is considerable, though it could be reduced to 136 gallons per day if more efficient door-assignment solutions are implemented in the facility. The same exercise can be repeated for a typical diesel engine, whose conversion factor is 10.18 Kg of CO_2 per gallon. On that account, table 4.3 presents the experimental results previously described in terms of equivalent emissions, with their kilogram, metric-ton and gallon equivalents.

These results confirm that the environmental impact of internal operations is not negligible. Whilst organisations attempt to utilise more environmentally-friendly fuels (such as CNG or LNG), efforts to quantify and reduce emissions tied to material handling equipment are still falling behind. The integration of such concerns into everyday operations and tactical planning is becoming an increasingly urgent matter. Although it may appear that forklifts and other low-emission vehicles do not pollute as much as trucks, their impact on the environment can no longer be overlooked.

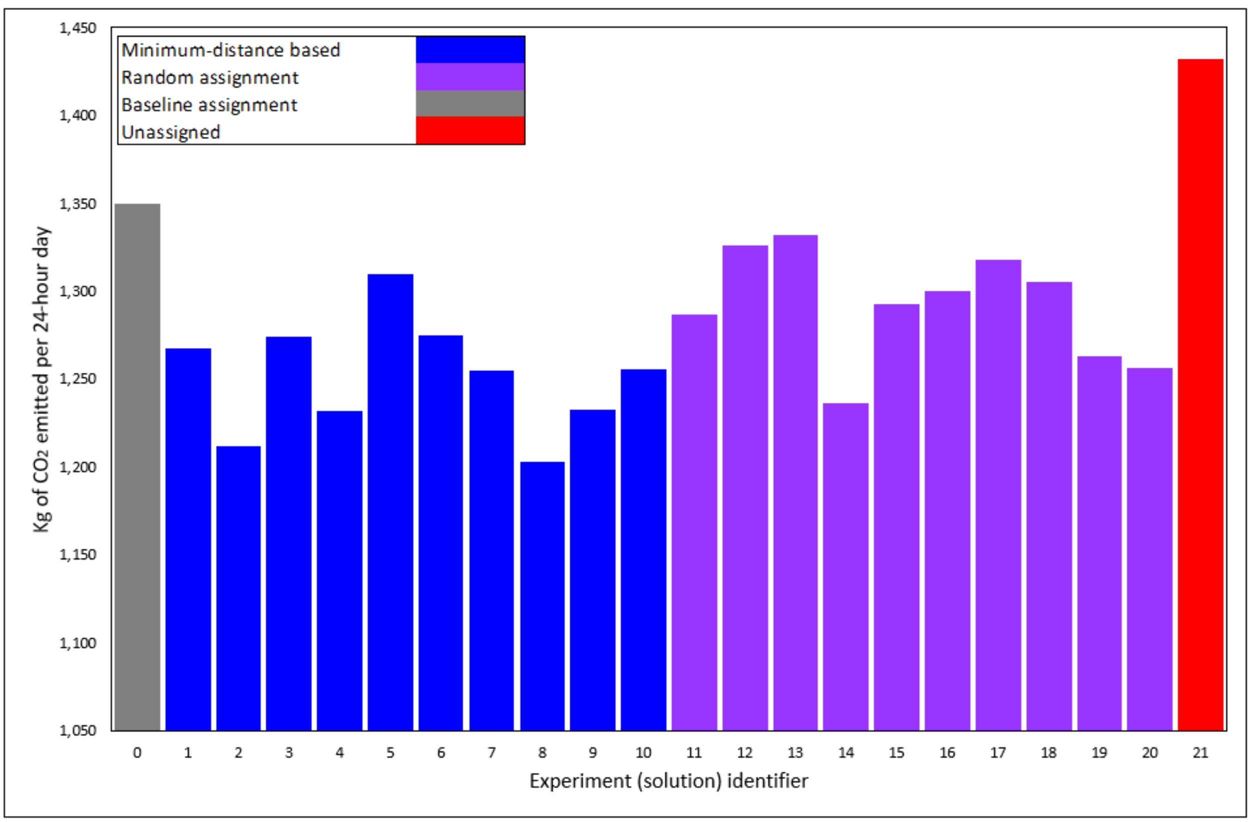


Figure 4.5 Experimental results as equivalent Kg of CO_2

Table 4.3 Experimental results: distance, CNG and CO_2

Solution	Description	Distance (ft)	CNG (m3)	CO_2 (Kg)	CO_2 (Tons)	Gallons	
						Gasoline	Diesel
0	Baseline assignment	514,656	702	1,350	1.35	152	133
1	Minimum-distance based	513,031	659	1,268	1.27	143	125
2	Minimum-distance based	492,872	630	1,212	1.21	137	120
3	Minimum-distance based	523,180	663	1,274	1.27	144	126
4	Minimum-distance based	499,975	641	1,232	1.23	139	122
5	Minimum-distance based	534,323	681	1,309	1.31	148	129
6	Minimum-distance based	513,882	663	1,275	1.27	144	126
7	Minimum-distance based	515,746	652	1,254	1.25	142	124
8	Minimum-distance based	489,673	626	1,203	1.20	136	119
9	Minimum-distance based	503,165	641	1,233	1.23	139	122
10	Minimum-distance based	518,413	653	1,256	1.26	142	124
11	Random assignment	539,214	669	1,286	1.29	145	127
12	Random assignment	551,003	690	1,326	1.33	150	131
13	Random assignment	543,552	692	1,331	1.33	150	131
14	Random assignment	515,107	643	1,236	1.24	140	122
15	Random assignment	524,709	672	1,292	1.29	146	127
16	Random assignment	538,505	676	1,300	1.30	147	128
17	Random assignment	522,317	685	1,318	1.32	149	130
18	Random assignment	525,575	679	1,305	1.30	147	129
19	Random assignment	514,709	657	1,263	1.26	143	125
20	Random assignment	489,176	653	1,256	1.26	142	124
21	Unassigned	531,663	745	1,432	1.43	162	141

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

From its early mapping phase to the final experimental stage, this project has allowed the involved parties to peer into the intricate details of cross-docking, building a well-rounded outlook on the generalities and particularities of the studied facility. Moreover, the study has led to an insightful perspective on improvement opportunities for the organisation, together with recommendations for the future of internal operations in the cross-dock. A summary of the exploits of the project is presented in this section, followed by a recommended course of action for the company. Finally, an overview of the limitations of the study is followed by an outline of potential avenues for future research.

5.1 Summary of Works

The inception of the cross-dock ABM was grounded on a comprehensive mapping of the current state of operations. The starting point for this endeavour was the development of a business process map, which was well-received by the organisation and used to identify possible communication pitfalls between departments participating in LTL transportation services. Similarly, a cross-dock characterization grid was created from an aggregation of criteria collected from relevant literature. Not only was this grid instrumental in comprehending the particular attributes of the studied facility, but it offered untapped potential in the portrayal and comparison of cross-docks both within and beyond the organisation. The most auspicious deliverable of the early stages of the project, though, was the analysis of operations based on the company's own databases. The definition of the load unit in terms of size, quantity, frequency and handling times had a remarkable impact on the definition of work-schedules and operational parameters. On that account, Groupe Robert decided to reduce its weekend operations. Likewise, the definition of zone codes was modified to group low-volume zones together. The feedback received was thus positive, highlighting the beneficial integration between academic research and large-scale supply-chain organisations. Moreover, it was established, as an indispensable rule of thumb, that comprehensive analyses were essential prior to decision-making, even on an operational basis. The company went even as far as creating a new performance department bestowed with the role of measuring and improving the operations of their various transportation facilities. Whilst these initial steps had a noticeable effect on the company, the simulation model was undoubtedly the utmost exploit of this research. On the one hand, existing discrete-event models and related guidelines were the cornerstone of the model. As a consequence, there is direct continuity with previous research. The chief innovation, on the other hand, lies on the integration of agents into the simulation, opening new opportunities for a more detailed modelling of cross-docking operations. The potential hidden in ABM will be further explored in a latter section of this chapter. Furthermore, a door-assignment algorithm was created based on pallet flow and internal distance. Both inputs apply to the reality of most transportation facilities, enabling the algorithm to be used in a plethora of different settings. Although the procedure may appear rather rudimentary when compared to the current state of the art, its practical value shall not be overlooked. In this specific case, the algorithm was utilized to generate complete assignment solutions. These assignment tables were then experimented upon by means of the simulation model, evaluating the response in terms of logistic and environmental performance. Most importantly, the experimental results are meaningful in that recommendations can be sketched around them. The recommended courses of actions for the organisation with respect to the studied cross-dock are explained next.

5.2 Recommendations

On first look, the modeller might feel tempted to directly recommend the assignment solution leading to the best performance, as quantified by CNG consumption and distance travelled. Such a verdict, howbeit intuitive, may prove misguided because the simulation model is only a partial representation of the real cross-docking system. In other words, logistic and environmental performance are not unhinged: supplementary real-world constraints must be considered prior to implementing any changes to current operations. In addition to further analysis, an open discussion should forego any operational amendments, together with the articulation of a communication strategy for the dissemination and application of new door assignments. A sensible approach could be the evaluation of a number of best assignment solutions reflecting a desired level of performance. Recommending a set of solutions instead of only one provides the organisation with greater flexibility while serving as a gateway for a broader discussion on performance indicators and workforce organisation. With that in mind, the best assignment solutions could be implemented following their approval at various levels of the company, ranging from managers to cross-dock directors. On that account, the scrutiny of forklift operators and cross-dock personnel is also key, given that these employees would be impacted the most by any door assignment modifications. Succinctly, four main recommendations have been outlined based on the works previously described:

1. Introduce periodical performance indicators in the company, together with a plan to measure, control and communicate them.

2. Utilise the assignment algorithm on a quarterly basis to assess potential changes in door assignments.
3. Revise and approve recommended assignment solutions prior to implementing them.
4. Extend both performance measures and door-assignment solutions to other facilities involved in the LTL business.

Environmental and logistic performance has thus far been represented by fuel consumption and distance, respectively. Nonetheless, a wider range of different indicators hold relevance, including handling times, trailer fill rates and pallet throughput - to name a few. These have all been defined throughout this study and are readily measurable. Notwithstanding the importance of additional performance indicators, the organisation should invest resources in monitoring forklift fuel consumption and distance in a more reliable manner, as current practices disregard both variables. As far as the algorithm is regarded, the impact of seasonality is yet to be addressed. Using the algorithm on a quarterly or even monthly basis could assist the company in understanding the significance of adapting door assignment to seasonal fluctuations in pallet flow. Finally, there is an important organisation-wide discussion to be held on performance, which was briefly hinted in chapters 1 and 3. Beyond organisational change, the acknowledgement of the limitations of this study is pivotal. The following section describes them in more detail.

5.3 Limitations

The main limitations of this study are related to either the simulation model or the door-assignment algorithm. First, the model excluded shunting operations, which were partially accounted for thanks to the introduction of wait times for inbound trailers. The exclusion of the detailed shunting process, unfortunately, limits the validity of the model as the impact of internal operations on truck movements is entirely neglected. In spite of generating a set of door assignment solutions, the effects of these changes on truck and trailer wait times cannot be studied by the existing ABM. Secondly, forklift fuel consumption was not modelled in the most precise fashion, mostly because fuel consumption figures were absent. The calibration of shunting parameters, CNG consumption rates and pallet weighing time allowed the model to reflect current operations, lest these inputs would have simply been replaced by guestimates. Last but not least, the generation of door assignments through a heuristic procedure could only yield sub-optimal solutions, which remain inferior in quality to MIP models or other forms of mathematical programming. What's more, the objective function of such deterministic models could include a wider array of criteria, beyond CNG consumption and distance.

All in all, these limitations must be taken into account when discussing recommendations based on the ABM. On a wider scale, these limitations also hold potential for future studies, as will be discussed next.

5.4 Future Research

Although the aforementioned limitations restrict the scope of this specific project, they also represent valuable research opportunities. The inclusion of the shunting grounds, for instance, could be accomplished by extending the existing model. A separate environment, following the agent logic, could be created to embody the whole shunting process, wherein already existing trailers would be the main agents, together with trucks and shunting vehicles. Similarly, *environment-environment interactions* would simplify the modelling of exchanges between forklifts operators (internal network environment) and truck drivers (external network environment). Another potential extension of the model involves the reproduction of the actual forklift drive cycle. The existing forklift agent could be modified by enhancing its level of cognition, becoming an *adaptive agent* whose actions are directed by a strategy based on both past experience and current inputs. The forklift could then alter its speed and decide when to stop on a case-by-case basis, modifying its fuel consumption accordingly. As a consequence, the drive cycle would be divided in at least two modes: rest (wait) and drive (movement), each with distinct fuel consumption rates. The possibility of integrating pallet weight into the agent's drive state and speed is even on the table. Finally, the response criteria of the model could be enlarged, as noted before, to include trailer fill rates, pallet throughout, temporary storage capacity, holding cost, amongst others. The environmental perspective maintained throughout this project, nevertheless, should remain at the heart of the study of transportation facilities. Beyond research trends and possibilities, environmental concerns ought to be at the core of supply chain developments, both on the road, behind desks and at the center of everyday seemingly menial material handling activities.

REFERENCES

[1] J. Van Belle, P. Valckenaers, and D. Cattrysse, "Cross-docking: State of the art," *Omega*, vol. 40, no. 6, pp. 827–846, Dec. 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0305048312000060

[2] K. Stephan and N. Boysen, "Cross-docking," *Journal of Management Control*, vol. 22, pp. 129–137, Dec. 2011. [Online]. Available: https://link.springer.com/article/10.1007/s00187-011-0124-9

[3] A.-L. Ladier and G. Alpan, "Cross-docking operations: Current research versus industry practice," *Omega*, vol. 62, pp. 145–162, Jul. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0305048315001991

[4] J. J. Vogt, "The successful cross-dock based supply chain," *Journal of Business Logistics*, vol. 31, no. 1, p. Journal of Business Logistics, Jan. 2010. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2158-1592.2010.tb00130.x

[5] P. Buijs, I. F. Vis, and H. J. Carlo, "Synchronization in cross-docking networks: A research classification and framework," *European Journal of Operational Research*, vol. 239, no. 3, pp. 593–608, Dec. 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0377221714002264

[6] O. Ulgen *et al.*, "Simulation methodology: A practitioner's perspective," *International Journal of Industrial Engineering, Aplications and Practice*, vol. 1, no. 2, Jun. 1994. [Online]. Available: https://www.pmcorp.com/Portals/5/_Downloads/SimulationMethodology_APractitioner'sPerspective.pdf

[7] Autodesk. (2020) Autocad: Computer-aided design (CAD) software (version 2018). [Online]. Available: https://www.autodesk.ca/en/products/autocad/overview

[8] The AnyLogic Company. (2020) Anylogic: Simulation modeling software (version 8.5.1). [Online]. Available: https://www.anylogic.com/

[9] F. Enderer, C. Contardo, and I. Contreras, "Integrating dock-door assignment and vehicle routing with cross-docking," *Computers and Operations Research*, vol. 88, pp. 30–43, Dec. 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0305054817301569

[10] M. Napolitano, *Making the move to cross docking: a practical guide to planning, designing, and implementing a cross dock operation.* Oak Brook, IL: WERC, 2000.

[11] Groupe Robert. (2020) Our services. [Online]. Available: https://www.robert.ca/en/services

[12] Y. Ye *et al.*, "Cross-docking truck scheduling with product unloading/loading constraints based on an improved particle swarm optimisation algorithm," *International Journal of Production Research*, vol. 56, no. 16, pp. 5365–5385, Aug. 2018. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00207543.2018.1464678

[13] C. Serrano, X. Delorme, and A. Dolgui, "Scheduling of truck arrivals, truck departures and shop-floor operation in a cross-dock platform, based on trucks loading plans," *International Journal of Production Economics*, vol. 194, pp. 102–112, Dec. 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S092552731730292X

[14] S. Rahmanzadeh Tootkaleh, F. G. S.M.T., and M. Sheikh Sajadieh, "Cross dock scheduling with fixed outbound trucks departure times under substitution condition," *Computers and Industrial Engineering*, vol. 92, pp. 50–56, Feb. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360835215004751

[15] E. Nassief, I. Contreras, and B. Jaumard, "A comparison of formulations and relaxations for cross-dock door assignment problems," *Computers and Operations Research*, vol. 94, pp. 76–88, Jun. 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0305054818300303

[16] Y. A. Bozer and H. J. Carlo, "Optimizing inbound and outbound door assignments in less-than-truckload crossdocks," *IIE Transactions*, vol. 40, no. 11, pp. 1007–1018, Mar. 2008. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/07408170802167688

[17] Y.-R. Zhu *et al.*, "New approach for the cross-dock door assignment problem," presented at the XLI SBPO, Porto Seguro , Brasil, Sep. 01-04, 2019, pp. 1226–1236. [Online]. Available: https://www.researchgate.net/publication/268188960_New_Approach_for_the_Cross-Dock_Door_Assignment_Problem

[18] K. E. Peck, "Operational analysis of freight terminals handling less than container load shipments," PhD dissertation, University of Illinois at Urbana-Champaign, Urbana, IL, 1983.

[19] K. Gue and K. Kang, "Staging queues in material handling and transportation systems," presented at the Winter Simulation Conference, Arlington, VA, Dec. 9-12, 2001, pp. 1104–1108. [Online]. Available: https://ieeexplore.ieee.org/document/977421

[20] A. Caris *et al.*, "Identifying opportunities of co-loading by means of simulation," presented at the 14th International Conference on Harbor, Maritime and Multimodal Logistics Modeling and Simulation, Vienna, Austria, Sep. 19-21, 2012, pp. 68–73. [Online]. Available: https://www.researchgate.net/publication/260554013_Identifying_opportunities_of_co-loading_by_means_of_simulation

[21] M. Rohrer, "Simulation and cross docking," presented at the Winter Simulation Conference, Arlington, VA, Dec. 3-6, 1995, pp. 846–849. [Online]. Available: https://www.researchgate.net/publication/3620025_Simulation_and_cross_docking

[22] G. M. Magableh, M. D. Rossetti, and S. Mason, "Modeling and analysis of a generic cross-docking facility," presented at the Winter Simulation Conference, Orlando, FL, Dec. 5-7, 2005, pp. 1613–1620. [Online]. Available: https://www.researchgate.net/publication/261481500_Modeling_and_analysis_of_a_generic_cross-docking_facility

[23] L. Leon Ojeda, A. Chasse, and R. Goussault, "Fuel consumption prediction for heavy-duty vehicles using digital maps," presented at the IEEE 20th International Conference on Intelligent Transportation Systems (ITSC), Yokohama, Japan, Oct. 16-19, 2017, pp. 1–7. [Online]. Available: https://www.researchgate.net/publication/323791934_Fuel_consumption_prediction_for_heavy-duty_vehicles_using_digital_maps

[24] A. Kontses *et al.*, "Particle number (PN) emissions from gasoline, diesel, LPG, CNG and hybrid-electric light-duty vehicles under real-world driving conditions," *Atmospheric Environment*, vol. 222, pp. 117–126, Feb. 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1352231019307654

[25] M. J. Economides, K. Sun, and G. Subero, "Compressed natural gas (CNG): An alternative to liquefied natural gas (LNG)," *SPE Production and Operations*, vol. 21, no. 2, pp. 318–324, May 2006. [Online]. Available: https://www.onepetro.org/journal-paper/SPE-92047-PA

[26] T. Tsutsumizaki, "Study of CNG fueled two-wheeled vehicle with electronically controlled gas injection system," SAE, Warrendale, PA, Technical report 2005-32-0034, 2005.

[27] D. D. Diggins, "CNG fuel cylinder storage efficiency and economy in fast fill operations," SAE, Deaborn, MI, Technical report 981398, 1998.

[28] U. Wilensky and W. Rand, *An Introduction to Agent-Based Modeling.* Cambridge, MA: MIT Press, 2015.

[29] The AnyLogic Company. (2019) Distribution center - simulation models in anylogic cloud. [Online]. Available: https://cloud.anylogic.com/model/fd24f59d-85cc-45d0-a327-ed551b983c43?mode=SETTINGS

[30] S. M. Ross, *The Exponential Distribution and the Poisson Process*, 5th ed. San Diego, CA: Academic Press, 1993, pp. 199–254.

[31] I. H. Al Ajarmeh, J. Yu, and M. Amezziane, "Framework of applying a non-homogeneous poisson process to model voip traffic on tandem networks," presented at the 10th WSEAS International Conference on Applied Informatics and Communications, Taipei, Taiwan, Aug. 20-22, 2010, pp. 164–169. [Online]. Available: https://www.researchgate.net/publication/234781479_Framework_of_applying_a_non-homogeneous_Poisson_process_to_model_VoIP_traffic_on_tandem_networks

[32] L. Brown *et al.*, "Statistical analysis of a telephone call center: A queueing-science perspective," *Journal of the American statistical association*, vol. 100, no. 469, pp. 36–50, Mar. 2005. [Online]. Available: https://doi.org/10.1198/016214504000001808

[33] H.-L. Wong, S.-H. Hsieh, and Y.-H. Tu, "Application of non-homogeneous poisson process modeling to containership arrival rate," presented at the 4th International Conference on Innovative Computing, Information and Control, Kaohsiung, Taiwan, Dec. 7-9, 2009, pp. 849–854. [Online]. Available: https://www.tib.eu/en/search/id/ieee%3Adoi~10.1109%252FICICIC.2009.111/Application-of-Non-Homogeneous-Poisson-Process/

[34] S. S. Mangiafico, *Traditional Nonparametric Tests.* New Brunswick, NJ: Rutgers Cooperative Extension, 2016, pp. 208 – 319. [Online]. Available: rcompanion.org/documents/RHandbookProgramEvaluation.pdf

[35] G. Raballand and E. Aldaz-Carroll, "How do differing standards increase trade costs? the case of pallets," *World Economy*, vol. 30, no. 4, pp. 685–702, Mar. 2007. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-9701.2007.01009.x

[36] *Laboratory Test Procedure for FMVSS 304: Compressed Natural Gas (CNG) Fuel Container Integrity*, Std. TP-304-03, 2003. [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/tp304-03.pdf

[37] S. M. Ross, *Simulation*, 5th ed. San Diego, CA: Academic Press, 1993, pp. 493–542.

[38] D. C. Montgomery, *Design and Analysis of Experiments*, eigth ed. Hoboken, NJ: John Wiley and Sons, 2012.

[39] RStudio Team. (2020) Rstudio: Integrated development environment for R (version 1.2.1335). [Online]. Available: http://www.rstudio.com

[40] U.S. Environmental Protection Agency (EPA. (2018) Emission factors for greenhouse gas inventories. [Online]. Available: https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf

APPENDIX A PALLET FLOW DATA

Table A.1 Pallet flow between origin and destination zones (3-month data)

Origin zone code	Destination zone code	Number of pallets per shift		
		00-08h	08-16h	16-00h
DR	DB	11,316	4,087	1,523
DB	DB	1,975	1,157	6,824
DM	DB	3,438	877	2,843
DB	DR	203	516	4,712
DB	DQ	533	279	4,614
DQ	DB	4,254	538	609
DR	DM	2,224	1,380	771
DB	DM	655	354	2,997
DM	DQ	539	169	2,314
DM	DR	97	160	1,925
DS	DB	1,429	186	311
DB	DH	219	128	1,475
DM	DH	308	97	1,351
US	DB	1,044	305	234
DB	DS	230	120	1,086
DR	DQ	340	482	585
DM	DM	224	119	973
DM	DT	411	46	451
DQ	DM	439	60	258
DB	US	26	30	685
DB	DT	343	29	361
DT	DB	62	198	283
DM	DS	104	47	372
DL	DB	265	91	86
DB	DL	32	8	391
DR	DT	291	94	35
DT	DQ	47	18	345
US	DM	195	72	135
DL	DM	208	117	72
DS	DM	165	58	115
DQ	DR	43	19	239
DL	DQ	82	100	74
DQ	DT	208	16	27
DH	DB	103	20	112
DM	US	16	21	178
DB	CAW	1		174
US	DT	133	25	22
DH	DM	75	31	72
DQ	US	19	23	130
DT	DM	20	6	132
US	DQ	43	37	67
DM	DL	43	2	97
CAM	DB	115	20	4
DR	DS	33	62	38
DS	DR	24	39	67
DQ	DH	31	12	78
DS	DT	109		7
US	DR	16	26	68
US	DS	19	21	40
DS	DH	61	10	8
DT	DR		5	74
DR	DR		30	44
US	CAW	6	4	58
DH	DR	19	10	33
DS	US	12	9	40
DT	DH	6	2	51
DR	DH	9	33	8
DQ	DS	17	4	24
DL	DT	32	2	10
DT	DT	12		29
DL	DH	25	8	7
DL	DS	16	4	20
DH	DQ	11	5	23
DT	DS	3	2	32
DM	CAW			34
DS	DQ	14		18
DQ	DQ	4	3	24
DT	US		3	20
DL	US	9	6	7
DL	DR	8	5	6
DQ	DL	14		4
US	DH	6		10
US	DL			13
DH	DT		3	6
DL	CAW	7		1
DT	CAW			6
DT	DL	1		4
CAW	DB	4		
DL	DL	2		2
DR	DL	2		2
DH	CAW		3	
DH	DH		1	2
DR	NL			3
DS	DS			3
DB	NL	2		
DH	DS		2	
DQ	CAW			2
DB	CAM			1
DH	DL			1
DS	CAW	1		
DS	DL			1

APPENDIX B DISTANCE BETWEEN DOORS

Origin Door		Destination Door																																										
		2	4	6	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	31	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
	Tall	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✗
2	✗		232	220	208	231	197	218	185	207	173	195	161	183	149	195	146	196	157	200	169	206	181	213	193	222	232	243	228	256	240	268	252	279	264	291	276	303	288	315	300	327	312	339	323	351
4	✓	232		209	197	219	185	207	173	195	161	183	149	171	137	183	134	184	145	188	158	194	169	202	181	210	220	232	217	244	229	256	241	268	252	280	264	291	276	303	288	315	300	327	312	339
6	✓	220	209		185	207	173	195	161	183	149	171	137	159	125	171	122	172	133	176	146	182	157	190	169	198	208	220	204	232	217	244	229	256	240	268	252	279	264	291	276	303	288	315	300	327
8	✓	208	197	185		195	161	183	149	171	137	159	125	147	113	159	110	160	121	164	134	170	145	178	157	186	196	208	192	220	205	232	217	244	228	256	240	267	252	279	264	291	276	303	288	315
9	✓	231	219	207	195		183	205	171	193	159	181	147	169	135	181	132	183	143	186	156	192	167	200	179	208	218	230	215	242	227	254	239	266	251	278	263	289	274	302	286	313	298	325	310	337
10	✓	197	185	173	161	183		171	137	159	126	147	114	136	102	147	98	149	110	153	122	158	134	166	146	175	185	196	181	208	193	220	205	232	217	244	229	256	241	268	253	280	264	292	276	303
11	✓	218	207	195	183	205	171		159	181	147	169	135	157	123	169	120	170	131	174	143	180	155	187	167	196	206	218	202	230	215	242	227	254	238	266	250	277	262	289	274	301	286	313	298	325
12	✓	185	173	161	149	171	137	159		147	113	135	101	123	90	135	86	137	98	140	110	146	122	154	133	162	172	184	169	196	181	208	193	220	205	232	217	243	228	256	240	267	252	279	264	291
13	✓	207	195	183	171	193	159	181	147		135	157	123	145	111	157	108	159	119	162	132	168	143	176	155	184	194	206	191	218	203	230	215	242	227	254	239	265	250	278	262	289	274	301	286	313
14	✓	173	161	149	137	159	126	147	113	135		123	90	112	78	123	74	125	86	129	98	134	110	142	122	151	161	172	157	184	169	196	181	208	193	220	205	232	217	244	229	256	240	268	252	279
15	✓	195	183	171	159	181	147	169	135	157	123		111	133	99	145	96	147	107	150	120	156	131	164	143	172	182	194	179	206	191	218	203	230	215	242	227	253	238	266	250	277	262	289	274	301
16	✓	161	149	137	125	147	114	135	101	123	90	111		100	66	111	62	113	74	117	86	122	98	130	110	139	149	160	145	172	157	184	169	196	181	208	193	220	205	232	217	244	228	256	240	267
17	✓	183	171	159	147	169	136	157	123	145	112	133	100		88	133	84	135	96	138	108	144	120	152	132	161	171	182	167	194	179	206	191	218	203	230	215	242	227	254	239	266	250	278	262	289
18	✓	149	137	125	113	135	102	123	90	111	78	99	66	88		99	50	101	62	105	74	110	86	118	98	127	137	148	133	161	145	173	157	184	169	196	181	208	193	220	205	232	217	244	228	255
19	✓	195	183	171	159	181	147	169	135	157	123	145	111	133	99		96	147	107	150	120	156	131	164	143	172	182	194	179	206	191	218	203	230	215	242	227	253	238	266	250	277	262	289	274	301
20	✓	146	134	122	110	132	98	120	86	108	74	96	62	84	50	96		98	58	101	71	107	82	115	94	123	133	145	130	157	142	169	154	181	166	193	178	204	189	217	201	228	213	240	225	252
21	✓	196	184	172	160	183	149	170	137	159	125	147	113	135	101	147	98		109	152	121	158	133	165	145	174	184	195	180	208	193	220	205	231	216	243	228	255	240	267	252	279	264	291	275	303
22	✓	157	145	133	121	143	110	131	98	119	86	107	74	96	62	107	58	109		113	82	118	94	126	106	135	145	156	141	169	153	181	165	192	177	204	189	216	201	228	213	240	225	252	236	263
23	✓	200	188	176	164	186	153	174	140	162	129	150	117	138	105	150	101	152	113		125	161	137	169	149	178	188	199	184	211	196	223	208	235	220	247	232	259	244	271	256	283	267	295	279	306
24	✓	169	158	146	134	156	122	143	110	132	98	120	86	108	74	120	71	121	82	125		131	106	138	118	147	157	169	153	181	166	193	178	205	189	217	201	228	213	240	225	252	237	264	249	276
25	✓	206	194	182	170	192	158	180	146	168	134	156	122	144	110	156	107	158	118	161	131		142	175	154	183	193	205	190	217	202	229	214	241	226	253	238	264	249	277	261	288	273	300	285	312
26	✓	181	169	157	145	167	134	155	122	143	110	131	98	120	86	131	82	133	94	137	106	142		150	130	159	169	180	165	193	177	205	189	216	201	228	213	240	225	252	237	264	249	276	260	287
27	✓	213	202	190	178	200	166	187	154	176	142	164	130	152	118	164	115	165	126	169	138	175	150		162	191	201	213	197	225	210	237	222	249	233	261	245	272	257	284	269	296	281	308	293	320
28	✓	193	181	169	157	179	146	167	133	155	122	143	110	132	98	143	94	145	106	149	118	154	130	162		171	181	192	177	205	189	217	201	228	213	240	225	252	237	264	249	276	261	288	272	299
29	✓	222	210	198	186	208	175	196	162	184	151	172	139	161	127	172	123	174	135	178	147	183	159	191	171		210	221	206	233	218	245	230	257	242	269	254	281	266	293	278	305	289	317	301	328
31	✓	232	220	208	196	218	185	206	172	194	161	182	149	171	137	182	133	184	145	188	157	193	169	201	181	210		231	216	243	228	255	240	267	252	279	264	291	276	303	288	315	299	327	311	338
33	✓	243	232	220	208	230	196	218	184	206	172	194	160	182	148	194	145	195	156	199	169	205	180	213	192	221	231		228	255	240	267	252	279	263	291	275	302	287	314	299	326	311	338	323	350
34	✓	228	217	204	192	215	181	202	169	191	157	179	145	167	133	179	130	180	141	184	153	190	165	197	177	206	216	228		240	225	252	237	264	248	276	260	287	272	299	284	311	296	323	308	335
35	✓	256	244	232	220	242	208	230	196	218	184	206	172	194	161	206	157	208	169	211	181	217	193	225	205	233	243	255	240		252	279	264	291	276	303	288	314	299	327	311	339	323	351	335	362
36	✓	240	229	217	205	227	193	215	181	203	169	191	157	179	145	191	142	193	153	196	166	202	177	210	189	218	228	240	225	252		264	249	276	261	288	273	299	284	312	296	323	308	335	320	347
37	✓	268	256	244	232	254	220	242	208	230	196	218	184	206	173	218	169	220	181	223	193	229	205	237	217	245	255	267	252	279	264		276	303	288	315	300	326	311	339	323	351	335	363	347	374
38	✓	252	241	229	217	239	205	227	193	215	181	203	169	191	157	203	154	205	165	208	178	214	189	222	201	230	240	252	237	264	249	276		288	273	300	285	311	296	324	308	335	320	347	332	359
39	✓	279	268	256	244	266	232	254	220	242	208	230	196	218	184	230	181	231	192	235	205	241	216	249	228	257	267	279	264	291	276	303	288		300	327	312	338	323	351	335	362	347	374	359	386
40	✓	264	252	240	228	251	217	238	205	227	193	215	181	203	169	215	166	216	177	220	189	226	201	233	213	242	252	263	248	276	261	288	273	300		312	296	323	308	335	320	347	332	359	343	371
41	✓	291	280	268	256	278	244	266	232	254	220	242	208	230	196	242	193	243	204	247	217	253	228	261	240	269	279	291	276	303	288	315	300	327	312		324	350	335	363	347	374	359	386	371	398
42	✓	276	264	252	240	263	229	250	217	239	205	227	193	215	181	227	178	228	189	232	201	238	213	245	225	254	264	275	260	288	273	300	285	312	296	324		335	320	347	332	359	344	371	355	383
43	✗	303	291	279	267	289	256	277	243	265	232	253	220	242	208	253	204	255	216	259	228	264	240	272	252	281	291	302	287	314	299	326	311	338	323	350	335		347	374	359	386	370	398	382	409
44	✗	288	276	264	252	274	241	262	228	250	217	238	205	227	193	238	189	240	201	244	213	249	225	257	237	266	276	287	272	299	284	311	296	323	308	335	320	347		359	344	371	355	383	367	394
45	✓	315	303	291	279	302	268	289	256	278	244	266	232	254	220	266	217	267	228	271	240	277	252	284	264	293	303	314	299	327	312	339	324	351	335	363	347	374	359		371	398	383	410	394	422
46	✓	300	288	276	264	286	253	274	240	262	229	250	217	239	205	250	201	252	213	256	225	261	237	269	249	278	288	299	284	311	296	323	308	335	320	347	332	359	344	371		383	367	395	379	406
47	✓	327	315	303	291	313	280	301	267	289	256	277	244	266	232	277	228	279	240	283	252	288	264	296	276	305	315	326	311	339	323	351	335	362	347	374	359	386	371	398	383		395	422	406	433
48	✓	312	300	288	276	298	264	286	252	274	240	262	228	250	217	262	213	264	225	267	237	273	249	281	261	289	299	311	296	323	308	335	320	347	332	359	344	370	355	383	367	395		407	391	418
49	✗	339	327	315	303	325	292	313	279	301	268	289	256	278	244	289	240	291	252	295	264	300	276	308	288	317	327	338	323	351	335	363	347	374	359	386	371	398	383	410	395	422	407		418	445
50	✓	323	312	300	288	310	276	298	264	286	252	274	240	262	228	274	225	275	236	279	249	285	260	293	272	301	311	323	308	335	320	347	332	359	343	371	355	382	367	394	379	406	391	418		430
51	✗	351	339	327	315	337	303	325	291	313	279	301	267	289	255	301	252	303	263	306	276	312	287	320	299	328	338	350	335	362	347	374	359	386	371	398	383	409	394	422	406	433	418	445	430	

Figure B.1 Distance (ft) based on the first scale

Origin Door		Destination Door																																												
		2	4	6	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	31	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
	Tall	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✗
2	✗		417	405	393	366	381	354	369	342	357	330	345	319	333	307	321	295	312	283	302	271	295	259	289	247	235	242	277	254	289	266	301	278	313	290	325	301	337	314	349	325	361	337	372	349
4	✓	417		393	381	355	369	342	357	331	345	319	333	307	321	295	309	283	300	271	291	260	283	247	277	236	224	230	265	242	278	254	290	266	301	278	313	290	325	302	337	314	349	326	361	337
6	✓	405	393		369	343	357	330	345	319	333	307	321	295	309	283	297	271	288	259	279	248	271	235	265	224	212	218	253	230	266	242	278	254	289	266	301	278	313	290	325	302	337	314	349	325
8	✓	393	381	369		331	345	318	333	307	321	295	309	283	297	271	285	259	276	247	267	236	259	223	253	212	200	206	241	218	254	230	266	242	277	254	289	266	301	278	313	290	325	302	337	313
9	✓	366	355	343	331		319	292	307	280	295	268	283	257	271	245	259	233	249	221	240	209	233	197	227	185	173	180	215	192	227	204	239	216	251	228	263	239	275	252	287	263	299	275	310	287
10	✓	381	369	357	345	319		307	321	295	310	283	298	271	286	260	274	248	264	236	255	224	248	212	242	200	188	195	230	207	242	219	254	231	266	243	278	254	290	266	302	278	313	290	325	302
11	✓	354	342	330	318	292	307		295	268	283	256	271	244	259	233	247	221	237	209	228	197	221	185	215	173	161	168	203	180	215	192	227	204	239	216	251	227	263	239	275	251	286	263	298	275
12	✓	369	357	345	333	307	321	295		283	297	271	285	259	274	247	262	235	252	223	243	212	235	200	229	188	176	182	218	195	230	207	242	218	254	230	266	242	277	254	289	266	301	278	313	289
13	✓	342	331	319	307	280	295	268	283		271	244	259	233	247	221	235	209	226	197	216	185	209	173	203	161	149	156	191	168	203	180	215	192	227	204	239	215	251	228	263	239	275	251	286	263
14	✓	357	345	333	321	295	310	283	297	271		259	274	247	262	236	250	224	240	212	231	200	224	188	218	176	164	171	206	183	218	195	230	207	242	219	254	230	266	242	278	254	289	266	301	278
15	✓	330	319	307	295	268	283	256	271	244	259		247	221	235	209	223	197	214	185	204	173	197	161	191	149	137	144	179	156	191	168	203	180	215	192	227	203	239	216	251	227	263	240	274	251
16	✓	345	333	321	309	283	298	271	285	259	274	247		235	250	224	238	212	228	200	219	188	212	176	206	164	152	159	194	171	206	183	218	195	230	207	242	218	254	230	266	242	277	254	289	266
17	✓	319	307	295	283	257	271	244	259	233	247	221	235		224	197	212	185	202	173	193	162	185	149	179	138	126	132	167	144	180	156	192	168	203	180	215	192	227	204	239	216	251	228	263	239
18	✓	333	321	309	297	271	286	259	274	247	262	235	250	224		212	226	200	216	188	207	176	200	164	194	152	140	147	182	159	194	171	206	183	218	195	230	206	242	219	254	230	266	242	277	254
19	✓	307	295	283	271	245	260	233	247	221	236	209	224	197	212		200	173	190	161	181	150	173	138	167	126	114	120	156	133	168	145	180	156	192	168	204	180	215	192	227	204	239	216	251	228
20	✓	321	309	297	285	259	274	247	262	235	250	223	238	212	226	200		188	204	176	195	164	188	152	182	140	128	135	170	147	182	159	194	171	206	183	218	194	230	207	242	218	254	230	265	242
21	✓	295	283	271	259	233	248	221	235	209	224	197	212	185	200	173	188		178	149	169	138	161	126	155	114	102	108	144	121	156	133	168	144	180	156	192	168	203	180	215	192	227	204	239	216
22	✓	312	300	288	276	249	264	237	252	226	240	214	228	202	216	190	204	178		166	186	155	178	142	172	131	119	125	160	137	173	149	185	161	196	173	208	185	220	197	232	209	244	221	256	232
23	✓	283	271	259	247	221	236	209	223	197	212	185	200	173	188	161	176	149	166		157	126	149	114	143	102	90	96	132	109	144	121	156	132	168	145	180	156	191	168	203	180	215	192	227	204
24	✓	302	291	279	267	240	255	228	243	216	231	204	219	193	207	181	195	169	186	157		146	169	133	163	122	110	116	151	128	164	140	176	152	187	164	199	176	211	188	223	200	235	212	246	223
25	✓	271	260	248	236	209	224	197	212	185	200	173	188	162	176	150	164	138	155	126	146		138	102	132	90	78	85	120	97	132	109	144	121	156	133	168	145	180	157	192	169	204	181	215	192
26	✓	295	283	271	259	233	248	221	235	209	224	197	212	185	200	173	188	161	178	149	169	138		126	155	114	102	109	144	121	156	133	168	145	180	157	192	168	203	180	215	192	227	204	239	216
27	✓	259	247	235	223	197	212	185	200	173	188	161	176	149	164	138	152	126	142	114	133	102	126		120	78	66	73	108	85	120	97	132	109	144	121	156	132	168	145	180	156	191	168	203	180
28	✓	289	277	265	253	227	242	215	229	203	218	191	206	179	194	167	182	155	172	143	163	132	155	120		108	96	102	138	115	150	127	162	138	174	150	186	162	197	174	209	186	221	198	233	210
29	✓	247	236	224	212	185	200	173	188	161	176	149	164	138	152	126	140	114	131	102	122	90	114	78	108		54	61	96	73	108	85	120	97	132	109	144	121	156	133	168	145	180	157	191	168
31	✓	235	224	212	200	173	188	161	176	149	164	137	152	126	140	114	128	102	119	90	110	78	102	66	96	54		49	84	61	96	73	108	85	120	97	132	109	144	121	156	133	168	145	179	156
33	✓	242	230	218	206	180	195	168	182	156	171	144	159	132	147	120	135	108	125	96	116	85	109	73	102	61	49		91	68	103	80	115	92	127	104	139	115	150	127	162	139	174	151	186	163
34	✓	277	265	253	241	215	230	203	218	191	206	179	194	167	182	156	170	144	160	132	151	120	144	108	138	96	84	91		103	138	115	150	127	162	139	174	150	186	163	198	174	209	186	221	198
35	✓	254	242	230	218	192	207	180	195	168	183	156	171	144	159	133	147	121	137	109	128	97	121	85	115	73	61	68	103		115	92	127	104	139	116	151	127	163	140	175	151	186	163	198	175
36	✓	289	278	266	254	227	242	215	230	203	218	191	206	180	194	168	182	156	173	144	164	132	156	120	150	108	96	103	138	115		127	162	139	174	151	186	163	198	175	210	187	222	199	233	210
37	✓	266	254	242	230	204	219	192	207	180	195	168	183	156	171	145	159	133	149	121	140	109	133	97	127	85	73	80	115	92	127		139	116	151	128	163	139	175	152	187	163	198	175	210	187
38	✓	301	290	278	266	239	254	227	242	215	230	203	218	192	206	180	194	168	185	156	176	144	168	132	162	120	108	115	150	127	162	139		151	186	163	198	175	210	187	222	199	234	211	245	222
39	✓	278	266	254	242	216	231	204	218	192	207	180	195	168	183	156	171	144	161	132	152	121	145	109	138	97	85	92	127	104	139	116	151		163	140	175	151	186	163	198	175	210	187	222	199
40	✓	313	301	289	277	251	266	239	254	227	242	215	230	203	218	192	206	180	196	168	187	156	180	144	174	132	120	127	162	139	174	151	186	163		175	210	186	222	199	234	210	245	222	257	234
41	✓	290	278	266	254	228	243	216	230	204	219	192	207	180	195	168	183	156	173	145	164	133	157	121	150	109	97	104	139	116	151	128	163	140	175		187	163	198	175	210	187	222	199	234	211
42	✓	325	313	301	289	263	278	251	266	239	254	227	242	215	230	204	218	192	208	180	199	168	192	156	186	144	132	139	174	151	186	163	198	175	210	187		198	234	211	246	222	257	234	269	246
43	✗	301	290	278	266	239	254	227	242	215	230	203	218	192	206	180	194	168	185	156	176	145	168	132	162	121	109	115	150	127	163	139	175	151	186	163	198		210	187	222	199	234	211	245	222
44	✗	337	325	313	301	275	290	263	277	251	266	239	254	227	242	215	230	203	220	191	211	180	203	168	197	156	144	150	186	163	198	175	210	186	222	198	234	210		222	257	234	269	246	281	258
45	✓	314	302	290	278	252	266	239	254	228	242	216	230	204	219	192	207	180	197	168	188	157	180	145	174	133	121	127	163	140	175	152	187	163	199	175	211	187	222		234	211	246	223	258	234
46	✓	349	337	325	313	287	302	275	289	263	278	251	266	239	254	227	242	215	232	203	223	192	215	180	209	168	156	162	198	175	210	187	222	198	234	210	246	222	257	234		246	281	258	293	270
47	✓	325	314	302	290	263	278	251	266	239	254	227	242	216	230	204	218	192	209	180	200	169	192	156	186	145	133	139	174	151	187	163	199	175	210	187	222	199	234	211	246		258	235	269	246
48	✓	361	349	337	325	299	313	286	301	275	289	263	277	251	266	239	254	227	244	215	235	204	227	191	221	180	168	174	209	186	222	198	234	210	245	222	257	234	269	246	281	258		270	305	281
49	✗	337	326	314	302	275	290	263	278	251	266	240	254	228	242	216	230	204	221	192	212	181	204	168	198	157	145	151	186	163	199	175	211	187	222	199	234	211	246	223	258	235	270		281	258
50	✓	372	361	349	337	310	325	298	313	286	301	274	289	263	277	251	265	239	256	227	246	215	239	203	233	191	179	186	221	198	233	210	245	222	257	234	269	245	281	258	293	269	305	281		293
51	✗	349	337	325	313	287	302	275	289	263	278	251	266	239	254	228	242	216	232	204	223	192	216	180	210	168	156	163	198	175	210	187	222	199	234	211	246	222	258	234	270	246	281	258	293	

Figure B.2 Distance (ft) based on the second scale