

**FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO**



# **A Simulation Tool for Optimizing Port Operations**

**Catarina Coelho Carvalho**

Mestrado em Engenharia Eletrotécnica e de Computadores

Supervisor: Jorge Pinho de Sousa

July 29, 2023



# Resumo

Os terminais de contentores desempenham um papel fundamental nos sistemas globais de logística, funcionando como ponte entre o mar e a terra. A evolução da contentorização e os avanços tecnológicos tiveram um impacto significativo nos terminais de contentores marítimos, exigindo adaptações para lidar com os crescentes volumes e exigências. O principal desafio consiste na melhoria da produtividade, na redução dos custos operacionais e no aumento da competitividade, ao mesmo tempo que se enfrentam as limitações de espaço. Para enfrentar estes desafios, a automação tornou-se uma solução, permitindo que os terminais de contentores se adaptem dinamicamente às novas condições e optimizem o seu desempenho.

O crescimento do comércio internacional também provocou o surgimento do conceito de portos verdes, enfatizando práticas sustentáveis. A gestão eficaz dos sistemas logísticos é vital para alcançar um maior desempenho e valor. No entanto, é uma tarefa complexa devido ao envolvimento de múltiplas entidades e fluxos interligados de bens e informações. A simulação surge como uma ferramenta valiosa para a previsão e tomada de decisões estratégicas, permitindo a análise de cenários hipotéticos utilizando dados em tempo real. Nos terminais de contentores, onde vários processos interligados ocorrem em simultâneo, as decisões operacionais têm de dar prioridade à eficiência do tempo e à utilização do equipamento. Apesar dos esforços para coordenar as operações, as incertezas e perturbações persistem, sublinhando a necessidade permanente de melhoria contínua.

Neste contexto, esta dissertação centra-se no desenvolvimento de uma ferramenta de apoio à decisão no âmbito do software FlexSim, visando enfrentar os desafios destes sistemas complexos, especificamente na configuração de terminais de contentores considerando importantes aspetos como a automação e sustentabilidade. É desenvolvido um modelo de simulação de eventos discretos, constituído por um cais, uma área de transporte e por um parque de estacionamento de contentores, de forma a possibilitar a análise de diferentes cenários e os seus efeitos em métricas de desempenho cruciais como a produtividade, a utilização de recursos e os tempos de espera. O objetivo principal é identificar a quantidade ideal de equipamento e as características operacionais, particularmente relacionadas com o equipamento automatizado, através de um número limitado de experiências cuidadosamente concebidas. Este estudo contribui para o setor portuário ao introduzir uma abordagem baseada em simulação que facilita o teste e a avaliação de múltiplos cenários numa perspetiva multi-critério, oferecendo informações valiosas para os processos de tomada de decisão no domínio das operações dos terminais de contentores.





# Abstract

Container terminals play a critical role in global logistics systems as the bridge between the sea and the land. The evolution of containerization and technological advancements has significantly impacted maritime container terminals, requiring adaptations to handle the increasing volumes and demands. The primary challenge lies in improving productivity, reducing operational costs, and increasing competitiveness while grappling with spatial limitations. To address these challenges, automation has gained traction as a solution, enabling container terminals to dynamically adapt to changing conditions and optimize performance.

The growth of international trade has also brought about the emergence of the concept of green ports, emphasizing sustainable practices. Effective management of logistics systems is vital for achieving higher performance and value. However, it is a complex task due to the involvement of multiple entities and interwoven flows of goods and information. Simulation emerges as a valuable tool for prediction and strategic decision-making, enabling the analysis of hypothetical scenarios using real-time data. In container terminals, where numerous interconnected processes occur concurrently, operational decisions must prioritize time efficiency and equipment utilization. Despite efforts to coordinate operations, uncertainties and disturbances persist, underscoring the ongoing need for continuous improvement.

In light of this, this dissertation focuses on developing a decision-support tool within the FlexSim software to address the challenges in complex systems, specifically in configuring container terminals considering important aspects such as automation and sustainability. A discrete event simulation model is developed, encompassing the quay area, transport area, and storage yard, to enable the analysis of different scenarios and their effects on crucial performance metrics like productivity, resource utilization, and waiting times. The primary objective is to identify the optimal equipment quantity and operational characteristics, particularly of automated equipment, through a limited number of carefully designed experiments. This study contributes to the field by introducing a simulation-based approach that facilitates the testing and evaluation of multiple scenarios in a multi-criteria perspective, providing valuable information for decision-making processes in the field of container terminal operations.



# Agradecimentos

Em primeiro lugar, deixo o meu agradecimento ao Professor Doutor Jorge Manuel Pinho de Sousa pela oportunidade e pela confiança depositada em mim na realização desta dissertação, além de todo o apoio e valioso saber transmitido ao longo da execução deste trabalho.

Ao Engenheiro Romão Santos, por toda a ajuda e incansável disponibilidade, pelo conhecimento transmitido que tornou possível a realização deste trabalho, pela sua paciência e incentivo. Principalmente, durante os momentos de incerteza relativamente a mim e ao meu trabalho. Um enorme obrigada!

À Professora Doutora Catarina Marques pelas opiniões valiosas.

Ao Engenheiro Henrique Piqueiro e à Engenheira Ana Carolina Tavares da Silva pela ajuda, disponibilidade e amizade demonstrada ao longo destes meses.

To Dr. Mahdi Homayouni for all the availability and the valuable knowledge shared during the dissertation.

Um agradecimento ao INESC TEC pela oportunidade e pelas instalações cedidas, especialmente ao CESE, pelo acolhimento e pelo incrível ambiente de trabalho.

Ao Dr. Vieira dos Santos pelo incrível conhecimento transmitido sobre a logística portuária, por toda a disponibilidade e pela ajuda na melhor compreensão do funcionamento dos portos marítimos.

Aos meus pais, Jorge Carvalho e Mariline Carvalho, por serem as pessoas que mais admiro neste mundo, por todos os ensinamentos e conselhos que fizeram de mim a pessoa que sou hoje e por acreditarem sempre em mim, mesmo quando eu própria tenho dúvidas.

Ao meu irmão, Diogo Carvalho, por ser a pessoa que mais me faz rir nesta vida mesmo nos momentos mais difíceis, por todo o companheirismo e amizade.

Às minhas meninas, Bárbaras, Inês, Juls, Marias, Sara e Teresa por tornarem estes últimos anos inesquecíveis, pela amizade imensurável e por serem casa.

À Cati, por ser a irmã que nunca tive, pelo apoio incalculável, pelos risos, conversas e por saber sempre o que dizer em todos os momentos.

Ao Zé Pedro, por ser a melhor companhia que poderia pedir para partilhar este desafio que foi a tese.

Ao Pedro, Nuno e Rita pela amizade e carinho ao longo destes anos e por aturarem todos os meus desalentos e queixas durante a época de exames.

À Chica, Diogo e Pedro por estarem sempre lá quando preciso e por tornarem este último ano ainda mais especial.

Termino agradecendo à minha prima Magui que me acompanha em todas as etapas da minha vida.

Catarina Coelho Carvalho



*“If you do the work, you get rewarded.  
There are no shortcuts in life.”*

Michael Jordan



# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Contextualization . . . . .	1
1.2	Motivation . . . . .	2
1.3	Objectives . . . . .	3
1.4	Methodological Approach . . . . .	4
1.5	Dissertation Structure . . . . .	4
<b>2</b>	<b>Literature Review</b>	<b>7</b>
2.1	Physical Flows and Seaports . . . . .	7
2.2	Container Terminals . . . . .	9
2.3	The Operating Environment of Ports . . . . .	11
2.3.1	Operations Planning . . . . .	11
2.3.2	Material Handling Equipment . . . . .	11
2.3.3	Storage Yard Logistics . . . . .	14
2.3.4	Layout of Container Terminals . . . . .	15
2.4	Automated Container Terminals . . . . .	17
2.5	Environmental Sustainability in Ports . . . . .	17
2.6	Simulation . . . . .	18
2.6.1	Simulation as a Tool for Decision-support Systems . . . . .	19
2.6.2	Simulation Paradigms . . . . .	19
2.6.3	Application of Simulation to Ports . . . . .	20
<b>3</b>	<b>Case Study</b>	<b>21</b>
3.1	Problem Description . . . . .	21
3.2	Base Model . . . . .	22
3.2.1	Container Terminal Configuration . . . . .	23
3.3	Quay Area . . . . .	25
3.3.1	Ship Arrival . . . . .	25
3.3.2	QC Characteristics . . . . .	26
3.4	Transportation Area . . . . .	28
3.4.1	Electric AGVs . . . . .	29
3.4.2	AGVs' Battery Specifications . . . . .	29
3.4.3	AGVs' Route . . . . .	31
3.5	Storage Yard Area . . . . .	32
3.5.1	Storage Yard Dimensions . . . . .	32
3.5.2	Parallel Layout . . . . .	33
3.5.3	YC Characteristics . . . . .	34
3.6	Extensions of the Case Study . . . . .	35

3.6.1	Extension 1 (Impacts of Different AGV Speeds)	35
3.6.2	Extension 2 (Impacts of Different AGV Routes)	36
<b>4</b>	<b>Simulation Model for the Case Study</b>	<b>37</b>
4.1	A Simulation-Based Approach	37
4.2	FlexSim	38
4.2.1	Objects in the 3D Model	38
4.2.2	Process Flow	39
4.3	The 3D Model	40
4.3.1	QCs' Properties	40
4.3.2	YC's Properties	41
4.3.3	AGV's Properties	43
4.4	Parameters	46
4.5	The Process Flow	47
4.5.1	Shared Assets	49
4.5.2	Ships to Unload	50
4.5.3	Creation of Tokens for QCs, AGVs and YC	51
4.5.4	Ship's Unloading - QCs	52
4.5.5	Containers' Transport - AGVs	52
4.5.6	Containers' Unloading in the Storage Yard - YC	54
4.5.7	AGV Charging	54
4.5.8	Park AGVs	55
4.6	Dashboard	55
<b>5</b>	<b>Tests and Results</b>	<b>57</b>
5.1	Design of Experiments	57
5.1.1	Base Model	57
5.1.2	Extensions of the Base Model	58
5.2	Performance Measures	60
5.2.1	Total Operation Time	61
5.2.2	AGVs' Energy Consumption Cost	61
5.2.3	AGVs' Charging Cost	62
5.3	Experiments in FlexSim	63
5.4	Analysis of Scenarios	64
5.4.1	Base Model	64
5.4.2	Impacts of AGVs' Speed Decrease	71
5.4.3	Impacts of AGVs' Speed Increase	73
5.4.4	Impacts of Different AGV Routes	76
<b>6</b>	<b>Conclusions and future work</b>	<b>81</b>
6.1	Conclusions	81
6.2	Future Work	82
<b>A</b>	<b>Simulation Model for the Case Study</b>	<b>85</b>
A.1	Implementation in FlexSim	85
A.1.1	3D Model	85
A.1.2	Process Flow	87
A.1.3	Parameters	87
A.1.4	Dashboard	88



<b>B Results Analysis</b>	<b>91</b>
B.1 Design of Experiments . . . . .	91
B.1.1 Extension 1 (Impacts of Different AGV Speeds) . . . . .	91
B.2 Experiments in FlexSim . . . . .	92
B.3 Analysis Scenarios of Base Model . . . . .	92
B.4 Analysis Scenarios of Extension 1 (Impacts of Different AGV Speeds) . . . . .	99
B.5 Analysis Scenarios of Extension 2 (Impacts of Different AGV Routes) . . . . .	103
B.5.1 First Modification of AGVs' Route . . . . .	103
B.5.2 Second Modification of AGVs' Route . . . . .	105
<b>References</b>	<b>107</b>



# List of Figures

2.1	Types of Ports Terminals, adapted from [1]	8
2.2	Container Terminal Layout, adapted from [2]	9
2.3	Container Terminal Operations	10
2.4	Classification of containers in port container terminals	10
2.5	Quay Cranes [3]	12
2.6	Yard Truck [4]	12
2.7	AGV [5]	13
2.8	Straddle Carrier [6]	14
2.9	Yard Cranes	15
2.10	Types of Container Terminals Layouts [7]	16
3.1	Schematic container terminal layout [8]	22
3.2	Operation process at the container terminal case study	23
3.3	Schematic representation of the base case for simulation	23
3.4	Different profiles of a QC [9]	27
3.5	Specifications of a QC, adapted from [10]	27
3.6	AGV guide path, adapted from [11]	32
3.7	Layout of storage area of a container terminal [12]	33
3.8	Structure of a YC, adapted from [13]	35
4.1	ASRS vehicle in FlexSim	40
4.2	Crane in FlexSim	42
4.3	AGV Task Excuter in FlexSim	43
4.4	AGV's path using the AGV Network in FlexSim	44
4.5	Control Point in AGV Network in FlexSim	45
4.6	AGVs' charging points in AGV Network in FlexSim	45
4.7	Main process flow diagram of the operation	48
4.8	Process flow diagram of AGV charging	48
4.9	Shared Assets in the process flow	49
4.10	Process of ship creation in the process flow	50
4.11	Process of token creation in the process flow	51
4.12	Process of ship's unloading by QCs in the process flow	52
4.13	Process of containers' transport by AGVs in the process flow	53
4.14	Process of containers' unloading by YC in the process flow	54
4.15	Process of AGVs' parking in the process flow	55
5.1	First modification to the AGVs' route for extension 2	59
5.2	Second modification to the AGVs' route for extension 2	60
5.3	Replications Plot of Total Operation Time	65

5.4	Replications Plot of Energy Consumption Cost . . . . .	67
5.5	Replications Plot of Charging Cost . . . . .	68
5.6	Correlation Plot between Energy Consumption Cost and Charging Cost . . . . .	69
5.7	Correlation Plot between Total Operation Time and Energy Consumption Cost . . . . .	70
5.8	Replications Plot of Total Operation Time after decreasing AGVs' speed . . . . .	72
5.9	Replications Plot of Energy Consumption Cost after decreasing AGVs' speed . . . . .	72
5.10	Replications Plot of Charging Cost after decreasing AGVs' speed . . . . .	73
5.11	Replications Plot of Total Operation Time after increasing AGVs' speed . . . . .	74
5.12	Replications Plot of Energy Consumption Cost after increasing AGVs' speed . . . . .	74
5.13	Replications Plot of Charging Cost after increasing AGVs' speed . . . . .	75
5.14	Replications Plot of Total Operation Time after the first change of AGVs' route . . . . .	76
5.15	Replications Plot of Energy Consumption Cost after the first change of AGVs' route . . . . .	77
5.16	Replications Plot of Charging Cost after the first change of AGVs' route . . . . .	77
5.17	Replications Plot of Total Operation Time after the second change of AGVs' route . . . . .	78
5.18	Replications Plot of Energy Consumption Cost after the second change of AGVs' route . . . . .	79
5.19	Replications Plot of Charging Cost after the second change of AGVs' route . . . . .	79
A.1	Relevant properties of ASRS vehicle in FlexSim . . . . .	85
A.2	Relevant properties of the crane in FlexSim . . . . .	86
A.3	AGV type's features defined in FlexSim . . . . .	87
A.4	Ship arrivals table . . . . .	87
A.5	Model's parameters . . . . .	87
A.6	Example of a time plot indicating the AGV battery during the execution of replication 1 of scenario 7 . . . . .	88
A.7	Example of a time plot indicating the number of chargers of the AGVs during the execution of replication 1 of scenario 7 . . . . .	88
A.8	Example of a time plot indicating the AGVs' speed during the execution of replication 1 of scenario 7 . . . . .	89
B.1	Triangular distribution implemented in the AGV Network to increase the AGVs' speed by 20% . . . . .	91
B.2	Triangular distribution implemented in the AGV Network to decrease the AGVs' speed by 20% . . . . .	91
B.3	Experimenter interface in FlexSim . . . . .	92
B.4	Pie Chart indicating the state of the AGV during the execution of replication 1 of scenario 1 . . . . .	93
B.5	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 2 . . . . .	93
B.6	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 3 . . . . .	94
B.7	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 4 . . . . .	94
B.8	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 5 . . . . .	94
B.9	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 6 . . . . .	95
B.10	Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 7 . . . . .	95

B.11 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1 . . . . .	95
B.12 Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 2 . . . . .	96
B.13 Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 3 . . . . .	96
B.14 Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 4 . . . . .	96
B.15 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5 . . . . .	96
B.16 Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 6 . . . . .	97
B.17 Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 7 . . . . .	97
B.18 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2 . . . . .	97
B.19 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3 . . . . .	97
B.20 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4 . . . . .	98
B.21 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5 . . . . .	98
B.22 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6 . . . . .	98
B.23 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7 . . . . .	99
B.24 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1 after decreasing the AGVs' speed . . . . .	99
B.25 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 2 after decreasing the AGVs' speed . . . . .	99
B.26 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 3 after decreasing the AGVs' speed . . . . .	100
B.27 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 4 after decreasing the AGVs' speed . . . . .	100
B.28 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5 after decreasing the AGVs' speed . . . . .	100
B.29 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 6 after decreasing the AGVs' speed . . . . .	100
B.30 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 7 after decreasing the AGVs' speed . . . . .	101
B.31 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1 after increasing the AGVs' speed . . . . .	101
B.32 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 2 after increasing the AGVs' speed . . . . .	101
B.33 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 3 after increasing the AGVs' speed . . . . .	101
B.34 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 4 after increasing the AGVs' speed . . . . .	102

B.35 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5 after increasing the AGVs' speed . . . . .	102
B.36 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 6 after increasing the AGVs' speed . . . . .	102
B.37 Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 7 after increasing the AGVs' speed . . . . .	102
B.38 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2 after the first change of the AGVs' route . . . . .	103
B.39 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3 after the first change of the AGVs' route . . . . .	103
B.40 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4 after the first change of the AGVs' route . . . . .	103
B.41 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5 after the first change of the AGVs' route . . . . .	104
B.42 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6 after the first change of the AGVs' route . . . . .	104
B.43 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7 after the first change of the AGVs' route . . . . .	104
B.44 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2 after the second change of the AGVs' route . . . . .	105
B.45 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3 after the second change of the AGVs' route . . . . .	105
B.46 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4 after the second change of the AGVs' route . . . . .	105
B.47 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5 after the second change of the AGVs' route . . . . .	106
B.48 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6 after the second change of the AGVs' route . . . . .	106
B.49 Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7 after the second change of the AGVs' route . . . . .	106

# List of Tables

2.1	Types of transport vehicles . . . . .	13
3.1	Categorization of Ships . . . . .	25
3.2	QCs categorization based on container ship size . . . . .	26
3.3	Panamax Crane Technical Data . . . . .	28
3.4	Panamax Crane Technical Data in FlexSim . . . . .	28
3.5	AGV specification for container terminal application . . . . .	30
3.6	YC specifications for container terminal application . . . . .	34
5.1	Models simulated in FlexSim . . . . .	58
5.2	Scenarios considered in Experimenter . . . . .	63
B.1	Summary of charging cost values after the execution of the seven scenarios considering the base model . . . . .	92
B.2	Summary of energy consumption cost values after the execution of the seven scenarios considering the base model . . . . .	93





# Abbreviations

ACT	Automated Container Terminal
AGV	Automated Guided Vehicle
ALV	Automated Lifting Vehicle
CT	Container Terminal
DES	Discrete Event Simulation
QC	Quay Crane
RMG	Rail-Mounted Gantry Crane
RTG	Rail-Tired Gantry Crane
SC	Straddle Carrier
TEU	Twenty Foot Equivalent Unit
YC	Yard Crane
YT	Yard Truck



# Chapter 1

## Introduction

This introductory chapter will present the dissertation theme "A Simulation Tool for Optimizing Port Operations". Initially, in section 1.1 a brief contextualization of seaports and their challenges is given and in section 1.2 is presented the motivation of this dissertation. The goals of this dissertation are described in section 1.3, while a brief summary of the methodology and scientific approach used is provided in section 1.4. The organisational framework of this dissertation will be made clear in section 1.5.

### 1.1 Contextualization

In recent years, the international sea-freight container transportation industry has experienced remarkable growth, positioning container terminals as crucial players within the global shipping network. With escalating competition among terminals, achieving operational efficiency has become imperative for terminal managers. The focus is on minimizing ship turnaround time, a key performance indicator for shipping companies, and reducing operational costs to enhance competitiveness and attract new customers. Operations research methods and techniques have emerged as valuable tools for optimizing terminal operations and addressing these challenges effectively [14].

Container ports serve as vital interfaces between railroads, ocean-going ships, and over-the-road trucks, representing critical links in the intermodal chain. These ports demonstrate a high level of integration among various information systems and control engineering applications, forming comprehensive port information system architectures [15]. These architectures encompass vessel traffic services, sea/yard and freight station planning operations, administrative/financial management, and the management and control of handling activities, among others.

Increasing containerization and global trade have necessitated constructing and expanding container terminals worldwide to accommodate the growing number of containers and the larger vessels that transport them [16]. These terminals face the challenge of efficiently handling a multitude of operations, including unloading ships, goods inspection, container storage, export loading,

and internal transport. Given the diversity of machinery used and the volume of operations, container terminals have evolved into complex logistics systems, demanding effective management models and optimization approaches.

Innovative transportation facilities, equipment, and management practices dedicated to inter-modal freight movement have emerged to address these demands. Seaport container terminals have become focal points for logistics control, leading to extensive research in scientific literature. These studies have explored performance analysis, evaluating alternative configurations, berth allocation, stowage planning, scheduling of handling equipment, storage and stacking logistics, quayside and landside transportation planning, among other aspects [17]. Simulation-based tools have played a pivotal role, enabling the replication of terminal operations and facilitating performance evaluations under varying operating conditions.

In this context, the role of simulation modeling becomes paramount. Simulation offers decision-makers the ability to assess system performance, experiment with different parameters, and support critical decisions regarding facility layout, equipment selection, and resource adequacy. Recent simulation modeling advancements, enhanced software capabilities, and powerful computing technology provide opportunities for more robust and comprehensive simulations of container terminals [16].

In light of the evolving complexities and increasing demands on container terminals, this dissertation aims to design and optimize container terminal operations using a simulation-based approach to serve as a decision-support tool to test several container terminal operation simulation scenarios and evaluate their performances from a multi-criteria perspective.

This research addresses the fundamental operational processes occurring within a container terminal, taking into account the escalating trend of automation in port operations and the contemporary significance of sustainability. By examining various aspects such as total operation time, cost-effectiveness, and level of sustainability, this research intends to contribute to the development of efficient and sustainable container terminal management strategies.

## 1.2 Motivation

The significance of marine container ports within global supply networks cannot be overstated, as they handle over 80% of global commercial trade in terms of volume, with containerized trade accounting for 17.1% in 2017 [18]. Ensuring smooth and cost-effective operations of container terminals is crucial for both the economies relying on the transported commodities and the terminal owners to remain competitive. Consequently, extensive research has been conducted on container terminal operations [19]. However, the heterogeneous nature of container terminals, encompassing factors such as terminal layout, equipment usage, and varying degrees of automation and digitalization, presents a significant challenge in generalizing case study results and sharing best practices across ports.

Nonetheless, in order to maintain competitiveness, container terminals must adapt and draw lessons from successful practices in other industries. The complexity of container terminals and

the limitations of extrapolating conclusions from specific field research necessitates focusing on specific areas of investigation. While a comprehensive search is theoretically feasible, it often proves time-consuming for practical implementation. Therefore, approximations must suffice for real-world applications [19].

Among other methodologies, simulation-based optimization can be employed to predict input parameters with sufficient accuracy, and various optimization techniques can be applied to address the same issues. This leads to the research done in this dissertation.

Designing and testing various simulation scenarios of container terminal operations is made easy by utilizing the capabilities of simulation software. These simulations offer insightful information on how different variables and factors affect the performance metrics of container terminals. This work intends to provide a decision-support tool that may assist in efficiently planning and managing container terminal operations by systematically examining various scenarios.

### 1.3 Objectives

The primary goal of this thesis is to design a simulation model that will be used as a decision-support tool to optimize the management of container port activities from a multi-criteria perspective. The tool will be designed to take into account the unique challenges and complexities of container port operations. It will be used to evaluate container ports' global performance using several key performance measures. Through this research, it is aimed to achieve the following goals:

- Design a container port simulation model: The first goal of this dissertation is to create a simulation model designed solely for container port operations. The tool will consider the operations involved in handling and transporting cargo aiming to study the overall efficiency of several scenarios developed considering some important metrics.
- Validate and evaluate the simulation model's performance: The simulation model's efficiency will be assessed after it has been created. This will entail putting the tool through its tests with several data and evaluating its capacity to offer insightful analysis and suggestions about port operations.
- Contribute to the field of port logistics: By developing and evaluating this simulation model designed explicitly for port operations, its aim is to contribute to the field of port logistics. This research has the potential to likely provide valuable insights into how container ports can optimize their operations and improve efficiency.

The main goal of this dissertation is to formulate and construct a decision-support tool capable of assessing diverse configurations of container terminals to facilitate decision-making regarding the optimal composition of quay cranes (QCs) and automated guided vehicles (AGVs) within the terminal. Additionally, this tool will facilitate an evaluation of specific AGV characteristics that

influence the overall operational performance of the container port. By incorporating comprehensive performance evaluations, including the assessment of energy costs associated with the utilization of electric AGVs, this decision-support tool aims to address the escalating automation trends in container terminals and the imperative sustainability concerns pertaining to port management. The simulation model design diligently considered these critical factors to ensure a comprehensive analysis of container terminal operations.

## 1.4 Methodological Approach

The primary objective of this dissertation is to develop a comprehensive simulation model that encompasses the fundamental internal operations within container terminals. These operations entail the coordinated movement of diverse equipment across various areas within the terminal, necessitating a thorough understanding of port logistics and the underlying procedures involved in the arrival and departure of ships.

To achieve this objective, an extensive literature review was conducted to gain insights into the structure and functioning of container terminals, enabling a comprehensive representation of their operations. Subsequently, the base simulation model was meticulously designed and constructed, with preliminary tests conducted to familiarize oneself with the simulation software, FlexSim, and determine the optimal approach to represent the core operations of a container terminal.

During the implementation phase within FlexSim, in-depth research was conducted to obtain accurate equipment-specific information, ensuring a high degree of fidelity to real-world conditions. Validation exercises were performed to assess the logical coherence of the software program and its alignment with the conceptual model.

Furthermore, a range of performance metrics was developed using FlexSim's Dashboard, and custom functions were formulated to calculate three key performance measures, serving as benchmarks for evaluating the system's operational efficiency.

In addition to the base model, two individual modifications were introduced to investigate and evaluate the impact of AGV characteristics on container terminal operations, providing further insights into their influence.

Finally, a series of tests encompassing seven distinct scenarios, characterized by varying equipment quantities, were conducted. The results derived from executing these scenarios using the conceptual model served as a comparative reference against the outcomes obtained from the extensions introduced to the base model. Subsequent analysis of these results facilitated a concise reflection on the achievements and contributions of this dissertation.

## 1.5 Dissertation Structure

This document is structured based on the progress made throughout the project and is divided into six chapters. The first chapter serves as an introduction, providing contextualization and outlining the goals to be achieved.

Chapter 2 focuses on the literature review, delving into topics such as the structure of ports, container terminals, and the operational environment of ports. It also explores equipment used in ports, different port layouts, logistics processes, and environmental sustainability initiatives in ports. Additionally, the chapter covers the concept of simulation and its application as a decision-support tool, providing examples of simulation usage in the port industry.

In Chapter 3 it is presented the case study of the dissertation, addressing the research problem, research question, and the design of the container terminal model. This chapter introduces the conceptual base model and its extensions, which will be simulated to evaluate the performance of the container terminal. Moving forward, Chapter 4 provides an overview of the FlexSim software's features and capabilities and describes the implementation of the case study in FlexSim. It also presents the several metrics considered in FlexSim's dashboard that later were used to evaluate the system.

Chapter 5 focuses on the experimental design conducted in FlexSim, including the selection of performance measures to evaluate the different scenarios. The chapter also introduces the tool used for executing and evaluating the scenarios. Furthermore, it comprehensively analyzes the results obtained from both the base model and its extensions.

Finally, Chapter 6 offers conclusions derived from the dissertation, summarizing the main findings and insights gained from the research. It also discusses potential extensions of the work and outlines future research directions.





## Chapter 2

# Literature Review

The study done in order to comprehend the majority of the dissertation's core ideas led to the creation of this chapter, which covers the bibliographical review. This chapter was organized into sections after carefully weighing the goals to be accomplished and all the factors influencing the background and motivation.

Firstly, section 2.1 will provide the concept of seaports and their logistics, as well as their importance. Section 2.2 delves into the idea of container terminals and the primary operations that take place there. The classification of containers in container terminals is also addressed in this section.

Then, in section 2.3, the operations planning in a container terminal as well as the equipment used for transporting and storing containers will be covered. The different layouts of container terminals are also addressed in this section.

In section 2.4 is presented a brief explanation of automated container terminals and their characteristics.

Section 2.5 introduces the impacts of seaports on the environment, the concept of green ports, and the steps taken to achieve sustainability.

Finally, section 2.6 presents the key concepts related to simulation and its approaches. In addition, is evaluated some previous studies done to optimize container terminals' operations.

### 2.1 Physical Flows and Seaports

According to [1], a port is a logistical and industrial hub in global supply chains that has a strong maritime identity and a functional and spatial clustering of activities that are directly or indirectly related to the movement of goods, the transformation of goods, and the exchange of information within these supply chains. They are essential for global trade and commerce as they provide a vital link between maritime transportation and other modes of transportation, such as rail and road.

Seaports handle a variety of cargo, including containers, bulk goods, and liquid cargo [20]. Ports include a specific terminal or a variety of terminals according to the cargo handled. The

number and kind of these terminals dictate the port's purpose and role. Some ports are multifunctional, while others can be specialized [1]. Figure 2.1 shows the three main categories of port terminals.

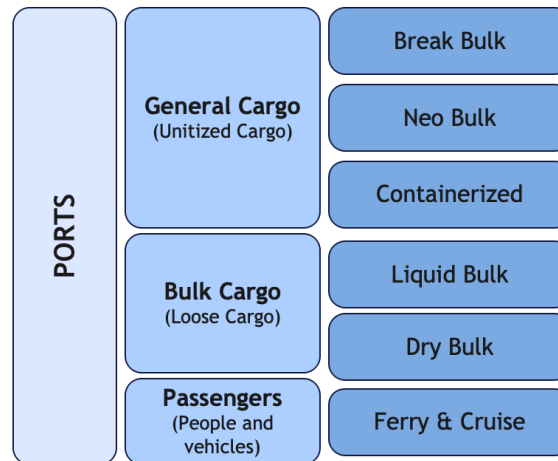


Figure 2.1: Types of Ports Terminals, adapted from [1]

**General Cargo** is characterized by three different types of specialist terminals with unique equipment and architectural considerations that can handle unitized cargo, which can be transported in batches. Because break-bulk and container terminals handle unit goods, they are built using the lift-on/lift-off principle, necessitating cranes and storage spaces. At vehicle terminals, a form of neo bulk terminal, parking lots predominate, and operations are based on the roll-on/roll-off principle [1]. On the other hand, **Bulk Cargo** is loose cargo; in other words, the cargo is carried in any quantity relative to the ship size and the storage capacity. Furthermore, the majority of bulk terminals are highly specialized to the point of a distinct product, such as coal, grain, iron ore, natural gas, or petroleum [1]. The third terminal is concerned with the **Passengers**, which corresponds to a minor component of contemporary port terminals, with the notable exception of regions with heavy ferry service density [1].

Seaport logistics refers to the management and coordination of the various activities involved in seaport operations, including cargo handling, transportation, security, and safety. Seaport logistics is a complex and dynamic field. It is essential for seaports to be able to optimize their operations to handle larger volumes of cargo, reduce costs, and improve efficiency.

Effective seaport logistics requires the integration of various stakeholders, including port authorities, shipping companies, terminal operators, and transport providers [21]. Seaport logistics involves the planning and coordination of the movement of cargo through the seaport, from the arrival of the vessel to the final delivery of the cargo. It also involves the management of storage facilities, transport networks, and other critical infrastructure. Seaport logistics faces several challenges, including the need to maintain security and safety standards, the increasing size of vessels, and the constantly evolving nature of global trade [1].

## 2.2 Container Terminals

Containerization is a transportation method that revolutionized the way goods are moved across the world [22]. Container ships are the backbone of global trade, transporting everything from raw materials to finished goods. Container terminals are critical infrastructures for handling and transferring containers between ships and other modes of transportation [23].

The five primary sections of a container terminal are the berth, quay, transport, storage yard, and terminal gate. Seaside refers to the berth and quay sections, whereas landside refers to the storage yard and gate sectors. The landside and seaside areas meet at the intersection of the transportation area.

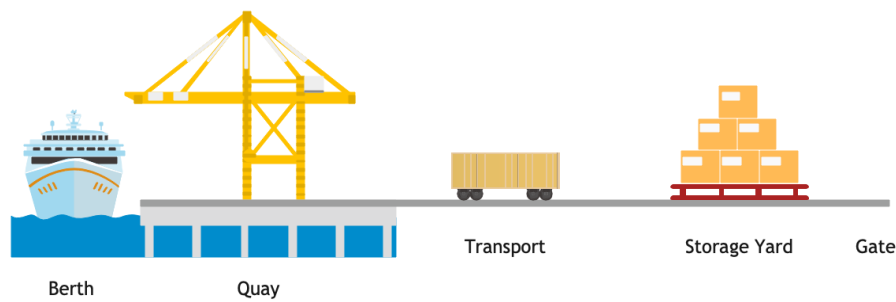


Figure 2.2: Container Terminal Layout, adapted from [2]

Container terminals are facilities that handle the movement of containers between different modes of transportation, such as ships, trucks, and trains [21]. They are designed to store, load, and unload shipping containers, which come in standardized sizes and shapes [24]. Container terminals are typically located near seaports, inland waterways, or railroads and are connected to these transportation networks. Their primary function is to provide a connection point between different modes of transportation. This involves transferring containers from ships to trucks, trains, or other ships, and vice versa. Container terminals also serve as storage facilities for containers, providing a secure location for containers to be held before they are transported to their destination [25].

Although the types of handling equipment used and the geometric size and layout substantially vary between port container terminals, several processes and terminal operations are universal to all container terminals, especially the unloading of a ship which is briefly summarized as follows [26]:

- 1. Ship arrival:** When a container ship arrives at a terminal, it is guided to its designated berth by tugboats. Once the ship is secured at the berth, container unloading operations begin.

- 2. Container unloading:** Containers are unloaded from the ship using cranes, which lift the containers off the ship and onto the dock.

- 3. Storage:** Once the containers are unloaded, they are moved to storage areas within the terminal.

**4. Container handling:** When a container is ready to be transported, it is moved from the storage area to a truck, train, or another ship. This involves the use of cranes, forklifts, and other equipment to lift and move containers.

**5. Customs clearance:** All containers passing through a terminal must be properly documented and comply with relevant regulations. Container terminals work with customs officials to ensure containers are cleared for export or import.

**6. Transportation:** Once a container is cleared for export, it is transported to its destination by truck, train, or another ship.

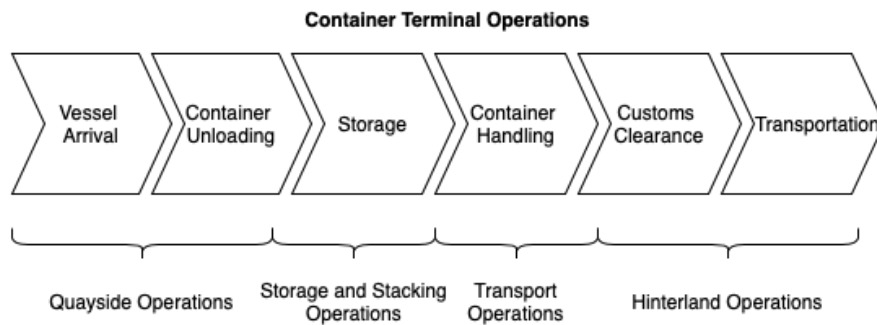


Figure 2.3: Container Terminal Operations

The processes involved in outbound containers are the same as those involved in inbound containers, but the order is reversed.

Based on [27], in port container terminals, containers are categorized in one of two ways. According to the container flow paths, containers can be divided into three groups in the first categorization scheme: inbound containers, outbound containers, and transshipment containers. Containers that are discharged from ships and transferred to recipients in the hinterland are considered inbound. The containers that are delivered to ships from hinterland shippers are known as outbound containers. Containers for transshipment are unloaded from one vessel and then loaded onto another. According to the type of handling by quay cranes (QCs), containers can be divided into two groups in the second classification method: loading containers and discharging containers. Whereas inbound containers are categorized as discharging containers, outbound containers are loading containers. Both loading and discharging containers include transshipment containers.

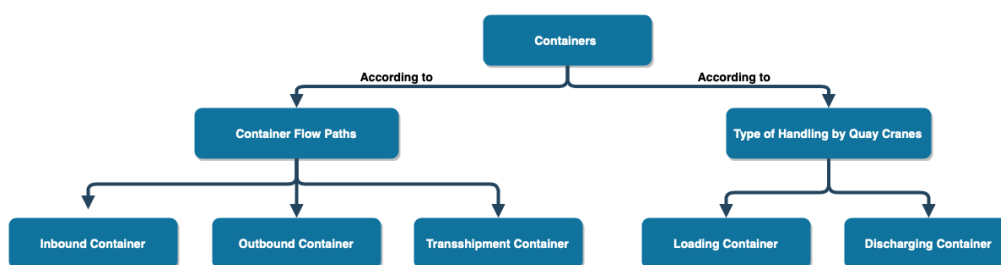


Figure 2.4: Classification of containers in port container terminals

## 2.3 The Operating Environment of Ports

This section will delve into the core operations of a container terminal and the equipment used for the handling, transportation, and storage of containers. Additionally, the diverse layouts implemented in container terminals will be analyzed too, shedding light on the various configurations and spatial arrangements adopted to accommodate the complexities of container handling and ship operations. All of the logistics and features of a container terminal were considered while dividing this section into its seven subsections.

### 2.3.1 Operations Planning

The process of developing an operations plan outlines how the terminal will be utilized to transport and store containers. The Operations Planner takes into account the kind and size of containers, the terminal's design, the equipment that is available, and the flow of traffic into and out of the port [21].

Container terminals may work more effectively and avoid delays by developing a well-thought-out Operations Plan. All container terminal activities are coordinated and managed by operations planners to ensure efficient and successful operations. Although it is an essential component of every organization, managing it in a container port with plenty of moving elements may be particularly difficult.

The movements of ships, trucks, and cranes, as well as the arrival and departure of container goods, must be considered by operations planners. They must also make sure that the terminal can satisfy the needs of its consumers, which complicates matters even further. Although maintaining this equilibrium can be challenging, it is necessary for the terminal to function properly [21].

### 2.3.2 Material Handling Equipment

Upon the ship's berth, the inbound containers are unloaded by quay cranes (QCs) and transported from the quayside, located in the vicinity of a reception terminal, to the storage yard.

There are restrictions on how far handling equipment can transport a container, and the majority of them can only transport one container at a time. Huge cranes, usually rail-mounted, QCs, or container cranes, are used to load and unload containers as containerships berth. In order to move the container from the ship to the quay area and vice versa, the QCs are outfitted with trolleys that can travel along the crane arm [27]. The spreader of a QC grabs a container on the ship, raises it vertically to a safe height, carries it horizontally over the dock, and either sets it on a vehicle or the ground during unloading duties [24]. Figure 2.5 presents three ship-to-shore cranes in the Container Terminal St. Petersburg, Russia.



Figure 2.5: Quay Cranes [3]

Because of their relatively low initial investment cost and high capacity, conventional yard trucks (YTs) illustrated in figure 2.6 and rail-based handling equipment were the only ones utilized initially and for a while. Unfortunately, they require human drivers, which raises operational costs [24].



Figure 2.6: Yard Truck [4]

### **Automated Guided Vehicles - AGVs**

The option has more recently been automated guided vehicles (AGVs), which are fully automated and are managed by a centralized computer that determines the dispatching and movement of each vehicle [24]. AGVs can move objects, but they cannot lift containers on their own. Therefore, they need a crane to pick up and/or deliver the containers. Figure 2.7 is a picture of an AGV in operation at the Container Terminal Altenwerder (CTA) in Hamburg, Germany.





Figure 2.7: AGV [5]

Labor savings and improved freight routing and tracking are AGVs' main advantages over manually operated vehicles [28]. The difficulty in achieving high system safety when AGVs run at high speeds and are combined with people or, possibly, non-automated vehicles is a significant drawback of AGVs [28]. This difficulty also contributes to the high initial investment cost. But, more intelligent and flexible AGVs have been designed that travel freely in the transferring area, avoid collisions, and use computer vision or wires, lasers, or markings to direct them [22].

Transport vehicles are characterized as either passive or active. Passive vehicles cannot independently raise containers from the ground and must thus interact with other equipment, necessitating a higher level of coordination between the various equipment types. Active vehicles, on the other hand, do not require additional equipment to raise a container. This implies they can lift and transfer containers between the ship and the buffer region. However, the size and availability of buffer spaces are crucial considerations for the practical deployment of active vehicles [24].

Table 2.1: Types of transport vehicles

Passive	Active
Yard Trucks	Straddle Carriers
AGVs	Automated Lifting Vehicles

A straddle carrier (SC) is a vehicle with wheels and rubber tires that can lift containers and stack them on top of one another and move them to and from different locations inside of the port, as figure 2.8 shows. SCs can only handle the small number of containers that small seaport terminals must now handle manually, and they cannot meet the capacity and space utilization needs of major seaport terminals. They are able to move between rows of containers and can stack them up to four tiers most of the time [29]. SCs are widely used as transportation/stacking equipment at small and medium-sized container ports [24].



Figure 2.8: Straddle Carrier [6]

Based on the principles of SCs, automated lifting vehicles (ALVs) have been developed to lift and transport containers from the ground as well as move them automatically and more swiftly, like an AGV. ALVs do not need to wait for a transport truck and have a separate work cycle from QCs or storage yard cranes [24].

### 2.3.3 Storage Yard Logistics

Containers that have been unloaded from a ship may be placed on the quayside, on an over-the-road truck chassis, or on a port truck chassis using quay cranes. Containers are transported by yard trucks to the port's stack storage area or rail yard if they are mounted on port chassis [26].

The containers are removed from the chassis and placed in stack storage yards using yard cranes (YCs). Containers can be moved from the port's quayside to the port's stack storage area or rail yard using port straddle carriers. This procedure will be reversed for outbound containers [20]. For loading onto a containership, quay cranes reclaim containers from port vehicle chassis or the quayside itself. Quay rail cranes can load and unload containers into and out of each ship's bay since they are mounted on rails and can move laterally along moored containerships [20].

Yard cranes are similar to ship-to-shore cranes in that their spreaders are attached to containers for raising and lowering, as depicted in 2.9. Containers may be lifted and lowered from and onto rail trains, vehicle chassis, container stacks, and maybe rail or rubber tires [20]. Yard cranes come in a variety of designs, including rubber-tired gantry cranes (RTGs) and rail-mounted gantry cranes (RMGs). While moving from one container storage yard to another, RTGs are more mobile than RMGs. Yet, because RMGs are more stable when placed on rails, ports can utilize them to stack containers higher, increasing the density of container stacks in storage facilities [20].

Yard cranes lift and lower cargo from above like straddle carriers do. Contrary to straddle carriers, yard cranes have the drawback of being unable to quickly move containers from one specified area of the port to another [20]. Yet when it comes to container stacks, yard cranes have an edge over straddle carriers in terms of selectivity capability, which means they can typically pick



and remove or move containers in the stacks more quickly [20]. This benefit grows as container stacks get taller and wider, which tends to increase with the price of the port property [20].



(a) RTG [30]



(b) RMG [31]

Figure 2.9: Yard Cranes

As inbound containers from ships arrive at port rail yards, they are unmounted from port chassis and put onto rail cars. Stack-stored inbound containers are unstacked, put on port chassis, transported to rail yards, taken off the chassis, and loaded onto rail cars [20]. Rail-delivered outbound containers are unloaded and put on port chassis for transportation to stack storage, where they are taken off the chassis and stacked [20]. Additionally, they may be towed to the port's quayside, lifted off the chassis by the quay cranes there, and put onto ships [20]. Reshuffling the containers is another ineffective activity carried out in container terminals, but it is necessary when the desired container has been piled below other containers.

It can be challenging to extend storage yards because many container terminals lack the space to do so and because the land might occasionally be prohibitively expensive. Also, the reshuffling procedures necessary in storage yards for stacking are time-consuming. So, in order to expand storage capacity, researchers have recently begun considering the fundamentals of automated storage and retrieval systems to be used in container ports.

### 2.3.4 Layout of Container Terminals

Today, a sizable terminal may handle millions of containers every year. Paying closer attention to the layouts and handling technologies used to stack containers is essential for boosting containerized freight transportation efficiency [23]. Containers are frequently kept in stacks at terminals as they wait to be transported further by seagoing boats or by land-based forms of transportation [23]. The layout of container terminals today is typically rectangular, with many bays and rows stacked next to one another in multiple, usually four-tiered stacks [23].

According to the orientation of the storage blocks concerning the quay line, there are two main types of yard layouts: parallel and perpendicular [26], as figure 2.10 illustrates. Container terminal designs vary depending on some factors [26]:

- The region in which they are located.

- Container throughput.
- Morphological layout.
- The needs of transportation companies.
- The type of terminal in terms of handling and transportation equipment, namely automated, semi-automated, or conventional terminals.

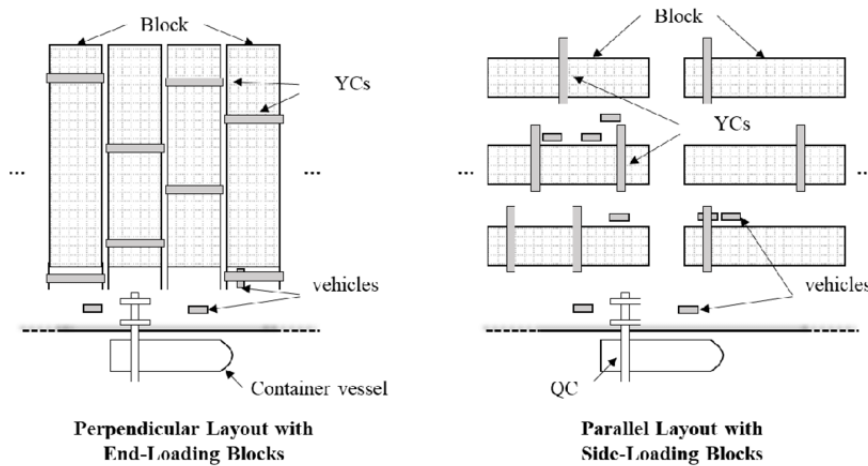


Figure 2.10: Types of Container Terminals Layouts [7]

Vehicles are required to interact with YCs at the extremities of the block in the perpendicular layout with end-loading blocks [7]. This block layout is more common in export and import terminals, and it is advantageous for container yards because the landside and seaside traffic controls are separate, allowing only vehicles to access the landside blocks for receiving and delivery activities. In contrast, only road trucks can access the seaside blocks for loading and unloading activities [7]. To facilitate traffic management, road trucks and carriers are not permitted to enter the vertical aisles between neighboring blocks. Hamburg's Altenwerder Terminal and Rotterdam's Euromax Terminal serve as good examples of real-world applications. As a result of the end-loading block architecture, YCs must do a round-trip for each handling task, which could cause vehicles to wait for a while [7].

Many traditional container terminals, like Pasir Panjang Terminal in Singapore and Modern Terminal in Hong Kong, have a parallel layout with side-loading blocks, which presents demanding traffic control needs for various types of handling equipment [7]. This design is more common in transshipment terminals [23]. RTGs or RMGs are used in parallel layouts, and it is necessary for vehicles to temporarily park next to the block so that YCs can perform handling operations nearby, usually within close proximity to the block, in order to increase operational efficiency by minimizing YC gantry travels [27].

## 2.4 Automated Container Terminals

In response to the surge in global trade, port authorities are actively exploring strategies to enhance the efficiency of their existing facilities. One promising approach to improve operational efficiency, expand capacity, and cater to future demands is the implementation of advanced technologies and automation, which facilitate accelerated terminal operations [32].

The growth of automation in various industries can be attributed to two primary factors: the imperative to minimize manual labor costs and address the scarcity of skilled labor. When it comes to repetitive tasks, relying solely on manual labor can result in lower productivity and increased unreliability. Conversely, automation offers enhanced output levels with greater precision, all while reducing long-term costs. Hence, automated container terminals with high-density capabilities have emerged as potential solutions for enhancing the performance of container terminals and addressing future challenges in marine transportation. Recent advancements in electronics, sensors, information technologies, and automation have made the development of fully automated terminals technically viable. According to [32], the Port of Rotterdam has successfully implemented a fully automated terminal that utilizes automated guided vehicles (AGVs) and automated yard cranes for container handling. Similarly, the Port of Singapore and the Port of Hamburg are also exploring similar concepts.

As stated by [33], the most advanced kind of container terminal is called an automated container terminal (ACT), which employs automated machinery and sensors to carry out autonomous tasks such as container loading and unloading, horizontal transit, and yard operations. The configuration of an ACT, including its storage capacity, number of gate lanes, berths, quay cranes, and other features, is determined by considering both the projected maximum container volume to be handled by the terminal and the equipment specifications. A classic ACT's usual configuration consists of berths, yard blocks, gates, lanes in the terminal, terminal cranes (such as quay cranes (QC) and rail-mounted gantry cranes (RMG)), transport vehicles (such as automated guided vehicles (AGV) and container trucks) and transport vehicles.

Several studies have been conducted to evaluate each ACT's performance and improve container handling efficiency. At current, the evaluation of automated container terminals (ACTs) has concentrated chiefly on examining the performance of various ACT types using sophisticated event-based simulation models [34].

In a nutshell, the use of ACTs has shown promise in resolving issues that traditional container terminals have to deal with. ACTs provide the possibility for better performance, more efficiency, and increased production through sophisticated technology and automation.

## 2.5 Environmental Sustainability in Ports

Since trade can be conducted more quickly and effectively at ports, their significance has only grown to grow. The ports' strategic location, rising transaction volume, development of environmentally friendly systems, and proximity to vital trade routes all contribute to an unavoidable

process of change. The notion of the green port has now been created as a result of growing awareness [35]. The goal of green ports is to use energy resources effectively and efficiently to meet energy needs while having the most negligible detrimental impact on the ecosystem and the environment possible while the ports continue their operations [35]. The attention to environmental issues is particularly intense for vessel and cargo handling operations, industrial activity in ports, port development and extension plans, and hinterland accessibility. Pollution from port-related operations and construction is one of the main causes of seaports' negative environmental effects. They include terminal handling machinery, logistics, and industrial activity in the port, as well as air pollution from berthed ships. In addition to the environmental effects and potential congestion caused by the landside operations of barges, trains, and trucks, port-related operations also cause noise [1].

Since reducing energy consumption allows for both significant energy cost savings and significant environmental benefits, it is crucial to consider the trade-off between energy consumption and operational efficiency as well as its effects on the integrated scheduling of quay cranes and intraterminal vehicles [22].

During operation, diesel-powered cargo handling equipment in ports releases gases such as SO<sub>2</sub> (sulfur dioxide), NO<sub>x</sub> (nitrogen oxides), CO (carbon monoxide), HC (hydrocarbon), PM (particulate matter), and so on [36]. Low air pollution, high energy savings, and high working effectiveness are the goals of green container handling issues in order to meet the requirements for effective terminal operations [37]. Currently, diesel equipment is being abandoned in favor of electric vehicles in order to produce a sustainable and environmentally friendly atmosphere. Green container ports should be built with efficiency in mind, as well as with the goal of saving energy and cutting carbon emissions [38]. Electric-powered AGVs make a big difference in how efficiently they operate, how much energy they save, and how much CO<sub>2</sub> they emit. Furthermore, rising diesel prices in recent years increased terminal operating costs, and new regulations pushed port officials to switch to electric handling equipment [39] [40]. The change results in energy savings and improved air quality, as well as a reduction in greenhouse gas emissions and noise pollution at the terminals [38].

The necessity for operational activity coordination will become even more crucial in the future as containerization grows in order to maintain productivity. In the very near future, there will be a significant increase in the requirement for integrated approaches, according to the study by [38]. Additionally, as automation increases at container terminals, it will be necessary to optimize the automated vehicles and handling equipment. This will also require effective planning of integrated operations involving this equipment. Also, brand-new terminal layouts will quickly evolve into "green port terminal" layouts that take into account energy-efficient handling machinery and lower air pollution [38].

## 2.6 Simulation

In this section, the role of simulation as a tool for decision support systems will be explored. The different paradigms of simulation utilized will be examined. Emphasis will be placed on the

significance of simulation in providing insights and supporting decision-making processes, with the aim of highlighting its relevance and potential for enhancing port operations and optimizing performance.

### 2.6.1 Simulation as a Tool for Decision-support Systems

According to [41], simulating the behavior of a system or process in the real world over time is known as simulation. In order to simulate a system, an artificial history of the system must be created. This artificial history must then be observed in order to make conclusions about the operating characteristics of the real system being simulated [41].

For the resolution of many real-world issues, simulation is a crucial approach to problem-solving. For describing and analyzing a system's behavior, posing hypothetical "what-if" scenarios, or helping to develop actual systems, simulation is often employed. Simulation can be used to model both real-world and hypothetical systems [41].

Simulation has been used in research and development efforts in container terminal operations. Modeling is a way of solving problems that occur in the real world. It is applied when prototyping or experimenting with the real system is expensive or impossible [42].

Analytical forecasting of the terminal's performance under particular layouts and configurations is challenging due to the sheer size of the facilities and the complexity of the equipment used. The need for a tool that can accurately simulate the behavior of an actual terminal arises from the difficulty of analyzing and benchmarking control strategies that relate to the dynamic behavior of the equipment [43].

### 2.6.2 Simulation Paradigms

There are several types of simulation used in decision support systems, including System Dynamics (SD), Agent-Based Modelling (ABM), and Discrete Event Simulation (DES).

The **System Dynamics** approach is frequently employed in long-term, strategic models and presupposes very high degrees of object aggregation: SD models use quantities to represent people, things, events, and other discrete objects [44]. In System Dynamics, the representation of real-world processes takes the form of stocks, flows between these stocks, and data that establishes the values of the flows. By abstracting from discrete events and entities, System Dynamics adopts an aggregate perspective that focuses on policy. To tackle the problem in the System Dynamics way, one must define the system behavior as a collection of cooperating feedback loops, balancing or reinforcing structures, and delay structures [42].

The use of **Agent-Based Simulation** (ABS) aids in the comprehension of real-world systems where the representation or modeling of many individuals is crucial and where the individuals have autonomous behaviors. ABS provides something new, intriguing, and possibly quite useful for manufacturing and supply chains. The focus of ABS models is on simulating the entities and their interactions, where each agent has a separate control thread [45].

The **Discrete Event Simulation** approach is an effective tool for reviewing and assessing production flows without compromising output [46]. The state variables of a discrete-event simulation model only change at the discrete points in time where events take place. Activity times and delays have an impact on events. Entities may compete for system resources, possibly forming queues while they wait for a resource to become available. Each event updates the system state and captures and releases any resources that may become available at that moment [41].

The quality of discrete event simulation models is highly dependent on the input data. In actuality, the compatibility between data sources and simulation models, as a first step to assure high-quality input data and to minimize data gaps or limited accessibility, might be crucial to decide the simulation's success [47].

The use of discrete event simulation provides engineers with a versatile modeling capability for a thorough examination of a production flow and its dynamic behavior. Considering this and the goal of this dissertation, which is designing a simulation model for optimizing port operations, this type of simulation model will be the one used.

### 2.6.3 Application of Simulation to Ports

It has already been studied and developed some simulation models mainly focused on container terminals to encourage sustainable ship-port connections and supply chain networks. According to [48], the development of ports, and more specifically container terminals, has been proven to benefit significantly from the usage of simulation models over the past 50 years. In several experiments, testing the viability of a general technique or design element was the main goal rather than simulating a specific port [43].

Authors like Ho and Chien (2006) [49] and Soriguera, Espinet, and Robuste (2006) [50] assess the management of vehicles for the internal movement of containers; Arango, Cortés, Onieva, and Escudero (2013) [51] and Arango, Cortés, Muuzuri, and Onieva (2011) [52] assess and optimize the allocation of docks and wharf cranes to ships. Lee, Cao, and Shi (2007) [53] and Legato, Canonaco, and Mazza (2009) [54] review and optimize the operations of dock cranes and gantry cranes as stated by [55].

The optimization of seaport logistics is therefore essential for ensuring the smooth and efficient operation of seaports and for maintaining their position as critical infrastructure for global trade and commerce. The development of simulation tools for optimizing seaport operations is a promising avenue for addressing these challenges and improving seaport logistics.

## Chapter 3

# Case Study

This chapter provides a description of the problem that this dissertation seeks to resolve before diving into a thorough analysis of the case study. There will be six sections in this chapter, each of which has a number of subsections.

The purpose of section 3.1 is to address the present problem by providing a thorough explanation of the issue. Section 3.2 then presents a description of the base model. The container terminal design is also thoroughly explored in this chapter, covering elements like the quay area (3.3), transportation area (3.4), and storage yard area (3.5). Each area is scrutinized, highlighting specific characteristics and specifications contributing to overall operational dynamics.

Finally, section 3.6 presents the explanation of the two extensions of the case study.

### 3.1 Problem Description

As mentioned in the previous chapter, a seaport is the place of connection between land and sea, where the logistic pipeline rupture occurs due to the modal transfer between a mode of land transport and an aquatic, fluvial, or maritime transport.

The effectiveness and efficiency of the port and its terminals are appreciated by the speed with which the discontinuity dictated by that rupture is resolved. In an ideal situation, land transport and maritime/inland waterway transport should coincide in time and space so that cargo is transferred between them without a break in continuity. However, the reality is different, discontinuity happens, and the port will have to deal with it by ensuring spaces for cargo reception while waiting for the connection to land or sea/river, depending on the direction of movement.

To guarantee the maximum efficiency and performance of a container terminal, the important key research question to be answered in this dissertation is:

- What is the optimal solution considering the container terminal's resources to obtain the minimum unloading time of a container ship?

Thus, this dissertation was motivated by the necessity to solve the daily difficulties and complexity that container terminals face. Given the rising demand for efficient container handling and the



growing automation of terminal operations, the need for decision-support tools that can simulate different scenarios and evaluate their performance impact is crucial. The goal of this dissertation is to aid in creating a reliable instrument that facilitates the administration of container terminals through informed decision-making. In this dissertation it will be addressed the problem of resource use management at container terminals, such as quay cranes and AGVs, using a multi-criteria approach in combination with a simulation model where the relative importance given to selection criteria and the performance of container terminals are both varied due to the available resources and their characteristics. This provides a means to assess how container terminal performance and productivity are affected by changes in different criteria related to the operational areas, specifically the quay cranes, the storage yard, and the transportation system.

### 3.2 Base Model

Container terminals are complex infrastructures where multiple operations take place involving many resources and human operators. As mentioned in 3.1, container terminals are places of connection between the sea and the land, giving rise to all port logistics and the planning of all operations.

This complex system comprises several types of equipment, such as QCs, transport vehicles, and YCs. Figure 3.1 shows a schematic container layout where it is possible to see its different areas. As specified in 2.2, a terminal can be divided into several areas dedicated to specific operations: quay area, transport area, yard area, and hinterland area.

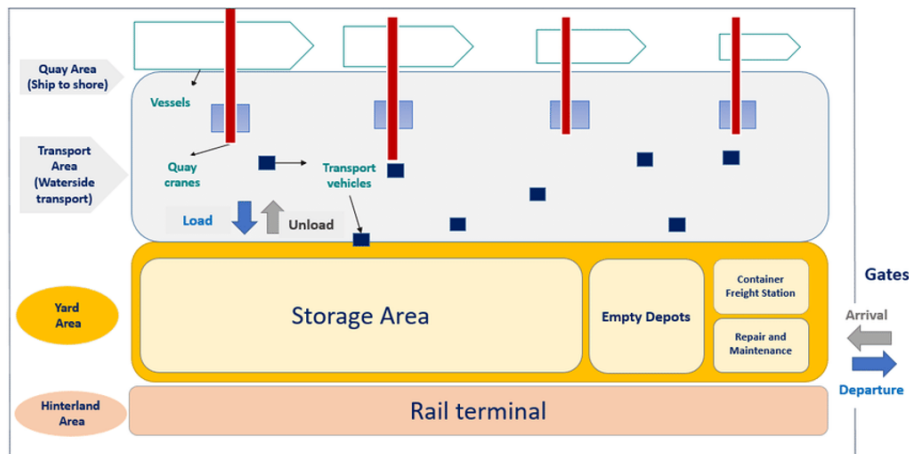


Figure 3.1: Schematic container terminal layout [8]

This dissertation considers all the operational areas, except the hinterland area, since the core of this research is to study and optimize the internal operations of a container terminal. These operations involve the cooperation between the QCs, vehicles, and yard cranes for unloading or loading a ship.



Analyzing the critical components of the real system is the first stage in creating the model. It is essential to first create a conceptual model before it is possible to begin the analysis. The conceptualization of the model depicts the process that will be examined and describes the flow of the entities inside the system. The base case built for this study only deals with the unloading operation of a ship. In this case, the main discussion topics were managing ship-delivered containers and their transfer from the quay area to the storage yard. Inbound containers are unloaded at the quay utilizing QCs that take them up from the ship, and they are then transported through internal vehicles to the storage yard, where they are stacked before being dispatched via the gate as part of the unloading sequence. The various stages of the ship unloading operation taken into consideration for this case study are illustrated in figure 3.2.

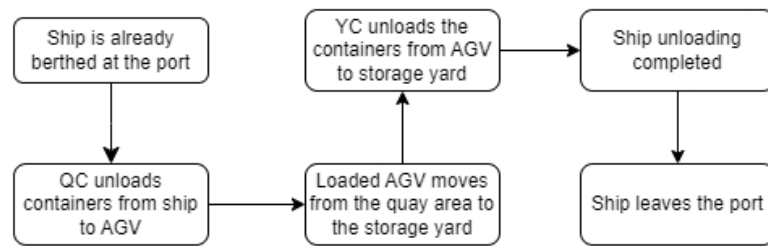


Figure 3.2: Operation process at the container terminal case study

### 3.2.1 Container Terminal Configuration

The terminal configuration considered in the analysis consists of one berth, the quay cranes working along it, and the handling equipment assigned to this berth. This dissertation analyses one handling equipment unit: electric Automated Guided Vehicles (AGVs). It transports containers from the quay area to the storage yard. The selection of AGVs as the mode of transportation is driven by the increasing automation trends observed in container terminals in recent years. Moreover, the emphasis on sustainability in seaport operations has led to the adoption of electric AGVs as a means to reduce carbon emissions and promote environmentally friendly practices. Figure 3.3 illustrates the primary operations and equipment considered in this simulation model.

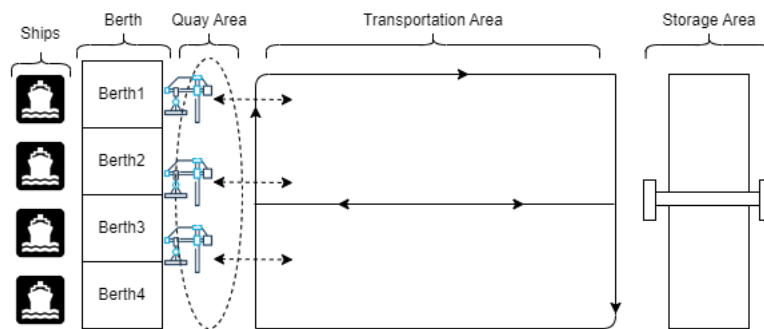


Figure 3.3: Schematic representation of the base case for simulation

A QC in a container port is not permanently stationed in one area. Hence their primary duties involve moving containers around and traveling. Once more, the three components of the transfer function are picking-up, vertical/horizontal transference, and release. In particular, a spreader moves vertically, whereas a crane trolley goes horizontally. These functions are all taken into account by the simulation model. As a result, the QCs in the simulation model function like actual terminals. In this base case, AGVs move along specified tracks for potential routes, and their actual speed is applied to the model. The main difficulties in the travel region, such as congestion, can be primarily remedied even though this technique does not completely solve all problems with transportation modeling. Every container, whether it is in a ship or a storage yard, is handled as an object in the simulation model. In a container-terminal simulation, when many containers must be handled, the precise characteristics of the containers, including their location, are typically left out for efficiency and to prevent unmanageable complexity. On the other hand, the storage yard can only be viewed as a container block where the containers unloaded from a ship are stored utilizing a single-yard crane. Since the gantry, trolley, and hoist speeds were considered for the simulation, this yard crane functions as it would at actual container terminals.

In this base model, it is assumed that only one ship arrives to be discharged. For this process, there are two QCs available to unload the vessel and four AGVs available to transport the containers from the quay area to the storage yard for storage. As mentioned earlier, only one yard crane is available to store containers in the container block. The number of QCs and AGVs involved in the ship unloading process constitute two decision variables of the model that consequently affect the total operation time.

To develop a highly realistic simulation model, extensive research has been conducted on the characteristics of quay cranes, AGVs, and yard cranes. This research aimed to capture the intricate details and nuances of these components that play a crucial role in port operations. By thoroughly examining this machinery's operational aspects and technical specifications, the simulation model was designed to replicate their behavior and performance within the port environment accurately. Particular emphasis was given to the characteristics of electric AGVs in this research due to the recent trend of automation in container terminals. As sustainability becomes an increasingly important aspect of port operations, adopting electric AGVs offers significant benefits. By focusing on the specific features and capabilities of electric AGVs, this dissertation aims to highlight their potential contribution to sustainable and eco-friendly port logistics.

By combining extensive research on quay cranes, AGVs, yard cranes, and on other port logistics players with a detailed exploration of operational areas, this dissertation strives to contribute to the advancement of simulation models in port logistics and to create a simulation model that is as accurate to reality as feasible, constantly striving for the best outcome with the least amount of overall operational time. The subsequent sections will provide a comprehensive overview of each operational area, shedding light on their unique characteristics and offering valuable insights into their optimization potential.

### 3.3 Quay Area

The initial step in constructing the simulation model involved meticulously analyzing the various containerships, containers, and quay cranes prevalent in port operations. A comprehensive examination of containerships was conducted to understand their diverse configurations, dimensions, and capacities. A comprehensive understanding of cargo handling requirements was achieved by studying the characteristics of different containers, including their sizes, types, and stacking capabilities. An in-depth analysis of quay cranes was undertaken, considering their lifting capacities, outreach capabilities, and operational constraints. This thorough investigation of containerships, containers, and quay cranes provided a solid foundation for building an accurate and realistic simulation model that could effectively replicate the dynamics and complexities of a functioning container terminal.

#### 3.3.1 Ship Arrival

Firstly, research was done on the types of ships that exist according to the capacity they can carry. According to [56] and as table 3.1 shows, ships are categorized according to approximate capacity measured by TEUs (Twenty Foot Equivalent Units).

Table 3.1: Categorization of Ships

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

The measurement of a container's size, commonly referred to as TEU or Twenty Foot Equivalent Unit, serves as the standardized unit in shipping. It means that two TEUs can be either two 20-foot containers or a single 40-foot container, with the latter being the more prevalent length. A TEU represents a length of 20 feet. Similarly, the terms "two TEU" or "one FEU," where FEU stands for "forty-foot equivalent unit," are often used to denote standard 40-foot containers. However, it is essential to note that container weight can vary significantly depending on the contents being transported, thus adding complexity to considerations of space limitations.

In this conceptual model, it is considered the standard 40-foot container. These containers arrive at the port in a Feeder Ship. The choice of the Feeder Ship as the containership to be incorporated into the conceptual model stems from its significant role in the global shipping industry. Feeder Ships are vital in transporting containers between smaller ports or terminals and significant hub ports. These vessels are designed to accommodate smaller capacities than their larger

counterparts, such as Panamax or Post-Panamax vessels. By focusing on Feeder Ships, the conceptual model aims to capture the intricacies of container transport within regional or short-sea routes, providing insights into the specific operational considerations and challenges associated with these types of vessels. Additionally, incorporating Feeder Ships into the model allows for a more comprehensive analysis of container flow, optimizing the overall efficiency and logistics planning within a broader port system. As can be seen in table 3.1, a Feeder ship can transport up to 2000 TEUs. For this base case, it was considered that a Feeder ship would always arrive at the port containing 500 TEUs, in other words, 250 40-foot containers.

### 3.3.2 QC Characteristics

The crucial role of unloading the chosen ship concerns QCs, which are essential for container terminals as they facilitate the efficient transfer of containers between ships and the terminal yard. With their impressive lifting capacities and outreach capabilities, these cranes handle containers of various sizes and weights. Their fast and precise operations contribute to minimizing vessel berthing times, optimizing cargo flow, and maximizing terminal productivity. QCs also ensure operational safety through advanced control systems and monitoring features. Overall, their role in container terminals is crucial for maintaining smooth logistics operations, enhancing efficiency, and ensuring the safe handling of cargo.

According to [9], with regard to the classification of QCs, these can be divided into several categories. The container vessel size that can service QC is used to classify the first potential type, which can be seen in table 3.2.

Table 3.2: QCs categorization based on container ship size

Type of QC	Size of Containership
Panamax QC	11-13 containers wide and outreach of 30-40m
Post-Panamax QC	17-19 containers wide and outreach of 45-55 m
Super Post-Panamax QC	21-23 containers wide and outreach of 60-70 m

Another classification of quay cranes is based on their boom mechanization [9]:

- High profile, also known as the A-Frame profile, features a tip-up boom positioned above the water surface and relies on the vessel's anchor for stability. This profile exhibits the lowest cost and the lowest wheel loads.
- Low profile cranes have a boom that can either push forward or retract above the vessel deck. These cranes are suitable, especially for their minimum height near airports and for reduced visual impact. This profile exhibits higher costs and higher wheel loads.

The observation of figure 3.4 provides a visual representation that enhances comprehension of the contrasting characteristics between high profile and low profile quay cranes.

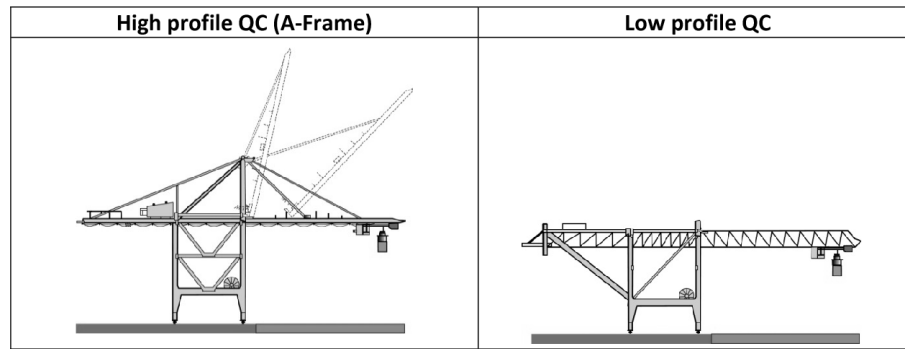


Figure 3.4: Different profiles of a QC [9]

Once the classifications of quay cranes have been explored, examining the various components that make up these machines and comprehending their specific roles becomes essential. Quay cranes comprise several integral components that work in tandem to ensure effective cargo-handling operations. These components synergistically contribute to the overall functionality of a typical quay crane, enabling efficient loading and unloading of containers. By understanding these components' functions, it is possible to understand how quay cranes facilitate seamless and productive operations in container terminals.

The process of loading and unloading containers is called a "move" in quay crane operations. The quay crane's spreader is positioned on the container and secured using twistlocks to unload the container. The hoist then lifts the container, and the crane's trolley moves it towards the quay. The spreader is lowered, and the container is placed on the ground or onto a transport vehicle at the wharf. Releasing the container involves unlocking the twistlocks, and the spreader is lifted again. The loading process follows the same crane operations in reverse, with containers being lifted, moved, and secured before being placed onto the vessel [57][9]. These specifications of QCs can be better understood by looking at figure 3.5.

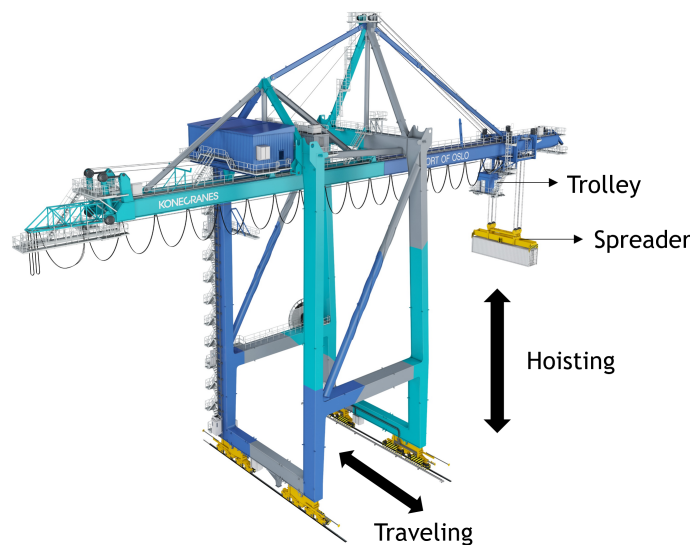


Figure 3.5: Specifications of a QC, adapted from [10]

The Panamax QC, with a high profile and a single lifting mechanism, was chosen for this base model. This QC is the typical QC for operating a Feeder ship [58]. In order to add fidelity to the model, the QC characteristics, such as speed and average load/unload time, were taken into account for the simulation model in FlexSim. With the information gathered from [9] and [58], it was possible to assess all the technical data needed to build the base case. Table 3.3 shows the hoisting, trolley, and traveling speeds.

Table 3.3: Panamax Crane Technical Data

	<b>Hoisting Speed</b>	<b>Trolley Speed</b>	<b>Travel Speed</b>
Panamax Crane	50-125 m/min	150-180 m/min	45 m/min

Considering the specifications of the objects used in FlexSim and in order to simplify the model, an average value for the hoisting and trolley speed has been considered. In this sense, the values of the speeds considered for the simulation model are those listed in the table 3.4.

Table 3.4: Panamax Crane Technical Data in FlexSim

	<b>Hoisting Speed</b>	<b>Trolley Speed</b>	<b>Travel Speed</b>
Panamax Crane in FlexSim	87.5 m/min	165 m/min	45 m/min

The comprehensive collection of characteristics and technical data of Panamax QCs makes it possible to incorporate a QC model into the simulation that accurately replicates the operation of actual container terminals. A thorough understanding of the crane's hoisting speed, travel speed, and main trolley speed provides a solid basis for designing a realistic and efficient QC model.

By incorporating these parameters into the simulation, the virtual QC can mirror the performance of its real-world life counterpart, enabling accurate analysis of operational scenarios and optimization of terminal processes. This realistic representation enables the evaluation of various factors, such as container handling efficiency and overall productivity. Using precise technical data ensures that the simulated quay crane behaves in a way consistent with real operations. This provides valuable insights and supports container terminal planning and management decision-making processes.

### 3.4 Transportation Area

A growing emphasis on automation in container terminals has led to the selection of the AGV as the primary vehicle in this conceptual model for transporting containers from the quay area to the storage yard. With the increasing adoption of automated solutions, AGVs have emerged as the ideal choice due to their inherent efficiency, reliability, and sustainability advantages [59].

### 3.4.1 Electric AGVs

Considering the sustainability aspect, the decision was made in this conceptual model to use electric AGVs instead of diesel-powered counterparts. Considering the importance of minimizing environmental impact, electric AGVs offer a cleaner and greener solution for container transport within the terminal. Using electric power, these AGVs significantly reduce carbon emissions and help improve air quality, aligning with the industry's commitment to sustainability. This decision reflects a proactive approach to adopting environmentally friendly practices in container terminal operations and promotes a more sustainable and environmentally conscious future.

Having said that, several technical data about the AGVs had to be considered to simulate the required model, especially the battery features. The battery characteristics of an AGV hold significant importance in determining its performance and efficiency within container terminals, making them a crucial consideration in the context of this dissertation. Key aspects to consider include battery capacity, measured in ampere-hours (AH), which represents the total energy storage capacity of the battery [60]. A higher capacity enables prolonged operating times and increased productivity before requiring recharging. Additionally, the recharge rate, measured in amperes (A), is critical as it determines the speed at which the battery can be replenished during charging intervals. Faster recharge rates facilitate reduced downtime and enhance the overall operational efficiency of AGVs.

Moreover, the energy consumption or use during AGV operation is a vital parameter to optimize. This parameter signifies the amount of energy drawn from the battery during AGV motion, both when transporting containers and when traveling empty. By efficiently managing energy consumption, AGVs can achieve optimal operational ranges, minimize charging frequency, and reduce overall energy costs.

Furthermore, battery lifespan, compatibility with charging infrastructure, and robust battery management systems are crucial considerations. These factors contribute to the long-term reliability, cost-effectiveness, and sustainable operation of AGVs in container terminals. However, this model didn't consider these features to simplify its implementation and analysis.

In addition to these aspects of AGV battery use, and to approximate their behavior to the reality in container terminals, the speeds of AGVs when carrying cargo and running empty were considered. The acceleration of these vehicles under the same conditions was considered, as well as the deceleration.

### 3.4.2 AGVs' Battery Specifications

Consequently, some assumptions had to be made for this base model, as seen in table 3.5. All these figures were obtained by reading various articles and conducting an extensive search of the available literature on the operation of AGVs in container terminals.

Table 3.5: AGV specification for container terminal application

<b>Speed &amp; Acceleration</b>	
Max. Speed forward/reverse empty	6 m/s
Max. Speed forward/reverse loaded	3 m/s
Acceleration/Deceleration empty	2 m/s <sup>2</sup>
Acceleration/Deceleration loaded	0.50 m/s <sup>2</sup>
<b>Battery</b>	
Battery Capacity	400 AH
Battery Use empty	312.5 A
Battery Use loaded	208.3 A
Recharge Time	1.5 h

According to the findings presented by [22] and based on actual data from container terminals, it is assumed that the "nominal" travel speeds of AGVs are 6 m/s when empty and 3 m/s when loaded. The average energy consumption is 10 and 15 kW per second when traveling empty and loaded, respectively. Although AGVs can autonomously adjust their instantaneous speed based on the current demands of the schedule and trajectory, they are assumed to travel at a constant average speed in a given trip segment. As for the study conducted by [60], it is presented the values for the acceleration and deceleration of AGVs in container terminals, which is, respectively, 2m/s<sup>2</sup> and 0.5m/s<sup>2</sup>. To obtain all the crucial specifications of the AGV battery, it was possible to obtain information on battery capacity in a study prepared for the port of Antwerp-Bruges [61]. According to [62], all automated guided vehicles are powered by batteries ranging from 12 to 48 volts, usually designed to operate for at least 8 hours during regular operation. There are two basic methods of charging the battery. One method involves replacing the dead battery with a fully charged one; the other involves charging the battery while it is still in the vehicle. For this conceptual model, it was considered the last charging method and an AGV with a battery of 48V. This value enabled the calculation of battery usage values. The battery usage of an AGV refers to the amount of energy drawn from its battery during operation. It is usually measured in amperes (A) or kilowatts (kW).

In this model, assuming a battery capacity of 400Ah and an average energy consumption of 10 and 15 kW per second when empty and loaded, it is possible to calculate the battery use using Ohm's Law ( $P = VI$ ). Since the power ( $P$ ) is equal to the energy consumption, the voltage ( $V$ ) is constant, and the current ( $I$ ) is the unknown variable that represents the battery consumption:

$$BatteryUse(I) = \frac{Power(P)}{Voltage(V)} \quad (3.1)$$

Since power is given in kilowatts (kW), it is required to convert it to amperes (A) by dividing



it by voltage (V). Presuming a standard voltage of 48V commonly used in AGV systems:

$$BatteryUse(I) = \frac{10kW}{48V} = 208.3A \quad (3.2)$$

$$BatteryUse(I) = \frac{15kW}{48V} = 312.5A \quad (3.3)$$

Based on this calculation, the AGV with a battery capacity of 400Ah and an average energy consumption of 10 and 15 kW per second when empty and loaded would have a battery use of approximately 208.4 and 312.5 amperes, respectively, during operation.

A newspaper article on the completion of an AGV loading infrastructure project at Container Terminal Altenwerder indicates that the AGVs used there can reach a full load within about 1.5 hours [63]. This information provides valuable insight into the charging capabilities and efficiency of the AGV and highlights the technological advances in container terminal automation. The ability to load AGVs within a relatively short period increases operational productivity by minimizing downtime and ensuring the continuous availability of these vital transport vehicles. This insight contributes to a better understanding of the optimization of AGV use in container terminal operations.

### 3.4.3 AGVs' Route

In addition to this technical data required for the operation of AGVs in container terminals, it is essential to consider the problem of routing these vehicles. As previously mentioned, AGVs play a crucial role in the transportation of containers between QCs and the storage yard during both loading and unloading operations. These driverless vehicles operate along pre-defined paths, and effectively scheduling and controlling their movements is a critical and demanding task [64]. The routing of AGVs involves the determination of optimal routes for a set of AGVs to fulfill their assigned transport tasks. This routing aspect significantly impacts the productivity and flexibility of AGV systems, thereby influencing the overall performance of container terminals [65].

While many existing AGV systems utilize maps with predefined fixed paths for routing, it is worth noting that AGVs possess the inherent capability to navigate freely throughout the entire terminal area. Since the inception of the automated container terminal at ECT, Rotterdam, in 1993, numerous projects have been undertaken to enhance the performance of container terminals and AGV systems. Extensive research has been conducted on AGV routing, exploring various aspects such as fixed topology applications, including loop, tandem, and network layouts [65]. Scholars have focused on pickup and delivery point selection, topology design, and the application of operational research methods for route optimization.

Most existing research in the field of AGVs assumes fixed paths for their movements to simplify traffic management and vehicle control. However, it is worth considering that employing non-fixed paths for AGV movements has the potential to enhance transportation efficiency. Nonetheless, such an approach also introduces increased traffic complexity and new challenges in terms of control and coordination. Therefore, selecting routing strategies for AGVs necessitates careful

consideration of trade-offs between transportation efficiency and the associated complexities in traffic management and control.

In this conceptual model, the AGVs are driving along fixed paths, according to a so-called loop-layout, as shown in figure 3.6.

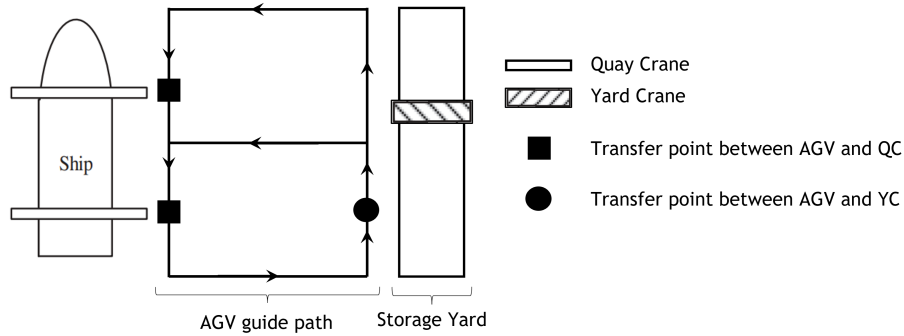


Figure 3.6: AGV guide path, adapted from [11]

Upon the arrival of the vessel at the designated berth within the terminal, the QC undertakes the pivotal task of lifting the container from the ship and conveying it to the transfer point, facilitating the subsequent handover to the AGV. Subsequently, the AGV assumes the responsibility of transporting the container to the designated transfer point in coordination with the YC. The YC, in turn, facilitates unloading the container within the storage yard. Once this operation is done, the AGV quickly takes further instructions and goes to the designated transfer point.

It is important to note that the aforementioned sequence of operations underscores the meticulous coordination between the different components involved in the container terminal ecosystem. Each stage, from the initial pickup by the QC to the final unloading operation done by the YC, necessitates precise synchronization and effective communication among the involved machinery. This intricate choreography ensures the seamless flow of container handling activities, optimizing the overall operational efficiency of the terminal.

### 3.5 Storage Yard Area

In the storage yard, the accommodation is made between what might be called "shore-side disorder" in relation to the movement of containers to the terminal (or the lifting of containers), a movement subject to various fortuitous circumstances controlled by the shipper or his agent, the Forwarder/Logistic Operator, and what might be called "seaward/river-side order," the loading/unloading operations must follow a plan that determines the alignments of the containers, during discharging/loading.

#### 3.5.1 Storage Yard Dimensions

The container blocks shown in figure 3.7 correspond to the organization of the terminal space by ship. In the blocks for export, the containers are received randomly from the shoreside and placed

in the block, taking into account the weight and the transport route. In the case of unloading, on the other hand, different import blocks are organized, which also receive the cargo from the ship according to the operational plan and are later randomly removed from the quay by the shippers or their representatives.

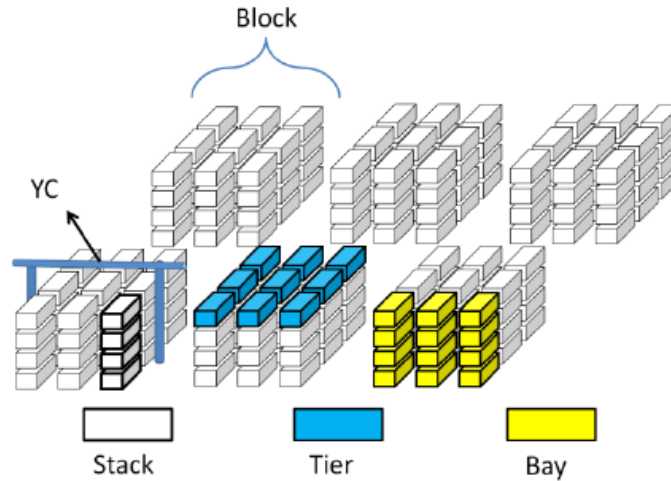


Figure 3.7: Layout of storage area of a container terminal [12]

The container terminals also have areas for parking empty containers, areas for their repair, and areas for handling goods stored or stored in containers (container freight station). In the parking areas for full containers, the terminals also have areas for parking temperature-controlled containers (reefers/containers).

A storage yard comprises blocks, each with a number of bays, stacks, and levels (figure 3.7). In this base model, as in container terminals, the storage yard is a temporary repository for containers arriving by ship. However, these different mentioned areas for parking empty containers and reefers are not considered, nor is the stacking plan. The containers that arrive by ship are randomly stored in the storage yard. As mentioned before, the storage yard only consists of a block of containers since it is only considered the arrival of a ship to the port. Assuming the ship always carries a fixed cargo of 500 TEU, i.e., 250 40-foot containers, the container yard must have sufficient capacity to store this quantity. Since a 40-foot container has a length of 12.03 meters, a width of 2.4 meters, and a height of 2.39 meters, it was determined that the container block would consist of 10 bays, 5 tiers, and 6 stacks in width. A slot has a length of 12.10 meters, a width, and a height of 2.50 meters to ensure the storage of the containers and to have a safety distance between them.

### 3.5.2 Parallel Layout

The choice of a parallel layout for the container terminal model was driven by several factors that contribute to operational efficiency and productivity. One important reason is the optimization

of internal transport and handling processes. The parallel layout allows streamlined and direct paths between the quay and the storage yard, distances and reducing the time needed for container transfers. This layout enables smoother operations as containers can be moved quickly between the ship and the storage yard, resulting in improved turnaround times for ships and efficient use of the storage yard. In addition, the parallel layout supports better coordination and synchronization of activities, which enables the simultaneous handling of multiple containers and increases the overall throughput of the terminal. Furthermore, the parallel layout offers flexibility and scalability, as it allows for easy expansion and the addition of new storage blocks or equipment in a modular way. Overall, the introduction of a parallel layout in the container terminal model aligns with the objective of optimizing operations, increasing productivity, and ensuring smooth and efficient container handling.

Several container terminals worldwide have implemented the parallel layout to enhance their operational efficiency. One of them is the Port of Rotterdam in The Netherlands. This layout allows for the efficient handling of containers from the quay to the storage yard, optimizing space utilization and minimizing container handling times.

### 3.5.3 YC Characteristics

The yard crane, specifically designed for the demands of container terminals, plays a pivotal role in container handling within the storage yard. As already stated, in this model, it is only used one YC with the technical data shown in table 3.6, based on [66][67].

Table 3.6: YC specifications for container terminal application

<b>Speed</b>	
Loaded/empty gantry travel	220 m/min
Loaded/empty trolley move	120 m/min
Loaded/empty hoisting/lowering	75 m/min
<b>Acceleration/Deceleration</b>	
Gantry	0.4 m/s <sup>2</sup>
Trolley	0.4 m/s <sup>2</sup>
Hoisting/Lowering	0.35 m/s <sup>2</sup>

The yard crane consists of several key components that work together to facilitate the movement and positioning of containers. The main structural element of the storage yard crane is the gantry, which consists of a horizontal beam supported by vertical legs or towers. The gantry is designed to span the width of the storage yard and provide a stable platform for the operation of the crane. The trolley is another vital component of the yard crane and is responsible for the horizontal movement of the crane along the gantry. It is usually equipped with wheels or tracks that allow it to move along the length of the gantry and position the crane precisely above the containers. The trolley may also have lift mechanisms such as hoists or spreaders to safely grip

and lift the containers during loading and unloading. From figure 3.8, it is possible to see where these yard crane components are located.

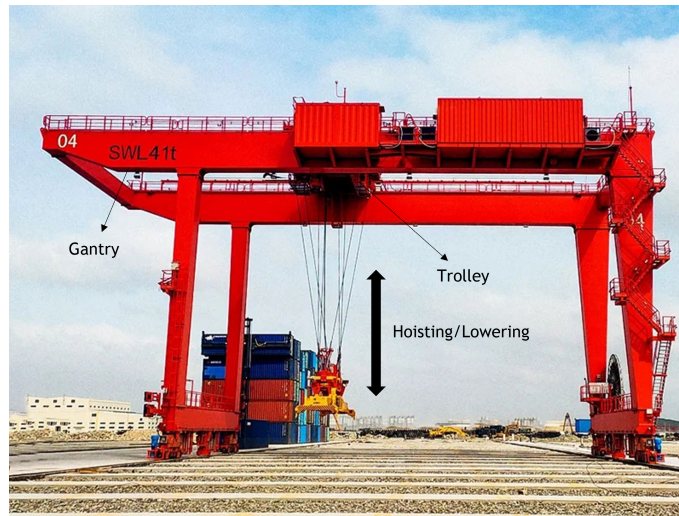


Figure 3.8: Structure of a YC, adapted from [13]

The combination of gantry and trolley components in a yard crane provides the strength, stability, and maneuverability needed to move containers around the storage yard. Their coordinated use enables efficient stacking, retrieval, and transfer of containers, optimizing the overall productivity of the container terminal.

### 3.6 Extensions of the Case Study

This section will delve into additional investigations conducted beyond the primary case study. Specifically, Extension 1 will focus on examining the impacts of different AGV speeds, while Extension 2 will explore the effects of different AGV routes. These extensions aim to provide valuable insights into the variables of AGV speed and route selection, shedding light on their influence on the overall performance and efficiency of the container terminal. By analyzing these extensions, a deeper understanding of their implications can be gained, contributing to the broader scope of the case study and offering potential avenues for further optimization and refinement.

#### 3.6.1 Extension 1 (Impacts of Different AGV Speeds)

This extension focuses on changing the AGV speeds, raising and lowering them by 20%. By making these adjustments, it will be possible to compare the effects of different AGV speeds on performance and operational outcomes.

It is important to note that apart from the alterations made to the AGV speeds, all other simulation model aspects and parameters remain consistent with the base model. This ensures that the

comparison between the different scenarios is valid and that the observed differences in performance can be attributed solely to the variations in AGV speeds. By isolating this specific variable, a more precise understanding of its impact on key performance indicators can be obtained, providing valuable insights for optimizing the container terminal's operations.

The decision to assess the system by incorporating variations in AGVs' speeds was motivated by the objective of accounting for the potential occurrence of unexpected factors and events within a container terminal, particularly in the transport area. These factors can introduce fluctuations in AGVs' speeds due to the presence of sensors within the vehicles, which detect surrounding activities, and the implementation of mechanisms that respond to external stimulation. Notably, one such mechanism involves speed control. Consequently, it becomes justifiable to evaluate the system under these circumstances in order to comprehensively examine the impact of speed variations and their potential implications on the operational efficiency of the container terminal. Through this modified model, comprehensive evaluations will be performed, focusing on key performance metrics such as total operation time, energy consumption cost, charging costs, and idle time of the QCs.

### **3.6.2 Extension 2 (Impacts of Different AGV Routes)**

The basic simulation model underwent some modifications while preserving consistency in all other areas to examine the effects of various AGV paths on the operational performance of the container port. The effects of these adjustments on the overall effectiveness and sustainability of the container terminal may be evaluated by modifying the AGV routes. This extension considers two scenarios, each with a unique set of AGV routes. This enables a thorough evaluation of the possible benefits and drawbacks of various routing strategies and aids in the determination of the best pathways for AGVs in the terminal environment.

It is significant to notice that, other than the AGV routes, none of the other characteristics, attributes, or restrictions of the simulation model differ from those of the base model. This guarantees that any reported changes in performance are completely attributable to the variations in the AGV routes and that the comparison between the scenarios is relevant.

The effects of different AGV routes on performance indicators such as overall operation time, distance traveled, energy consumption cost, and charging cost will be thoroughly investigated using the upgraded simulation model. Later in this dissertation, the methodology utilized to incorporate the alterations to AGV paths, the specific scenarios developed, and a discussion of the study's findings will all be presented. This study aims to increase the understanding of how AGV routing strategies may impact container terminal performance in general, ultimately assisting in the development of more efficient and sustainable operating procedures.

## Chapter 4

# Simulation Model for the Case Study

This chapter delves into the implementation of the case study in the simulation software, FlexSim and presents the details of its development. Firstly, section 4.1 does an overview of the simulation-based approach employed to model. Afterward, section 4.2 introduces FlexSim, the simulation software used for implementing the 3D model.

Moreover, section 4.3 explains the implementation of the 3D model in FlexSim, including the properties of the critical objects such as the QCs, YC, and AGVs. Parameters that influence the simulation model are discussed in section 4.4, and the process flow of the simulation is outlined in section 4.5, covering various stages such as ship unloading, container transport, container unloading in the storage yard, AGV charging, and AGV parking.

Additionally, section 4.6 provides insights into the dashboard used for monitoring and analyzing the simulation results. By comprehensively exploring the simulation model and its components, this chapter sets the foundation for the subsequent analysis and evaluation of the case study.

### 4.1 A Simulation-Based Approach

Many studies have been conducted over the years using simulation models, which are typically used to develop solutions to enhance the performance of dynamic and complex systems, such as container terminals, to avoid delays, save time, and lower costs.

As mentioned in 2.6, one of the most cutting-edge and complex methods for system analysis is simulation [68]. Because simulation has fewer assumptions than any analytical model and accounts for the unpredictability and interdependencies common in the real world, simulation also makes it possible to represent the real system correctly. On top of that, it might be challenging to forecast the behavior of the system and its performance indicators without simulation when several resources of various sorts are functioning and interacting. Simulation makes it simple to make adjustments, run the simulation for several simulated months, and examine the results extremely rapidly because numerous situations need to be considered. Tracking each occurrence and validating the model is made feasible by the animated visualizations [69].

The analysis and optimization of port logistics may be investigated using simulation models, as explained by [70]. Furthermore, the same source notes that while numerous simulation models have previously been applied in maritime ports across various domains, modeling simulation software is seldom applied in case studies.

Therefore, a discrete event simulation model was developed in this dissertation using FlexSim Software to model a generic container terminal and its operations, aiming to design a decision-support tool able to test several simulation scenarios of container terminal operations and evaluate their performances. The performance of these container terminal models is assessed in this study using a range of indicators to pinpoint potential bottlenecks in the operational areas, specifically the quay cranes, the storage yard, and the transportation system. To help decision-making, the analysis would involve looking at numerous scenarios driven by changes in various inputs to assess their impact on the outputs, which include throughput, resource utilization, waiting times, and KPIs of sustainability.

The base simulation model was created with no specific port in mind. Instead, it was built as a generic model that could be applied to any port using its specific data. It manages loading and unloading operations at a generic container terminal. In light of this, this dissertation suggests a simulation model capable of simulating, testing, and evaluating the main events, operations, and equipment involved in loading and unloading tasks at container terminals.

## 4.2 FlexSim

The FlexSim software environment is a comprehensive platform for developing, simulating, visualizing, and monitoring dynamic process flows and systems. It is a powerful discrete event simulation (DES) tool that can be used in various fields, from manufacturing to logistics to healthcare. With its combination of process flow logic and a 3D simulation environment, FlexSim provides a critical level of validation and enables a high-level understanding of the system and observation of running processes. FlexSim offers the flexibility to create custom classes and libraries from scratch or modify existing ones. It also integrates seamlessly with the C++ compiler and supports FlexScript, a pre-compiled C++ library, and direct C++ programming, giving users extensive functionality and customization options within the FlexSim environment [71].

### 4.2.1 Objects in the 3D Model

The fundamental unit of a 3D simulation model is an object. The library uses a variety of objects, each with a distinct function. Among the most typical items are:

- **Flow Items:** These items are "flowing" through the simulation model from one station, often a fixed resource, to another downstream station. Products, clients, or any other object that passes through numerous stations can be represented as flow items.



- **Source:** The flow elements that move through a model are made using the source. Each source generates a single type of flow item, which it may subsequently customize with attributes like labels or colors.
- **Sink:** Flow objects finished in the model are disposed of in the sink. Once a flow item enters a sink, it is impossible to retrieve it.
- **Fixed Resources:** Objects that are "fixed" or stationary in the model are referred to as fixed resources. In the business system, fixed resources often interact with flow items in various ways, such as by altering or storing them. Fixed resources, such as processing stations or storage spaces, can represent a variety of stages or processes in your model.
- **Task Executors:** The top-level class for a number of library items is task executor. Other mobile resources such as operators, transporters, ASRS vehicles, cranes, and others derive from the task executor class. These objects may all move about, load and unload flow objects, serve as shared resources for processing stations, and carry out a variety of other simulation-related functions.

#### 4.2.2 Process Flow

The Process Flow tool is used to create a flowchart representing the simulation model's logic. The issue may be divided into individual activities that create activity blocks that perform specific model functions. These activity blocks can be linked to further individual or collaborative tasks. The flowchart also contains tasks that enable tiny pieces of pre-programmed logic. Small green circles, called "tokens" are used to execute the logic of each action in a simulation model. When the attributes of the activity are edited, it is possible to connect them to the objects of the 3D model.

- **Token:** Tokens are objects that flow through activities in a process during simulation runs. They are similar to flow items in a 3D model, moving from one activity to the next. However, tokens do not always represent physical objects in a business system. They can be abstract and represent concepts such as customer orders, call center interactions, or pallets for delivery. While tokens are often linked to physical objects, it is up to the user to define the nature of these links in the simulation model.
- **Activity:** A logical action or phase in a process flow is called an activity. Activities are hence the fundamental building elements of every process flow.
- **Shared Assets:** At specific times along the process flow, tokens have the ability to claim or release a shared asset, which is a limited resource. There are a few minor changes, although they are relatively similar to activities. If the desired asset is not accessible, shared assets have the power to place restrictions on the tokens by forcing them to wait.

- **Label:** Labels play a vital role in the functionality of the simulation software, as they enable the tracking of important information and facilitate dynamic changes in simulations based on different models and conditions. In the process flow, labels are utilized to establish flexible model logic that can adapt to changing circumstances. Tokens in the process flow are associated with labels, allowing them to traverse through various activities where labels can be created, modified, and referenced to control the model's logic. Labels also have the ability to be assigned to flow items and 3D objects, including fixed resources and task executers.

### 4.3 The 3D Model

The simulation software FlexSim has been used to build the model provided in this dissertation. The container terminal layout was modeled in FlexSim's 3D modeling environment to benefit from its visualization capabilities and intuitive user interaction. By using the 3D modeling environment, it is possible to immerse oneself in the virtual representation of the terminal and visually examine the objects and their movements. This enhanced visualization promotes a deeper understanding of system behavior and facilitates the identification of potential bottlenecks or inefficiencies. Furthermore, the ability to interact with the model in a 3D space enables the exploration of different scenarios and the making of informed decisions based on real-time feedback.

#### 4.3.1 QCs' Properties

In the simulation model, the decision was made to use an automated storage and retrieval system (ASRS) in FlexSim (figure 4.1) as a representation of a quay crane (QC) because it is similar to QC tasks. Since there is no specific quay crane-like object in the simulation software, the decision to use an ASRS vehicle seemed to be the right choice as it can move horizontally and vertically, similar to hoisting and lowering operations in a QC. The characteristics associated with ASRS vehicles, such as sliding back and forth in an aisle between two racks to pick up and drop off flow items and the animated lifting and moving movements, corresponding to the required QC functions in the simulation model.

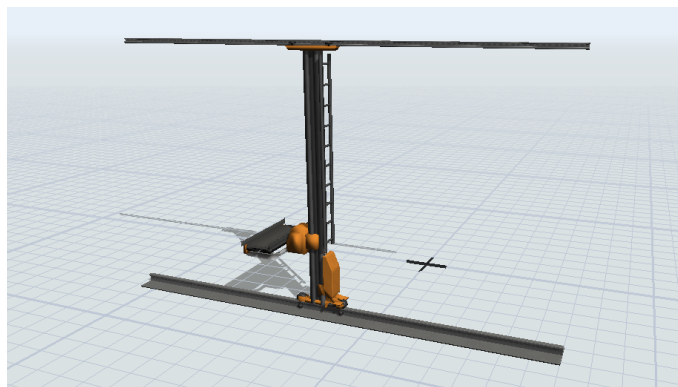


Figure 4.1: ASRS vehicle in FlexSim

Within the FlexSim ASRS vehicle module, the ASRS vehicle serves as a task executor, implementing offset travel solely along its own x-axis. It reaches the destination location, lifts its platform, and performs loading or unloading tasks based on the loading/unloading time set by the user. The ASRS vehicle has parameters defined by the modeler for the lifting speed and initial lifting position of its platform. Whenever the ASRS vehicle is idle or not performing offset travel, the platform returns to the designated position. The unique feature of the ASRS vehicle is that it can only move along the x and z-axis without rotating. This makes it suitable for various applications where rotation is not required [72].

The use of the ASRS vehicle in the FlexSim simulation model effectively represents a QC that captures the essential features and functionalities required to simulate QC operations within the simulated environment, as shown in figure A.1. Of utmost importance were the values assigned to key parameters such as "Lift Speed," "Extension Speed," and "Max Speed" of the ASRS vehicle, effectively representing the respective hoisting, trolley, and travel speeds of the QCs. The "Lift Speed" parameter accounted for the vertical hoisting speed of the QC, while the "Extension Speed" parameter governed the horizontal trolley speed. Lastly, the "Max Speed" parameter defined the maximum travel speed of the QC, ensuring that its movement within the simulated environment adhered closely to the actual operations of the real-world equipment.

In order to simulate the variability in the time taken for loading and unloading containers by the QC, a triangular distribution was employed in the simulation model. This distribution was chosen due to its flexibility in capturing the inherent uncertainty and randomness associated with the process.

The triangular distribution was defined with a maximum value of 60 seconds, a minimum value of 30 seconds, and a mode of 40 seconds [66]. These parameters allowed for a range of possible durations, with the most likely duration centered around 40 seconds. By utilizing this distribution, the simulation model introduced realistic variations in the loading and unloading times, reflecting the inherent complexities and factors that influence the efficiency of QC operations. This variability can be influenced by factors such as the size and weight of the containers, the availability of resources, and the proficiency of the QC operators. By incorporating a probabilistic approach, the simulation model was able to provide a more comprehensive understanding of the QC operations and their impact on the overall performance of the container terminal.

#### 4.3.2 YC's Properties

In the context of the simulation model, the selection of a crane in FlexSim to represent the YC was a conscious decision, justified by its close resemblance to the functions of a real YC. The crane object available in FlexSim has specific characteristics that fit well with the operational aspects of yard cranes.

The crane module in FlexSim operates within a fixed space. It follows defined rectangular movements along the x, y, and z axes that mimic the typical movement patterns of a YC. This

accurately represents the crane's reach and capabilities within the simulated environment. In addition, the graphical representation of the crane has been adapted to mimic the visual appearance of a YC, further increasing the realism of the simulation, as can be seen by figure 4.2.

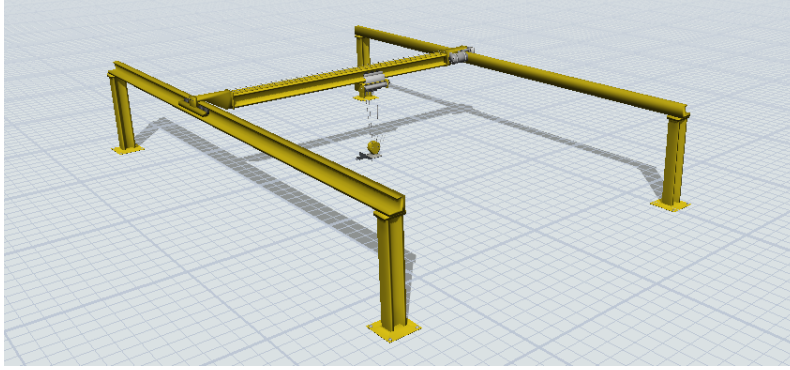


Figure 4.2: Crane in FlexSim

A notable feature of the crane module is the behavior of the crane after picking up or dropping off a flow item. The crane picker automatically adjusts its height to that of the crane object, as is common with YCs. This ensures the flow item is safely positioned before the crane moves to its next destination. By utilizing these inherent features, the selected crane module in FlexSim serves as a reliable substitute for the YC. It allows for comprehensive analysis and optimization of container handling within the simulated yard environment.

Similar to the consideration given to the representation of QCs in FlexSim, the specifications outlined in subsection 3.5 were taken into account when incorporating the YC in the simulation model as illustrated in figure A.2. These specifications provided valuable insights into the characteristics and functionalities of a real YC, guiding the accurate portrayal of the YC within the simulation environment.

The simulation model considered the gantry, trolley, and hoisting/lowering speeds of the YC specified in table 3.6, as well as container load and unloading time, for this feature was implemented a triangular distribution. The maximum value of 102 seconds represents the upper bound of the load/unloading time, considering potential delays or complex operations. The minimum value of 36 seconds represents the lower bound, indicating the shortest possible time required for efficient load/unloading. The mode of 60 seconds represents the most likely or commonly observed duration for the load/unloading process.

The inclusion of these crucial parameters not only enhances the accuracy and reliability of the simulation results but also enables the evaluation and optimization of container handling operations involving the YC. This comprehensive approach facilitates valuable insights and informed decision-making in the design and management of the storage yard area.

### 4.3.3 AGV's Properties

In this simulation model, the AGVs play a crucial role in efficiently transporting and handling containers between the quay area and the storage yard. The AGV Task Executer module in FlexSim efficiently manages and executes tasks for Automated Guided Vehicles (AGVs) in simulation models. It handles task assignment, routing, resource utilization, and performance analysis. Its advanced algorithms optimize task allocation based on availability, proximity, and priority, considering factors like traffic and constraints. Real-time tracking of performance metrics helps identify bottlenecks and improve workflows. The user-friendly interface allows easy customization of AGV properties, making it a powerful tool for simulating and optimizing AGV operations.

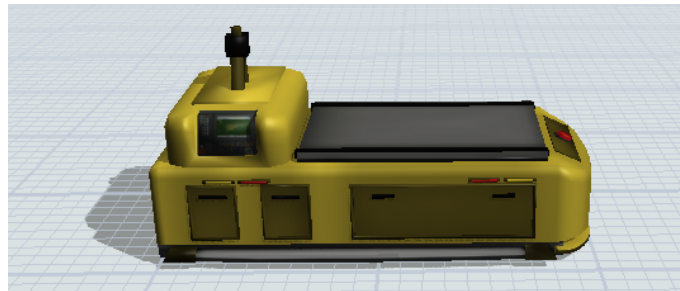


Figure 4.3: AGV Task Excuter in FlexSim

- **AGV Network.**

The decision to use the AGV Network module in FlexSim for the container terminal simulation model was driven by the need to accurately represent the movement and interactions of automated guided vehicles used as primary vehicles for container transport. The AGV Network module effectively modeled the complex network of AGVs within the terminal, including the definition of routes, load handling capabilities, and control strategies.

By using the AGV Network module, the movement of containers by AGVs from the quay area to the storage yard and vice versa can be faithfully simulated, replicating the operational dynamics of an actual container terminal. The module's advanced features, including dynamic path-finding algorithms and collision avoidance mechanisms, ensured efficient and safe navigation of the AGVs. Different scenarios could be analyzed, parameters adjusted, and the overall performance of the container terminal evaluated. The visual representation provided by the module contributed to the intuitive visualization and understanding of the simulation.

The AGV Network module in FlexSim was found to be ideal for improving the realism and efficiency of the container terminal simulation and creating travel paths for the AGVs, as can be seen in figure 4.4. Its ability to capture the subtleties of AGV movements and evaluate system performance made it the preferred choice for the simulation model.

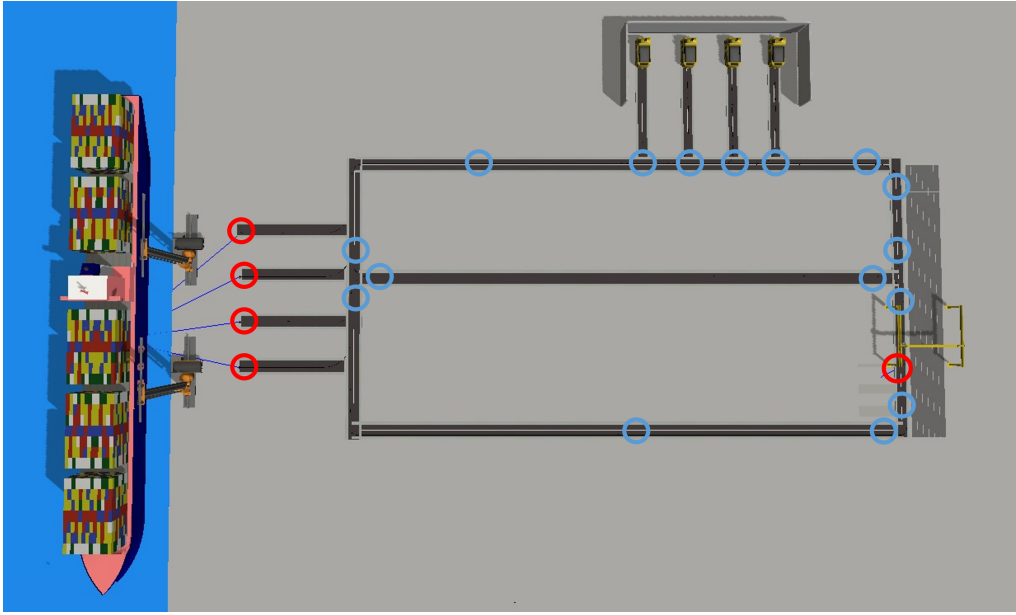


Figure 4.4: AGV's path using the AGV Network in FlexSim

AGV Paths specify the paths used by AGVs on the AGV network to arrive at their destinations. A decision was made to establish one-way paths for all routes except for the path situated in the center of the rectangle, which was designated as a two-way path. By defining the directions of these paths, the AGVs were granted greater flexibility in their decision-making process, enabling them to select the most optimal route based on the utilized path-finding algorithm.

In the AGV network, the determination of optimal travel routes is achieved by utilizing Dijkstra's algorithm. This algorithm finds the shortest path between two specified vertices in a graph by employing the Greedy Algorithm as its underlying principle [73]. During the traversal of the network, the algorithm evaluates the "costs" associated with traveling on each path segment. Subsequently, the AGV selects the route that incurs the least total cost to reach its intended destination. By default, the cost assigned to traversing a particular path segment is equivalent to the distance of that segment.

Furthermore, the AGV Network was strategically equipped with multiple control points in addition to designing AGV paths. Control Points are points on the AGV network, as illustrated by figure 4.5, where various decision logic happens. Control points in the simulation model can have multiple functions. They serve as locations for AGVs to pick up and/or drop off flow items. Control points also act as stopping points where AGVs wait before entering specific areas or sections of a path. Additionally, they serve as decision points for AGVs to find available tasks and dispatch points to assign AGVs to different locations based on network conditions. These control points enhance coordination, task allocation, and routing efficiency within the AGV system.

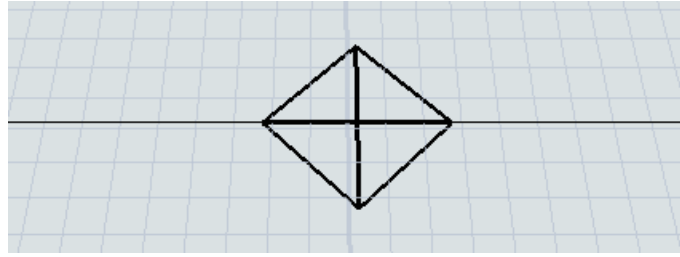


Figure 4.5: Control Point in AGV Network in FlexSim

In the context of this simulation model, control points serve two key purposes. Firstly, they facilitate the smooth picking up and dropping off of flow items, specifically in the form of containers. These control points act as designated locations where AGVs can efficiently handle the transfer of containers during the simulation. Secondly, control points also function as strategic stopping points along the network. These points allow AGVs to wait before entering certain areas or sections of a path, ensuring smooth flow and avoiding congestion. Visualized in figure 4.4, the control points symbolized by red circles denote container load/unload points. In contrast, blue circles indicate their additional role as stopping points where AGVs may temporarily pause in the presence of other AGVs.

In addition to the aforementioned control points, additional control points were explicitly designated as "Home Points" for the AGVs within the simulation model. As illustrated by figure 4.6, these Home Points serve as the initial starting locations for the AGVs and also function as their designated areas for battery recharging. They play a vital role in ensuring the operational efficiency of the AGVs by providing a dedicated space for recharging their batteries and serving as a central hub for the AGVs before commencing their assigned tasks. As such, these control points can be seen as the AGVs' charging stations, where they replenish their energy reserves, and as their designated parking points, where they wait before embarking on their operational activities.

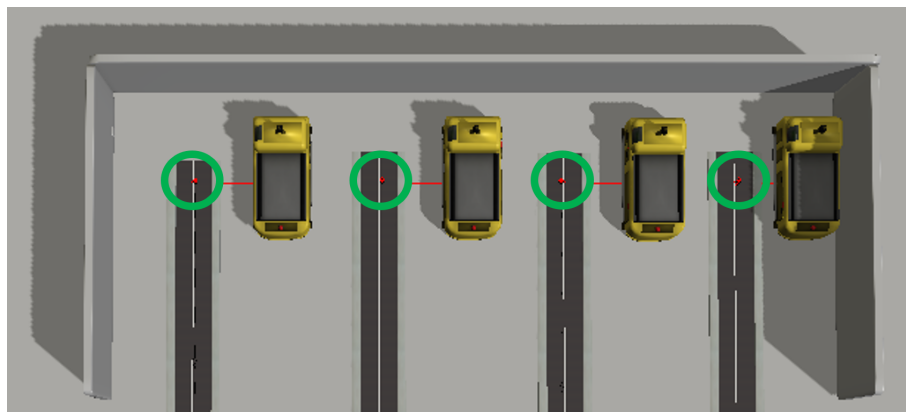


Figure 4.6: AGVs' charging points in AGV Network in FlexSim

The AGV Network incorporates the use of AGV Types, which serve to define one or more categories of AGVs. Within this specific model, a single type of AGV has been defined, characterized by the following set of behaviors:

- Acceleration
- Deceleration
- Forward Max Speed
- Reverse Max Speed
- Battery Capacity
- Battery Depletion Rate
- Battery Recharge Rate

The values assigned to these features can be found in figure A.3, which provides a comprehensive overview of the defined characteristics.

The calculations and explanations for the values of acceleration, deceleration, speed, battery use, and battery capacity were previously presented and discussed in subsection 3.4. The recharge rate in amperes was determined by calculating the amount of current flowing into the battery during the charging process. The equation 4.1 is the formula to calculate the charging rate in amperes.

$$ChargingRate(I) = \frac{BatteryCapacity(Ah)}{ChargingTime(h)} \quad (4.1)$$

Considering that the AGV's battery capacity is 400Ah and its charging time is about 1.5h, the charging rate is calculated as 4.2 shows:

$$ChargingRate(I) = \frac{400Ah}{1.5h} = 267A \quad (4.2)$$

Therefore the charging rate of this AGV type used in the model is approximately 267A.

## 4.4 Parameters

Before the simulation starts, some input variables of the model are defined in the Model Parameter Tables of FlexSim as figure A.5 shows.

The following parameters have been defined:

- AGVs\_type1\_capacity: With this parameter of the model, it is possible to change the capacity of the AGVs, i.e., the number of containers they can transport. This model's value is always 1, considering that the containers considered in this simulation model are 40-foot containers and the AGVs can currently only transport one 40-foot container at a time.



- **Number\_QC:** This input variable determines the number of QCs used in the model. This quantity can only vary between 1 and 2, as only a maximum of 2 QCs are available in this container terminal model.
- **Number\_AGV:** This parameter strictly constrains the range of AGVs utilized in the model, allowing only values between 1 and 4.
- **BatThresholdMin:** This input parameter represents the minimum acceptable battery level for an AGV before it needs to be recharged.
- **BatThresholdMax:** This input parameter specifies the maximum battery level of the AGVs, which serves as the criterion for determining the completion of their charging process.
- **Load:** This parameter represents the cargo load carried by the ship. In the current model, this value remains constant, and a fixed number of 250 40ft containers are always generated.

This allows for greater control over the simulation and enables the study of various scenarios and configurations.

## 4.5 The Process Flow

In addition to the 3D modeling aspect, FlexSim's process flow functionality was used to model the complicated logic of container terminal operations. The process flow tool could accurately represent and simulate complex workflows and activities within the terminal. The graphical interface provided an intuitive platform for creating process flow diagrams illustrating the sequential flow of tokens through various activities. This approach facilitated the modeling of various operations, such as container handling, storage, and transport. It enabled a detailed analysis of the terminal's performance and the identification of potential process improvements. The flexibility and power of the process flow tool played a crucial role in capturing the intricacies of the terminal's operations. They enabled a comprehensive assessment of its efficiency and effectiveness.

In this simulation, the logic was built in different blocks which are related to different processes. The processes consist of the following:

- Start the simulation and create a new ship.
- Create tokens for the QCs, the AGVs, and the YC when the ship is created.
- Unload the ship by the QCS.
- Transport of containers from the quay area to the storage yard by the AGVs.
- Storage of containers in the storage yard by the YC.
- Park of the AGVs for charging.
- Charge of the AGVs.

The Process Flow of the model regarding the handling and transportation of containers is illustrated in figure 4.7, in which it is possible to see the decision-making logic applied.

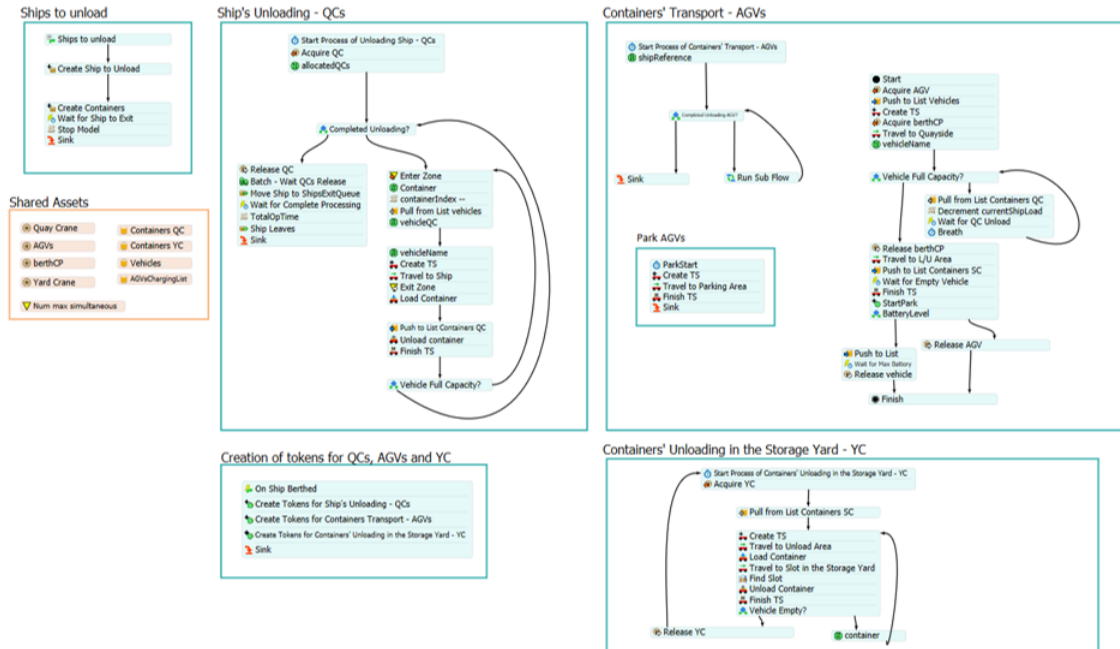


Figure 4.7: Main process flow diagram of the operation

It was also implemented a process flow for the AGVs to charge them when their battery reaches a certain threshold. Figure 4.8 shows the process flow dedicated to the AGV charging.

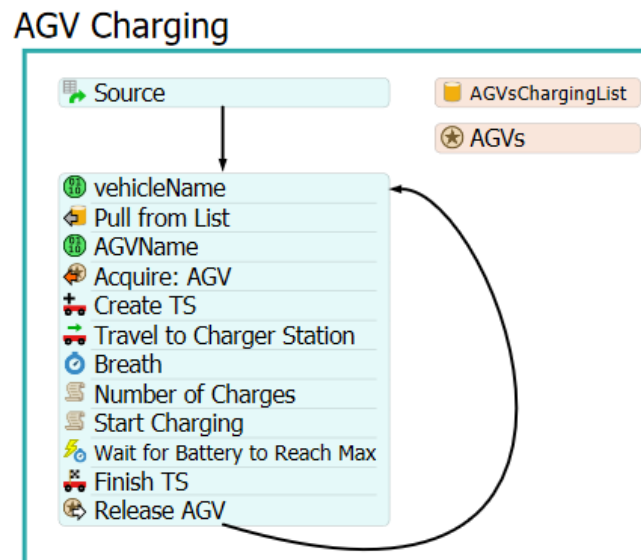


Figure 4.8: Process flow diagram of AGV charging

The logic of unloading the ships and handling the containers was developed using the blocks already existing in FlexSim. However, some of the logic of this model had to be designed through programming. Therefore script programming was used to complement some of the functions. The subsequent points will delve into the processes systematically incorporated into the Process Flow, presenting them in an organized manner and addressing each topic in detail.

#### 4.5.1 Shared Assets

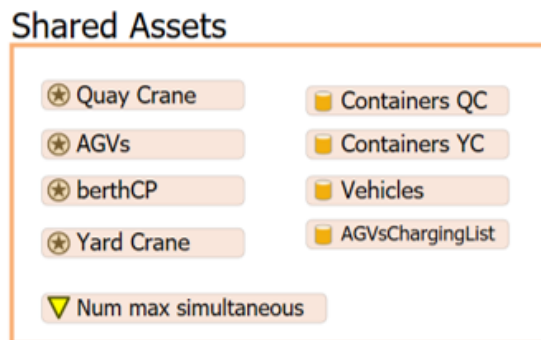


Figure 4.9: Shared Assets in the process flow

The process flow in FlexSim utilizes shared assets depicted in figure 4.9, which are finite resources that tokens can acquire or release at specific stages. These shared assets serve distinct purposes and can be categorized into three types, each with its own unique characteristics and functionalities. These types are outlined below:

- **Resource:** It stands for the quantity of a resource that may be collected and used only in a restricted manner. It may imitate a supply of products, services, resources, labor, etc.
- **List:** This shared asset enables adding or removing tokens, flow items, task executors, numbers, strings, and other elements to a list. It is a valuable tool for synchronizing multiple tokens within a process flow or a versatile resource offering enhanced dynamism.
- **Zone:** This feature enables the collection of statistical information that may not be readily available for standard activities. Additionally, it can control access to specific sections of the process flow based on relevant statistics or other predefined criteria.

As illustrated in figure 4.9, four shared resources were used in this simulation model. The resources, namely "Quay Crane," "AGVs," and "Yard Crane," represent the available QCs, AGVs, and YCs, respectively. Notably, only one YC is assigned to execute the container unloading task at the storage yard, as mentioned earlier. The resource "berthCP" embodies all the control points situated in the quay area, facilitating container transfers between the QCs and AGVs. Incorporating shared resources in this model enables the assessment of equipment availability. Specifically,

the control points resource verifies available space in the quay area to accommodate the AGVs, facilitating their loading with containers.

The simulation model incorporates several lists to store and manage information related to the unloading process of containers by various equipment. The "QC Containers" list serves the purpose of tracking containers that are off-loaded from the QCs onto AGVs. Conversely, the "YC Containers" list is responsible for recording containers that are unloaded from AGVs by the Yard Cranes (YC). These lists effectively store information on the containers that have been loaded or unloaded by the respective equipment, facilitating the tracking and management of container movements.

During the unloading process from the vessel, the QCs require information on the availability of AGVs for container transfer. The "Vehicles" list plays a crucial role in conveying this information to the QCs. It provides details on the AGVs' availability, ensuring efficient coordination between the equipment. In the event that no AGVs are available, the list provides awareness of this worst-case scenario.

To ensure a seamless connection between the main process flow and the AGV charging process flow, the "AGVsChargingList" is utilized. This list serves as a communication channel, relaying information about AGVs that have reached their minimum battery level threshold and are thus in need of recharging. By incorporating this mechanism, the model effectively manages the charging requirements of AGVs, optimizing their operational efficiency and maintaining smooth workflow throughout the simulation.

#### 4.5.2 Ships to Unload

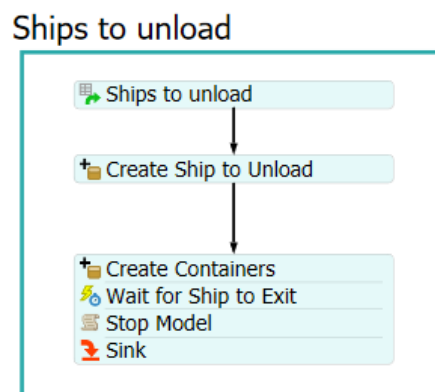


Figure 4.10: Process of ship creation in the process flow

The process shown in figure 4.10 implements the creation of ships to unload and the containers they carry. In this model, only one ship is created, so the time the simulation takes to run represents the total time a ship remains at the port. The "Ships to unload" activity is a schedule source that creates new tokens as specified in its "Arrivals" table A.4. This table defines the time (in model

units) tokens should be created, the name assigned to the new tokens, and the number of tokens to create.

In addition to those features, it is attributed three labels to the created ship: an id ("id\_ship"), a berth ("Berth"), and the load that it carries ("Load"). As already stated, the load is a model parameter that can be defined before the simulation runs. In this model, the load is always 250, representing 250 40ft containers. As seen in the process, the simulation only stops when the ship exits the port, i.e., when its unloading operation is completed.

### 4.5.3 Creation of Tokens for QCs, AGVs and YC

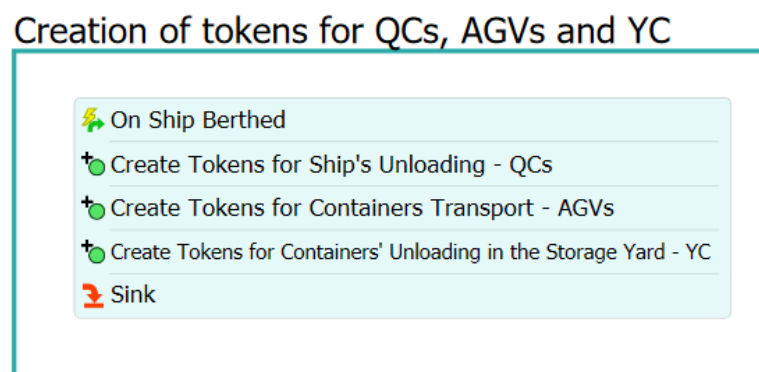


Figure 4.11: Process of token creation in the process flow

In this process demonstrated in figure 4.11, several tokens are created, which represent the number of QCs, AGVs, and YCs to be used in the simulation model. These tokens are generated when the ship is created and are subsequently directed to different activities to initiate tasks performed by the equipment. Since the model includes only one YC, no specific input parameter was required to define this variable. In every simulation iteration, a single token is consistently generated to initiate the YC operations.

The activity "Create Tokens for Ship's Unloading - QCs" creates the number of tokens previously defined in the model's parameters regarding the number of QCs available. After the tokens are created, they are automatically sent to another activity that starts the process of unloading the ship by the QCs.

The "Create Tokens for Containers Transport - AGVs", as the name suggests, creates the tokens associated with the number of AGVs previously defined in the model parameters. They are subsequently directed to another activity to initiate the process of container transportation by the AGVs.

In the "Create Tokens for Containers' Unloading in the Storage Yard - YC" activity, only one token is created to initiate the YC process.

#### 4.5.4 Ship's Unloading - QCs

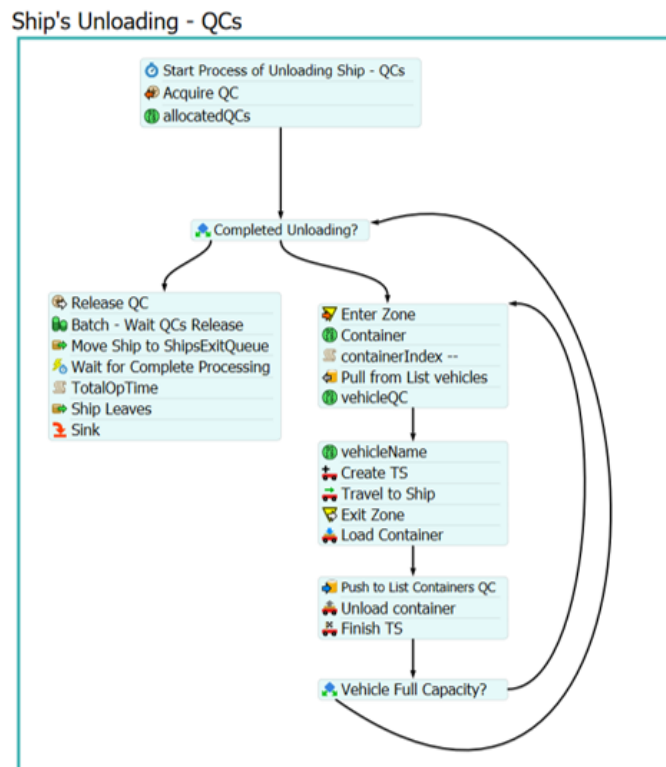


Figure 4.12: Process of ship's unloading by QCs in the process flow

In summary, the process as illustrated by figure 4.12 begins by acquiring the required number of QCs based on the model parameters. Subsequently, these QCs are assigned to the ship for unloading operations. The decision activity "Completed Unloading?" ensures the ship is fully unloaded. If the ship is empty, the QCs are released, the ship departs from the port, and relevant performance measures are calculated. If the ship still needs to be unloaded, a check is conducted to determine if there is an available AGV to transport the containers from the quay area to the storage yard. Once an AGV is obtained, the QC approaches the ship and picks up containers individually. After loading a container, the QC moves to the quay area and places it onto the AGV. During the unloading of containers from the AGV, the QC verifies whether the AGVs have reached their maximum capacity in the "Vehicle Full Capacity?" activity.

#### 4.5.5 Containers' Transport - AGVs

Similar to the previous process, this procedure demonstrated in figure 4.13 incorporates the decision activity "Completed Unloading?" to monitor the current status of the ship's load and determine if it has been fully unloaded. If the current load is zero, the process concludes. However, if there are remaining containers, a sub-process flow is initiated to facilitate container transport operations conducted by the AGVs.

Within this sub-flow, AGVs are acquired in accordance with the predefined quantity specified in the model parameters. Once acquired, the AGVs proceed to the quay area to receive containers from the QCs.

#### Containers' Transport - AGVs

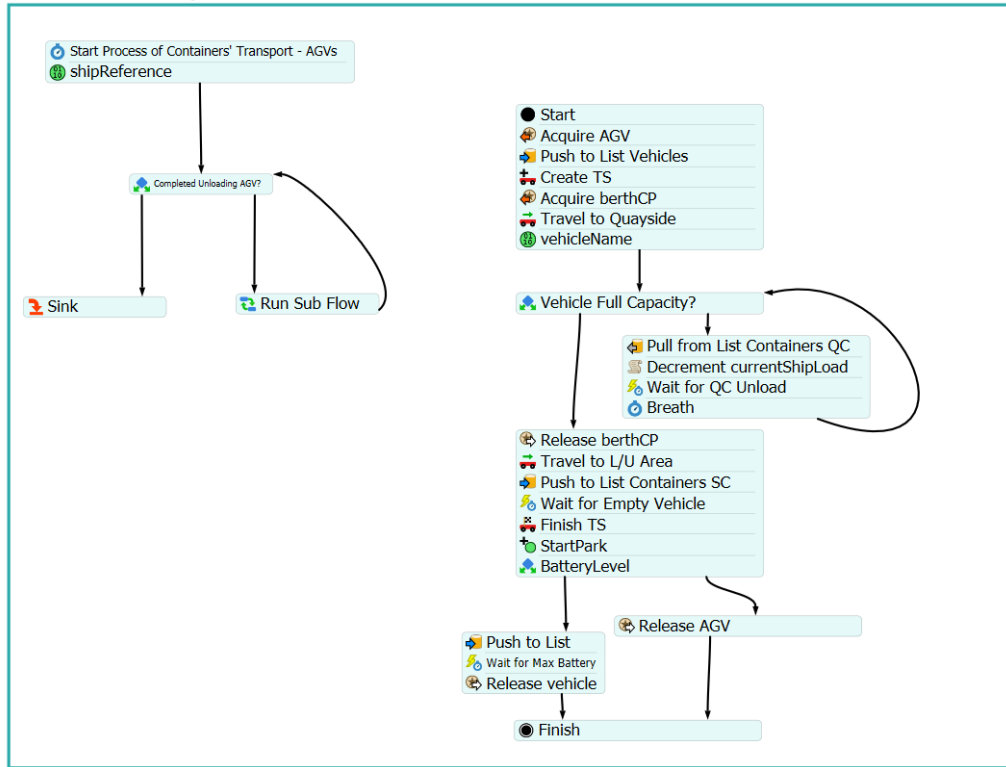


Figure 4.13: Process of containers' transport by AGVs in the process flow

The decision activity "Vehicle Full Capacity" ensures that the AGVs transport cargo up to their maximum capacity, mirroring the previous process. Subsequently, loaded AGVs move to the load/unload area, where the YC unloads their cargo. At this stage, the AGV's battery level is regularly examined. If the battery level falls at or below a certain value, the AGV necessitates recharging. This value is calculated by multiplying the predefined minimum threshold "BatThresholdMin" by the vehicle index, which can be 1, 2, 3, or 4. The purpose of this computation is to control the charging process of AGVs in a way that ensures they don't all reach their minimum battery levels at the same time and it introduces a gradual and staggered charging pattern. This approach helps to prevent all AGVs from requiring charging simultaneously, which could potentially cause long periods of downtime in the simulation. Instead, the AGVs are managed in a way that distributes their charging needs more evenly over time, maintaining the operational continuity of the simulation. Conversely, if the battery level exceeds the minimum threshold, the AGV is released, and the system verifies once again whether the ship unloading process is complete. The aforementioned steps are then reiterated.

#### 4.5.6 Containers' Unloading in the Storage Yard - YC

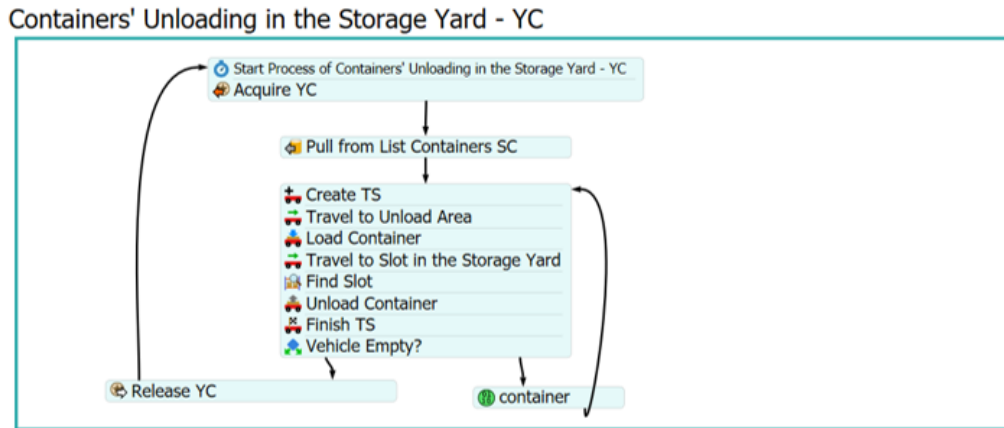


Figure 4.14: Process of containers' unloading by YC in the process flow

The process shown in figure 4.14 encompasses the unloading of containers into the storage yard, which the YC facilitates. Initially, the YC is acquired and positioned in the load/unload area, awaiting the arrival of an AGV. Upon the AGV's arrival, the YC proceeds to remove the container from the AGV and commences its movement toward an available slot within the storage yard for storage purposes. Subsequently, the decision activity "Vehicle Empty?" evaluates whether the YC has completed unloading all containers. If the vehicle is indeed empty, the YC is released, and the aforementioned process is repeated. However, if there are still remaining containers within the AGV for unloading, the cycle recommences, beginning with the YC's movement back to the load/unload area. In this particular model, as the maximum capacity of the AGVs is consistently set at one, the vehicle promptly becomes empty following each cycle. Nevertheless, it is essential to note that the model has been designed to accommodate alternative maximum capacity values for the AGVs.

#### 4.5.7 AGV Charging

The depicted process in figure 4.8 represents the mechanism of AGV battery charging, which is implemented as a Task Executer Process Flow. The process initiation involves a "Schedule Source" activity that creates one token corresponding to an AGV. Once the battery level of an AGV reaches its minimum threshold, it is pushed to the "AGVChargingList" by the main process flow and it is pulled by this "AGV Charging" process to start its charging activity after proceeding to the designated charging station.

It is worth noting that the AGV's battery charging takes place exclusively after the completion of its current task, namely the unloading of containers from the load/unload area. Upon reaching the specified maximum battery level, the AGV is released, and the unloading operation of the



vessel resumes if it remains incomplete. It is also in this process flow that the number of charges is counted to be considered in the calculation of a performance measure.

#### 4.5.8 Park AGVs

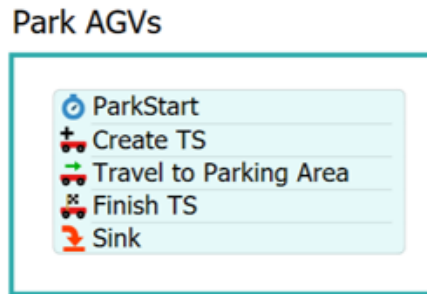


Figure 4.15: Process of AGVs' parking in the process flow

The process illustrated in figure 4.15 orchestrates the transfer of AGVs to the dedicated charging station to commence the recharging of their batteries. The "ParkStart" activity is initiated when the AGV's battery level dips below the specified minimum threshold and is only activated once the AGV has successfully concluded its unloading task within the unload/load area.

## 4.6 Dashboard

Once the simulation model completes the execution of different scenarios, dynamic dashboards are utilized to gather performance indicators for analysis by the decision planner. These indicators encompass essential metrics that provide insights into the system's performance, including:

- Time plot for the AGV battery to monitor its level (example depicted in figure A.6).
- Number of charges of the AGVs in each scenario (example depicted in figure A.7).
- Pie Chart of each AGV state.
- Bar chart for the distance traveled by the AGVs in each scenario.
- Bar chart indicating the state of each QC.
- Time plot of each AGVs' speed (example illustrated in figure A.8).

Upon the completion of the designated scenarios, these graphical representations will yield significant insights into the performance of the container terminal under investigation. The evaluation will primarily focus on the operational dynamics of the equipment, particularly the AGVs, and QCs, as they play a pivotal role in the terminal's overall functionality. Furthermore, an in-depth assessment of the model will be conducted, centering around three distinct performance measures that closely align with the terminal's sustainability and efficiency objectives. A detailed exposition of these measures can be found in the subsequent chapter.



## Chapter 5

# Tests and Results

This chapter will provide an in-depth exploration of the experimental tests conducted and the corresponding outcomes. This chapter is divided into four sections, each addressing specific aspects of the analysis. Firstly, section 5.1 will elucidate the methodology employed for structuring the experiments, including the base model and the extensions of the base model. Next, in section 5.2, key metrics for evaluating the system's performance will be discussed, encompassing total operation time, AGVs' energy consumption cost, and AGVs' charging cost.

The subsequent section, 5.3, will delve into the execution of the experiments using the FlexSim simulation software. It will outline the simulation setup and provide insights into the simulated environment.

Finally, section 5.4 will focus on the evaluation and comparison of different scenarios. Specifically, it will cover the analysis of the base model and examine the effects of AGVs' speed decrease, AGVs' speed increase, and different AGV routes.

### 5.1 Design of Experiments

This section will focus on the methodological framework employed for conducting the experiments. The design and setup of the experiments will be presented, outlining the variables, parameters, and factors considered in each model variation. The objective is to establish a robust experimental foundation that allows for a comprehensive exploration of the system's behavior and performance under different conditions.

#### 5.1.1 Base Model

After all the development explained throughout this chapter, the base model was built and implemented in FlexSim.

The container terminal consists of the following:

- 1 berth
- 1-2 QCs

- 1-4 AGVs
- 1 storage yard (block of containers)
- 1 YC

The base model of the container terminal simulation consists of essential equipment and components that reflect the operational dynamics of the real-world terminal. It includes one berth where the ship is already berthed, carrying a specific load of 250 40 ft containers. The base model incorporates the features and characteristics explained earlier in the previous chapters to ensure a realistic representation of the equipment's functions.

Prior to running the simulation, the number of QCs and AGVs available to unload the ship is determined. These decision variables allow for flexible evaluation of different scenarios and analysis of the impact of different resources on the terminal's performance. The number of QCs and AGVs available is a crucial parameter in determining the efficiency and productivity of container handling.

By simulating the base model, the results obtained serve as a benchmark for subsequent extensions and modifications of the model. By comparing the base model results with the extended models, insights can be gained into the effectiveness of the proposed improvements and optimizations in improving terminal operations and productivity. Table 5.1 shows the different characteristics of the three models simulated in FlexSim.

Table 5.1: Models simulated in FlexSim

	Number of AGVs	Number of QCs	AGVs' Speed	AGVs' Path
<b>Base Model</b>	1 to 4	1 to 2	Constant	Rectangle
<b>Extension 1</b>	1 to 4	1 to 2	Variable	Rectangle
<b>Extension 2</b>	1 to 4	1 to 2	Constant	Different

### 5.1.2 Extensions of the Base Model

#### • Extension 1 (Impacts of Different AGV Speeds)

As an extension to the base model, the AGV speeds were deliberately altered to evaluate their influence on performance measures and previously considered metrics.

To incorporate this modification, the AGV Network module, precisely the way points functionality, was utilized. Way points serve as control points along the AGVs' paths, enabling the definition of specific AGV control logic when they traverse these points. In this extension, additional control points were introduced in the AGV paths to facilitate speed changes throughout the entire trajectory rather than confining them to a specific location. By leveraging the way points feature, the speed adjustments were seamlessly integrated into the AGV movements.

The AGVs' speed was defined by two triangular distributions, one for the loaded state and another for the empty state. In the loaded state, the standard speed of 3 m/s was reduced by 20%

using the triangular distribution (2.4, 3, 2.7) m/s (figure B.2). This distribution ensured that the AGVs' speed varied within a specific range while being loaded. Similarly, in the empty state, the standard speed of 6 m/s was also reduced by 20% using the triangular distribution (4.8, 6, 5.4) m/s (figure B.1). This allowed for variations in speed when the AGVs were empty.

Conversely, to simulate an increased speed scenario, the standard speed of 3 m/s, when loaded, was raised by 20% using the triangular distribution (3, 3.6, 3.3) m/s. Similarly, the standard speed of 6 m/s when empty was also raised by 20% using the triangular distribution (6, 7.2, 6.6) m/s. These distributions were implemented in the AGV Network module, specifically in the way points tab, to ensure that the AGVs followed the appropriate speed profiles during their movement within the terminal.

By incorporating these triangular distributions, the model allowed for the simulation and evaluation of different scenarios with varying AGVs' speeds. This extension provided insights into how changes in speed affected the overall performance measures of the container terminal, such as total operation time, distance traveled by the AGVs, energy consumption costs, and charging costs. Analyzing the results obtained from these scenarios would provide valuable information to optimize the AGVs' speed and enhance the efficiency and productivity of the container terminal operations.

- **Extension 2 (Impacts of Different AGV Routes)**

This extension to the base model considered two different routes for the AGVs. The first one considered is illustrated in figure 5.1. The path that was in the middle stopped being considered, and the route of the AGVs became a rectangle.

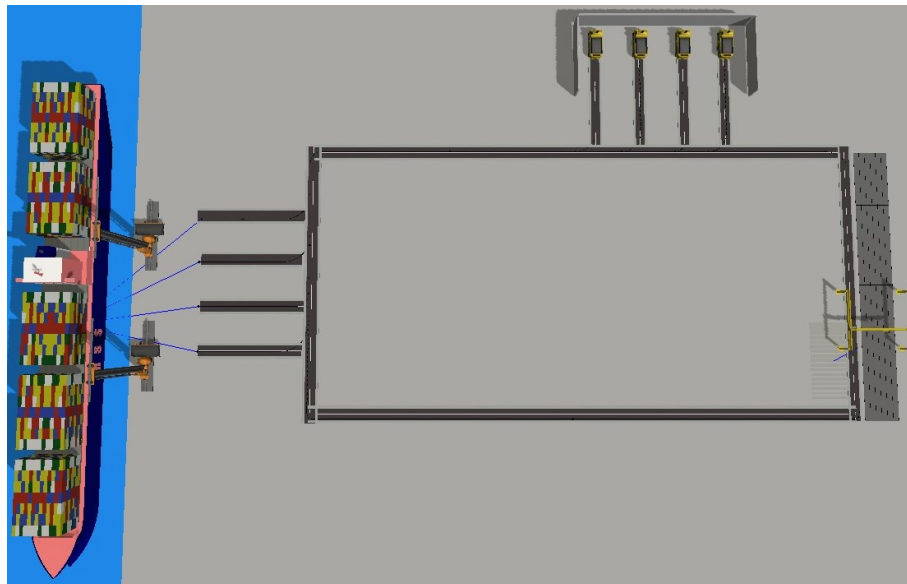


Figure 5.1: First modification to the AGVs' route for extension 2

This variation aims to represent a container terminal with limited flexibility for AGV movement within the transport area. Factors contributing to this limited flexibility may include small terminal size, higher pedestrian traffic in the shipping area, inadequate infrastructure to accommodate multiple AGVs simultaneously, or the utilization of the middle space for specific container storage or equipment.

In the second extension of the base model, a route with increased movement options for the AGVs was considered (figure 5.2). This modification reflects container terminals that offer greater flexibility in AGV movement. Such terminals may exhibit lower pedestrian activity within the transport area, possess more available space allowing for increased AGV circulation, or experience a higher influx of vessels with substantial cargo, necessitating more significant movement between the quay area and storage yard.

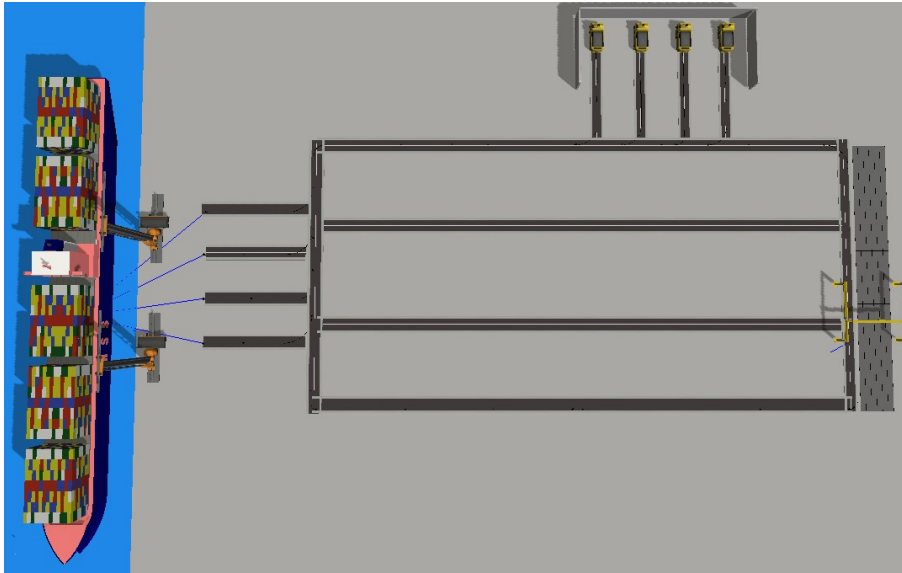


Figure 5.2: Second modification to the AGVs' route for extension 2

These two routes were intentionally designed to represent container terminals with distinct characteristics, thereby enabling the evaluation of different AGV routing strategies. It is noteworthy that the container transfer points between the QCs and AGVs and between the YCs and AGVs remain consistent throughout these route variations.

## 5.2 Performance Measures

As mentioned in section 3.1, this simulation model serves as a test bench to create an effective performance evaluation tool for a container terminal. The tool enables analysis of the current situation by utilizing predefined key performance indicators (KPIs), including:

- Total Operation Time
- AGVs' Energy Consumption Cost

- AGVs' Charging Cost

These KPIs provide valuable insights and assist in assessing the performance of the container terminal, aiding decision-making processes and identifying areas for improvement.

The implementation of these KPIs in FlexSim has facilitated the collection of crucial data from the simulation model. By incorporating these performance indicators, the model enables the extraction of meaningful insights and a comprehensive understanding of the container terminal's operational dynamics. In FlexSim, performance measures are used to capture and analyze relevant data during simulation. Performance measures are specific metrics tracked and recorded during the simulation run. By defining and monitoring these performance measures, it is possible to comprehensively understand the simulation model's behavior and evaluate its efficiency and effectiveness.

### 5.2.1 Total Operation Time

The total operation time performance measure has been implemented as a crucial indicator within the simulation model. It quantifies the overall duration of the unloading process for a ship, representing the time it takes to unload all containers from the ship completely. This performance measure holds significant importance for port management, as it provides a comprehensive understanding of the efficiency and effectiveness of the unloading operations.

### 5.2.2 AGVs' Energy Consumption Cost

The AGVs' energy consumption cost serves as a significant performance measure within the simulation model, allowing for the assessment of the energy expenditure associated with the operation of AGVs, whether they are carrying a load or empty. This measure considers various factors, including the energy consumption rate of AGVs when operating with a load or without, the cost per kilowatt-hour (kWh) of energy, and the duration of both loaded and empty operations. As demonstrated in equation 5.1, the energy consumption cost is determined by multiplying the energy consumption rate of the AGVs with their operational time, and further multiplying it by the energy cost per kilowatt-hour (kWh). This computation accounts for both scenarios: when the AGV is transporting a 40ft container and when it is empty. The total cost is obtained by summing the costs associated with these two situations.

$$EnergyConsumptionCost = EnergyConsumptionRate \cdot OperationTime \cdot CostperkWh \quad (5.1)$$

As discussed in subsection 3.4, the energy consumption of an AGV varies depending on its operational state. When traveling empty, the average energy consumption rate is considered to be 10 kW per second, while it increases to 15 kW per second when the AGV is loaded. These values serve as the basis for the Energy Consumption Rate variable in the simulation model.

The Operation Time variable represents the active duration of the AGV, encompassing the time during which it is actively involved in executing its tasks while excluding any idle periods. This

crucial metric is obtained using a dedicated command in FlexSim that retrieves the operating time of the AGV when it's loaded and when it's empty, which is measured in seconds.

The obtained operating time must be converted into hours to determine the total energy consumption cost. This conversion is accomplished by dividing the time value by 3600, corresponding to the conversion factor from seconds to hours. The resulting value, obtained by multiplying the operating time with the total energy consumed, represents the energy consumption in kilowatt-hours (kWh). To determine the financial implications of energy usage during the AGV's task execution, this energy consumption value is multiplied by the cost per kWh, which has been set at 0.14€ based on the information provided in [61]. This computation yields the total energy consumption cost, offering insights into the financial impact of AGV's energy consumption.

### 5.2.3 AGVs' Charging Cost

In addition to the aforementioned performance measures, an additional function was developed to assess the cost associated with charging the AGVs. This function takes into account the following variables:

- Number of chargers of the AGVs during the unloading operation of the ship.
- Average charging time of an AGV.
- Average charging rate of an AGV.
- Energy cost per kWh.

The number of charges represents the total number of times the AGVs need to be charged during the simulation run. The charging time refers to the duration required for a single charging session. The charging rate represents the average rate at which the AGVs consume energy during the charging process. Finally, the cost per kWh indicates the monetary value associated with each unit of energy consumed.

As mentioned in subsection 3.4, the average charging time for an AGV is 1.5 hours. To determine the average charging rate, it is considered a typical AGV with a voltage of 48V and a battery capacity of 400Ah. The average charging rate can be calculated using the formula presented in equation 5.2.

$$AverageChargingRate = \frac{BatteryCapacity \cdot Voltage}{AverageChargingTime} \quad (5.2)$$

By substituting the variables with their corresponding values, a value of 12.8 kW for the average charging rate is obtained. The energy cost per kW is the same as considered in the energy consumption cost function. Hence, it is possible to calculate the average charging rate considering the formula depicted in equation 5.3.

$$ChargingCost = NumberOfCharges \cdot ChargingTime \cdot ChargingRate \cdot CostperkWh \quad (5.3)$$



This computation comprehensively evaluates the overall cost incurred for charging the AGVs within the simulation model. It serves as a valuable indicator for evaluating the best scenario for a container terminal in terms of available resources, guiding effective resource allocation, and enabling the selection of cost-effective approaches. This performance measure supports informed decision-making, allowing container terminal managers to identify optimal charging strategies and achieve operational excellence while minimizing expenses.

### 5.3 Experiments in FlexSim

To collect data from these performance measures, it was necessary to use the Experimenter in FlexSim. It is a powerful tool that enables the design, execution, and analysis of simulation experiments. It provides a structured framework for running experiments by defining different experimental factors and their corresponding levels. These factors may include model parameters, input variables, or different simulation model configurations. The Experimenter facilitated the systematic exploration of these factors to assess their impact on the performance and behavior of the model.

One of the main features of the Experimenter is the ability to automate the execution of multiple simulation runs with different combinations of experimental factors. This enables the generation of a comprehensive data set for analysis and comparison. The Experimenter also allows for replication of runs to ensure the reliability and validity of results. In addition, the Experimenter provides powerful statistical analysis functions to analyze the output data generated from the simulation runs.

The analysis of the results for both the base case and its extensions involved the utilization of the Experimenter tool, with the number of AGVs and QCs serving as the decision variables. To ensure meaningful comparisons between different iterations of the simulation model, consistent scenarios were maintained throughout each experiment. Seven distinct scenarios were carefully constructed, taking into account the model parameters associated with the decision variables, namely the "Number\_AGV" and "Number\_QC" parameters as shown in table 5.2.

Table 5.2: Scenarios considered in Experimenter

	Number of AGVs	Number of QCs
<b>Scenario 1</b>	1	1
<b>Scenario 2</b>	2	1
<b>Scenario 3</b>	3	1
<b>Scenario 4</b>	4	1
<b>Scenario 5</b>	2	2
<b>Scenario 6</b>	3	2
<b>Scenario 7</b>	4	2

When constructing these scenarios, a critical consideration was made to ensure that the number of QCs never exceeded the number of AGVs. This was a deliberate choice to avoid a situation where there would be insufficient AGVs available to meet the demands of the QCs. Such an imbalanced configuration would result in excessive idle time for the QCs, rendering the scenario impractical and unprofitable. Furthermore, a decision was made to set the number of replications per scenario at 30. The choice of conducting 30 replications per scenario in the Experimenter tool of FlexSim was made to ensure reliable and statistically significant results for this dissertation. Additionally, conducting a sufficient number of replications helps minimize the influence of random variations and captures the underlying trends and patterns in the studied system.

Upon examining the figure [B.3](#), a comprehensive comprehension of the Experimenter tool interface can be attained. The deliberate selection involved solely two input parameters, signifying the decision variables that govern the trajectory of each scenario. Consequently, the outcomes derived from this base model are contingent upon the respective values assigned to these variables: the number of QCs and AGVs available within each scenario.

## 5.4 Analysis of Scenarios

The focus of this section is on examining and evaluating different scenarios within the context of the simulated container terminal. The primary objective is to gain a comprehensive understanding of the system's performance and behavior under varying conditions. The section begins by establishing a baseline with the base model, which serves as a reference point for comparison. Subsequently, it delves into the exploration of specific scenarios, such as the effects of decreasing AGVs' speed and increasing AGVs' speed, to assess their impact on overall system performance. Additionally, the section investigates the influence of different AGV routes on the efficiency and effectiveness of container handling operations.

### 5.4.1 Base Model

Upon completion of the base model's execution, encompassing all the scenarios outlined in table [5.2](#), a Performance Measure Report was generated through the Experimenter tool. This report facilitates a comprehensive comparison of the performance measure values attained across the diverse scenarios formulated. In conjunction with these indicators, the metrics derived from FlexSim's dashboard, as elaborated upon in subsection [4.6](#), were also taken into account. Notably, the assessment of the container terminal's performance within the base model entailed the manipulation of available AGV and QC quantities, coupled with the incorporation of stochastic times for container unloading and loading operations executed by QCs and YCs. The influence of these variables on the computed performance measures is contingent upon their respective values throughout each replication of the simulation model.

### • Total Operation Time

The outcomes obtained from the execution of the three designated scenarios were subjected to thorough comparison and analysis. The replications chart of the Total Operation Time, depicted in figure 5.3, visually represents the variations and dependability inherent in the simulation results. The chart's X-axis corresponds to each scenario, while the Y-axis pertains to the total duration required for ship unloading. Upon careful examination of the graph, it becomes evident that Scenario 7 exhibits the shortest time span for ship unloading. This can be attributed to the availability and utilization of all pertinent equipment, namely 4 AGVs and 2 QCs, which efficiently execute their respective tasks. Conversely, Scenario 1 encompasses the lengthiest unloading duration, encompassing approximately 45 hours to accomplish this operation. This scenario employs the minimum number of resources, namely 1 AGV and 1 QC, contributing to the prolonged time frame for task completion.

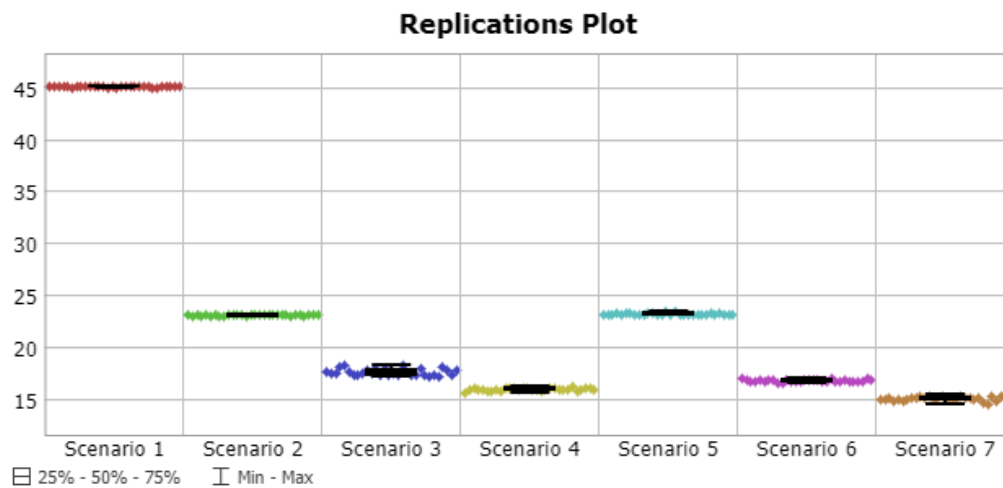


Figure 5.3: Replications Plot of Total Operation Time

In Scenarios 2 and 5, the utilization of two AGVs is common to both, with the sole distinction lying in the number of QCs employed. Scenario 2 entails the simulation of the model employing a solitary QC, while Scenario 5 encompasses the model incorporating two QCs. The graph shows that the total duration required to unload the 250 containers from the ship in both scenarios is notably similar, approximately 23 hours. This observation leads to the inference that introducing an additional QC when two AGVs are available does not yield substantial benefits in expediting the operation's pace.

Scenarios 3 and 6 involve the consideration of three AGVs, with the distinction lying in the availability of QCs. Specifically, Scenario 3 incorporates a single QC, whereas Scenario 6 features the operation of two QCs. In this particular context, the justification for employing an additional QC becomes evident as the total operation time in Scenario 6 is lower compared to that observed in Scenario 3. Throughout the execution of Scenario 3's replications, the maximum total operation

time recorded was approximately 18 hours, while Scenario 5 exhibited a maximum time of 17 hours. Although the difference may not be particularly substantial, it can impact the port's overall performance.

In Scenario 4, the provision was made for four AGVs and one QC. The maximum recorded operation time among the 30 replications of this scenario amounted to approximately 16 hours, reflecting a highly favorable outcome. However, it is crucial to note that the assessment of this performance measure cannot be conducted in isolation; it necessitates consideration of the remaining performance measures within the context of the study.

The presence of dispersion among certain data points in the scenarios can be attributed to the inherent variability in the loading and unloading times of the QCs and YC. This variability stems from the deliberate incorporation of stochastic times into the simulation model, aiming to mimic the inherent uncertainties encountered in real-world port operations. As a result, the resulting data points exhibit variations that are representative of the dynamic nature of the system under examination.

While the total operation time serves as a valuable indicator for analyzing the different scenarios, relying solely on this performance measure is insufficient to determine the most efficient scenario. If the optimization of a ship's unloading operation were solely based on this measure, Scenario 7, which employs the maximum number of available resources in the model, would be the preferred choice. However, it is crucial to recognize that increasing the utilization of equipment entails certain drawbacks, including an associated increase in energy consumption. Hence, to establish a sustainable model, it is imperative to consider the energy aspect alongside other performance considerations.

#### • Energy Consumption Costs

Figure 5.4 depicts the replications plot that examines the energy consumption cost across all performed scenarios. Upon scrutinizing the graph, it becomes apparent that the energy consumption by the AGVs is notably higher in Scenarios 3 and 4, which entail the utilization of 1 QC alongside 3 and 4 available AGVs, respectively. In contrast, Scenarios 6 and 7, which solely differ from Scenarios 3 and 4 in terms of the number of QCs employed (using 2), exhibit a comparatively lower energy consumption cost. The discrepancy in energy consumption costs between the scenarios with 1 QC compared to the scenarios with 2 QCs can be attributed to several factors. Firstly, the number of available QCs directly impacts the efficiency of the unloading process. With only 1 QC in the former scenario, the workload is concentrated on a single QC, potentially leading to longer waiting times for AGVs and increased idle time for the QC itself. Consequently, the AGVs may spend more time idling, resulting in prolonged operation time and higher energy consumption.

In contrast, the scenarios with 2 QCs allow for a more balanced distribution of the workload. The presence of an additional QC facilitates smoother and faster unloading operations, ensuring a more efficient flow of containers from the ship to the storage yard. As a result, the AGVs experience reduced waiting times, increased productivity, and optimized energy utilization. The

synergy between multiple QCs and AGVs leads to a more synchronized and coordinated operation, ultimately reducing energy consumption costs.

Additionally, the availability of multiple QCs enables parallel processing, allowing for simultaneous unloading activities. This parallelism enhances the system's overall throughput, reducing bottlenecks and minimizing idle time for both QCs and AGVs. The increased coordination and collaboration among the equipment in the scenarios with 2 QCs contribute to a more streamlined and energy-efficient operation, leading to lower energy consumption costs compared to the scenarios with only 1 QC.

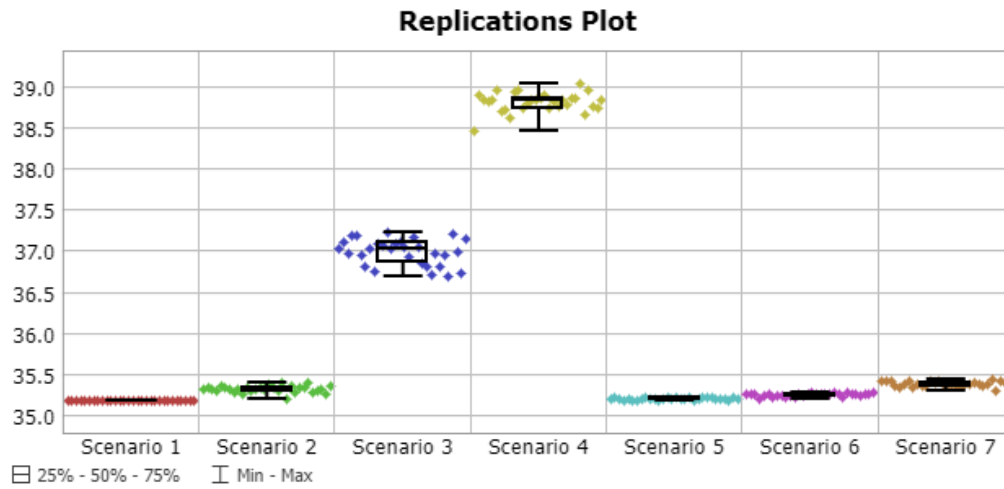


Figure 5.4: Replications Plot of Energy Consumption Cost

In conclusion, the higher energy consumption costs observed in Scenarios 3 and 4 can be attributed to the inefficient allocation of resources and the lack of parallelism in the unloading process. Scenarios 6 and 7 demonstrate the benefits of more balanced workload distribution and enhanced coordination, resulting in improved operational efficiency and reduced energy consumption costs.

#### • Charging Costs

The charging cost function, another crucial performance measure examined in the conducted scenarios, encompasses varying values in each replication influenced by the frequency of AGV battery recharging.

The graph depicted in figure 5.5 showcases the computed battery loading costs of the AGVs across all replications of the seven scenarios. As anticipated, the loading cost exhibits an upward trend in scenarios that involve a greater number of AGVs, specifically Scenarios 3, 4, 6, and 7. Conversely, Scenario 1, which employs only one AGV, exhibits the lowest loading cost among all the scenarios.

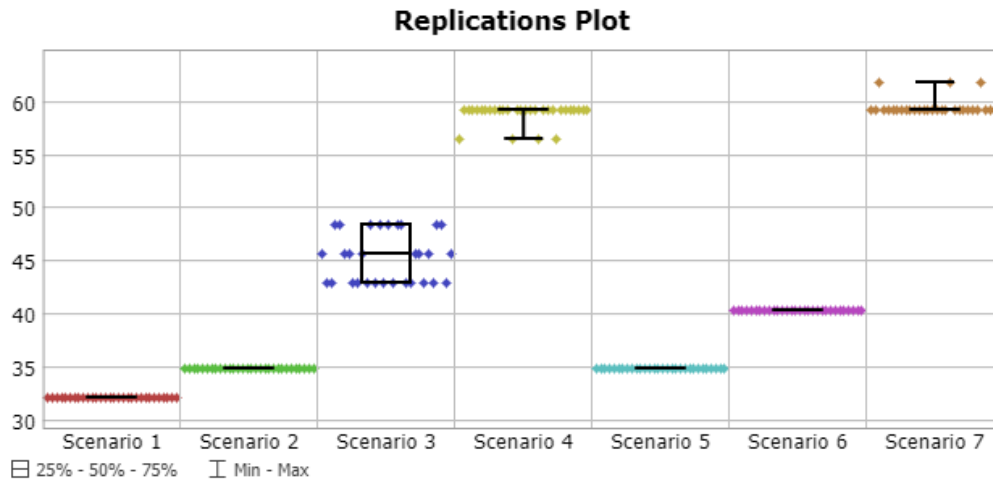


Figure 5.5: Replications Plot of Charging Cost

In Scenario 3, where there is 1 QC and 3 AGVs, the charging cost exhibits some variability due to the interaction between the limited resources and the stochastic nature of the loading/unloading operations. The random fluctuations in the timing of these operations can lead to variations in the charging requirements of the AGVs, resulting in different charging costs across the replications.

Similarly, in Scenario 4, with 1 QC and 4 AGVs, the increased number of AGVs introduces additional complexity and potential resource contention. The stochastic times of the loading/unloading operations, combined with the higher AGV count, can contribute to greater variability in the charging cost. The competition for resources among the AGVs may result in varying charging patterns and, consequently, different charging costs observed in the replications.

In Scenario 7, where there are 2 QCs and 4 AGVs, the presence of additional resources helps to mitigate the resource contention issues. As a result, the charging cost may exhibit relatively less variability compared to Scenario 3 and Scenario 4. The availability of multiple QCs allows for more efficient coordination and distribution of the charging process, reducing the impact of stochasticity on the overall charging cost.

#### • Performance measures interrelationships

In addition to individual analysis of the performance measures obtained from the execution of different scenarios, it is crucial to examine the interrelationships among them in order to make informed decisions regarding the most efficient and sustainable scenario. By considering the interplay between these performance measures, a comprehensive evaluation can be conducted, enabling a more holistic assessment of the scenarios' effectiveness and sustainability.

Figure 5.6 illustrates the correlation plot between energy consumption and charging costs, providing insights into the relationship between these variables across different scenarios. The correlation coefficient, denoted as "r", measures the strength and direction of the linear association between the variables.

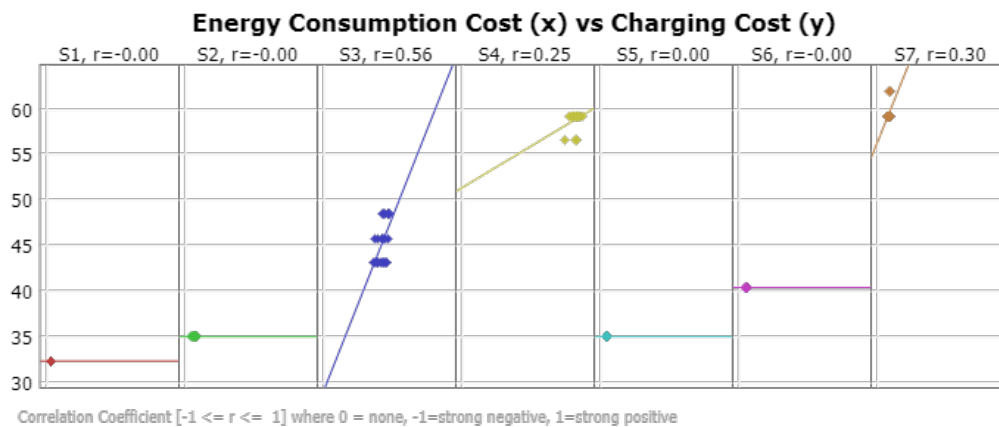


Figure 5.6: Correlation Plot between Energy Consumption Cost and Charging Cost

Scenarios 1, 2, 5, and 6, where there is no correlation (null  $r$ ) between energy consumption and charging costs, indicate no linear relationship between these variables. In other words, changes in one variable do not correspond to predictable changes in the other variable. This null correlation can be attributed to the low variability of the replications data for both measures. Tables B.1 and B.2 show the low variability of these performance measures data in what concerns these scenarios. The limited variability in energy consumption and charging costs indicates the system operates under relatively consistent conditions. In Scenario 1, with only one QC and one AGV, fewer factors influence energy consumption and charging costs, resulting in a more stable and predictable relationship between these two variables.

In Scenarios 3, 4, and 7, the positive value of " $r$ " indicates a positive correlation between energy consumption and charging costs. This suggests that as the energy consumption cost increases, the charging cost also tends to increase. The positive correlation may be attributed to higher energy consumption requiring more frequent, resulting in increased charging costs. The positive relationship between these variables implies that controlling and optimizing energy consumption can positively impact the overall charging cost. The correlation between energy consumption and charging costs can be evaluated in the considered scenarios due to the significant variability observed in their values, as depicted in tables B.1 and B.2. This variability provides an opportunity to examine the relationship between these two performance measures in a more comprehensive manner.

Another essential correlation plot to consider is between the total operation time and the energy consumption cost, as figure 5.7 shows. As anticipated, a positive correlation is generally observed between the total operation time and the energy consumption cost in most scenarios (positive  $r$ -value) since the higher the total operation time, the higher the energy consumption by the AGVs. The strongest correlation is observed in Scenario 4, which exhibits the highest correlation coefficient, followed by Scenario 3. This can be attributed to the prolonged waiting time experienced by the AGVs when only one QC is available for unloading containers from the ship resulting in more significant data variability. In such scenarios that have a higher data variability,

it is easier to make conclusions concerning the correlation between performance measures.

In contrast, Scenario 5 (2 QCs and 2 AGVs) demonstrates an inverse relationship between these variables, suggesting that the energy consumption cost decreases as the total operation time increases. One possible explanation for this unexpected result could be the presence of outliers or unusual data points in the dataset. These outliers might be caused by the stochastic times of the unloading/loading operation of the QCs and YC. These exceptional situations can lead to longer total operation times while the energy consumption cost remains relatively low. As a result, it can create a negative correlation between the two variables.

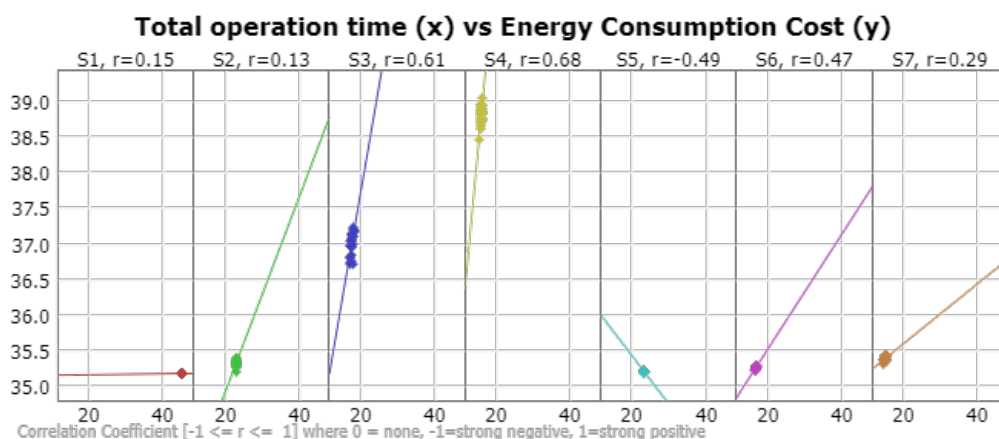


Figure 5.7: Correlation Plot between Total Operation Time and Energy Consumption Cost

The correlation charts provide valuable insights for informed decision-making, as they allow for an examination of the interdependencies between various performance measures and their mutual influence. By considering the relationships between these measures and their respective behaviors, a more comprehensive understanding of the system's performance can be obtained, enabling more informed decision-making processes.

#### • Metrics from the FlexSim's dashboard

In addition to the aforementioned performance measures, the evaluation of the extensions also took into account several metrics calculated within the FlexSim simulation software's dashboard. These metrics were deemed crucial indicators for comparing the results derived from the execution of the extensions.

Figures B.4 to B.10 depict a series of pie charts illustrating the state distribution of each AGV throughout the execution of the respective scenarios, explicitly focusing on replication 1. In Scenario 1, the transportation of containers between the quay area and the storage yard is solely assigned to a single AGV. Consequently, all the workload is concentrated on a single vehicle, as evident in figure B.4.

As the number of AGVs increases in the subsequent scenarios, the distribution of workload becomes more evenly spread, thereby contributing to a more efficient operation. Notably, in Scenarios 5, 6, and 7, the inclusion of additional QC results in a marginal rise in the "Travel Loaded"



state of the AGVs, mainly observed in Scenarios 6 and 7. This observation aligns with the earlier findings from the graph in figure 5.3, indicating that incorporating an extra QC when there are already 2 AGVs in operation does not significantly enhance the performance of the container terminal in terms of total operation time.

Figures B.11 to B.17 provide a visual representation of the behavior of the QCs throughout the different scenarios. As anticipated, an increase in the number of operating AGVs corresponds to higher utilization of the QCs. This relationship between the two equipment types is particularly evident in Scenarios 1, 2, 3, and 4, where only a single QC is employed. In these scenarios, the limited availability of QCs necessitates a more concentrated use of the single QC to accommodate the workload generated by the AGVs.

Conversely, in scenarios where two QCs are made available, Scenario 7 demonstrates a more effective utilization of the QCs. With the presence of four operating AGVs, as depicted in figure B.9, the workload distribution allows for a more balanced utilization of the two QCs. This observation is reinforced by figures B.15 and B.16, illustrating a notable QC usage disparity when transitioning from two AGVs to three AGVs. The inclusion of an additional AGV in Scenario 6 results in a significant increase in the demand for QC services.

The distance traveled by AGVs, a metric of interest, is depicted in the bar charts presented in figures B.18 to B.23. Notably, a comparison of scenarios with the same number of AGVs but differing numbers of QCs reveals a substantial reduction in AGV travel distance when two QCs are operational as opposed to only one.

The observed phenomenon, where the distance traveled by the AGVs is smaller when two QCs are considered instead of one, can be attributed to the efficient allocation of resources. When two QCs are available, the workload is distributed between them, allowing for a more balanced and optimized assignment of containers to the AGVs. As a result, the AGVs can handle the unloading tasks more effectively, minimizing unnecessary travel distances between the ship and the storage area. In scenarios with only one QC, the workload is concentrated on a single crane, potentially leading to suboptimal container assignments and longer travel distances for the AGVs.

#### 5.4.2 Impacts of AGVs' Speed Decrease

The analysis of the results obtained from this extension of the base model offers a comprehensive assessment of the effectiveness and implications of the introduced modifications.

Initially, it will be examined the effects of reducing the AGVs' speed by approximately 20% and its implications on the performance measures across all simulated scenarios compared to the obtained results from the execution of the base model.

As expected, this adjustment increased the total operation time, as evident in figure 5.8. The AGVs take longer to travel from the quay area to the storage yard and vice-versa, causing an increase in the transportation of the containers. Also, the incorporation of triangular distributions for the AGVs' velocities introduced a more significant variability in the data, deviating from deterministic times and embracing stochastic elements. This stochastic approach accounts for the inherent

uncertainties and unpredictability in the system, further enhancing the realism of the simulation model and reflecting real-world operational scenarios.

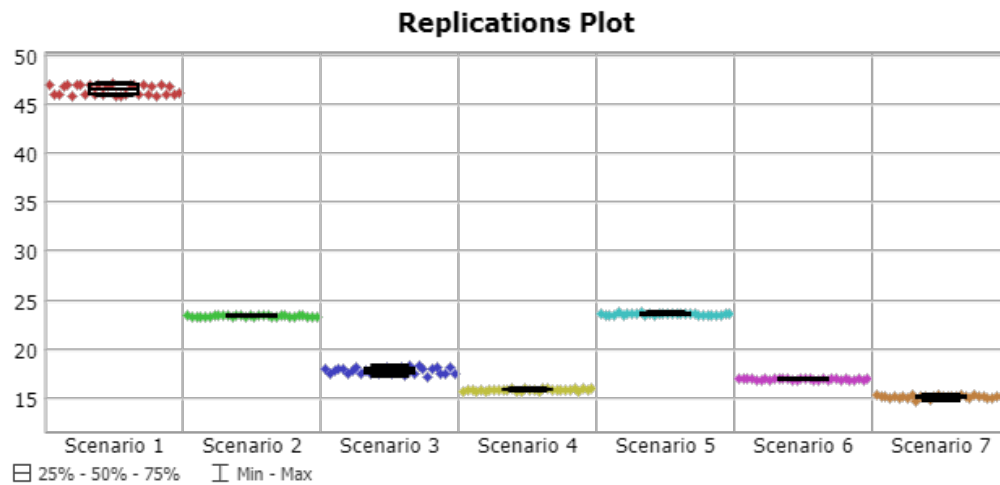


Figure 5.8: Replications Plot of Total Operation Time after decreasing AGVs' speed

Lowering the speed means it takes longer for the AGVs to complete their tasks, increasing the total operation time, as already mentioned. During this extended period, the AGVs continue to consume energy, causing a higher overall energy consumption, as figure 5.9 illustrates.

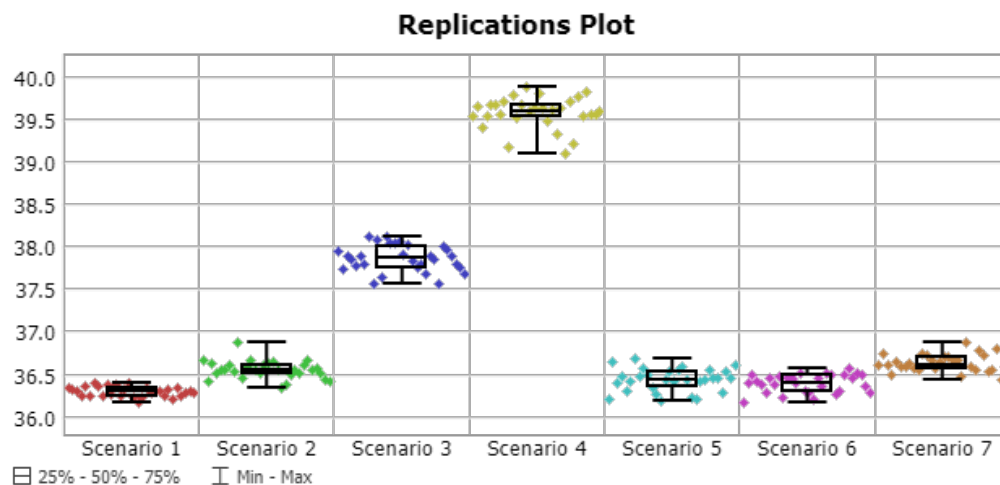


Figure 5.9: Replications Plot of Energy Consumption Cost after decreasing AGVs' speed

The longer operation time and increased energy consumption necessitate more frequent charging of the AGVs' batteries. Charging the batteries incurs charging costs, as electricity is needed to replenish the energy used by the AGVs. Therefore, the charging costs increase with longer operation times and increased energy consumption. The presence of outliers in the graph presented in figure 5.10, particularly in Scenarios 1, 3, 4, and 7, can be attributed to the inclusion of stochastic times in the AGVs' speeds and the loading and unloading operations conducted by the QCs and

YC. These stochastic times introduce variability and randomness into the simulation, resulting in occasional extreme values that deviate from the expected pattern.

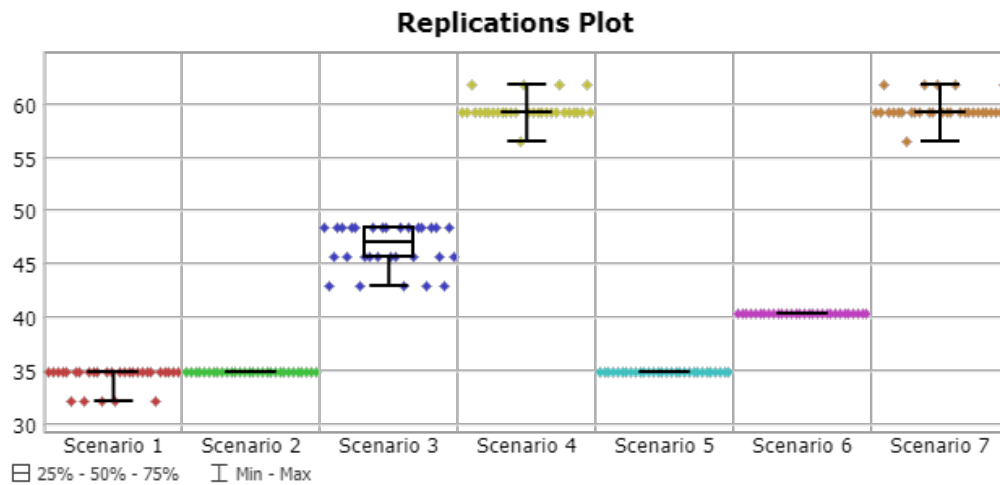


Figure 5.10: Replications Plot of Charging Cost after decreasing AGVs' speed

In summary, the analysis of the graphs leads to the conclusion that the reduction in AGV speeds has a significant impact on the unloading time of the ship, resulting in increased costs associated with energy consumption and AGV battery charging. This observation is consistent across all simulated scenarios.

Furthermore, an important indicator highlighting the consequences of this change pertains to the idle time of the QCs. As previously mentioned, the decrease in AGV speeds leads to prolonged transportation times for containers, subsequently increasing the waiting time for the QCs. This observation is evident when comparing the figures illustrating the idle time of QCs, [B.24](#) to [B.30](#). Notably, in all executed scenarios, the downtime of the QCs exceeds that of the base case.

These findings imply that the reduction in AGV speeds negatively affects the overall efficiency and performance of the container terminal operations. The increased unloading time and idle time of the QCs indicate a potential bottleneck in the system, resulting in more extended waiting periods for container transportation and subsequent processing.

The implications of these outcomes are significant, as they highlight the importance of maintaining optimal AGV speeds to ensure smooth and timely operations within the container terminal. By considering the impact of speed reduction on various performance measures, including unloading time, energy consumption costs, charging costs, and QC downtime, it becomes evident that a careful balance needs to be struck to achieve efficient and cost-effective operations.

### 5.4.3 Impacts of AGVs' Speed Increase

The second part of the extension to the base model focused on increasing the speeds of the AGVs by 20%. This modification aimed to assess the impact of higher AGV speeds on the performance and operational outcomes of the container terminal.

By enabling AGVs to operate at an increased speed, the unloading process of the ship in the container terminal is expedited, resulting in a reduction of the total operation time. This improvement arises from the AGVs' ability to transport containers more swiftly, thereby enhancing the overall efficiency and effectiveness of the model. The impact of increased AGV speeds on the "Total Operation Time" performance measure is clearly depicted in figure 5.11. Although the decrease in operation time may not be substantial compared to the base case, it becomes more evident when contrasting it with scenarios involving lower AGV speeds.

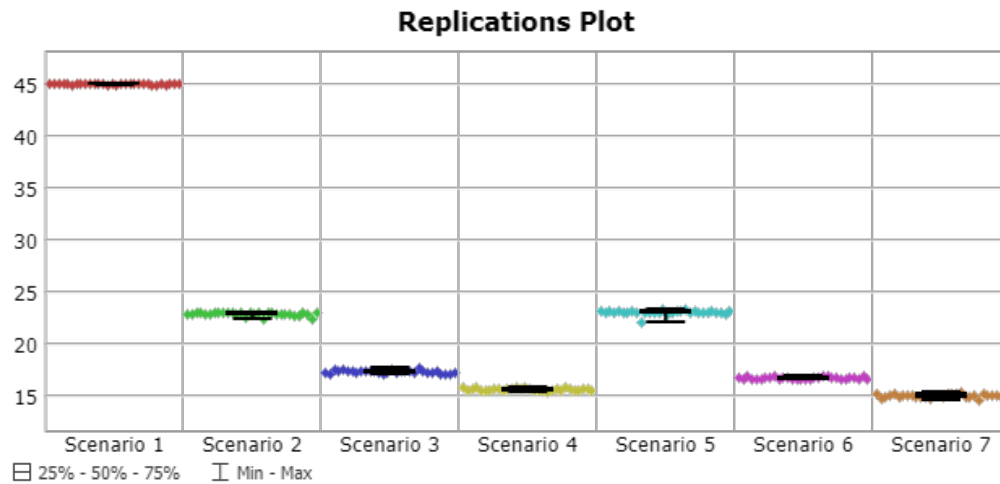


Figure 5.11: Replications Plot of Total Operation Time after increasing AGVs' speed

Figure 5.12 displays the relative costs associated with the energy consumption of the AGVs, resulting from the execution of the scenarios with the increased AGV speed.

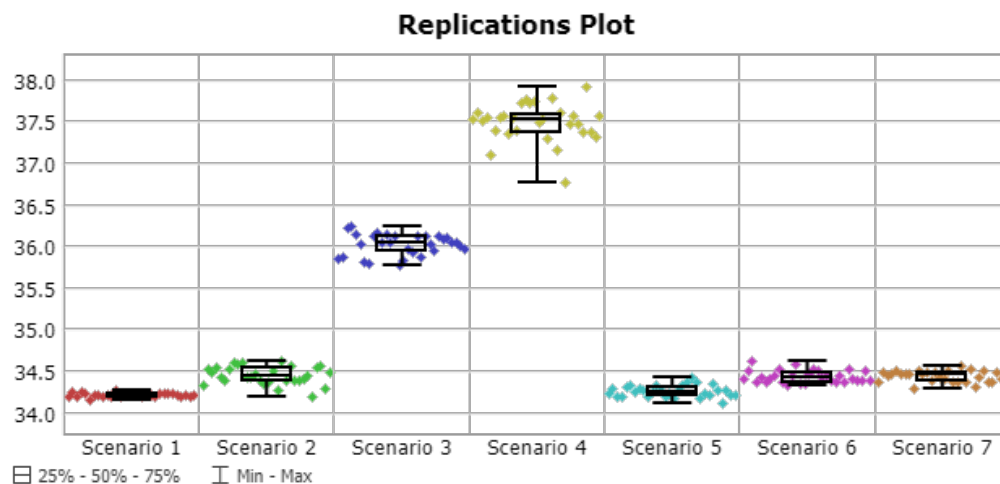


Figure 5.12: Replications Plot of Energy Consumption Cost after increasing AGVs' speed

This graph provides an overview of the energy consumption costs relative to the base case, allowing for a comparative analysis of the impact of AGV speed adjustments on energy usage. By examining the data, it is evident that the scenarios with increased AGV speeds exhibit a reduction

in energy consumption costs compared to the base case. This observed slight decrease in energy consumption costs across all simulated scenarios can be attributed to the increase in AGVs' speed. As the AGVs operate at a higher speed, they can complete their tasks more quickly, resulting in reduced overall operation time. The decreased operation time leads to a lower energy consumption cost, as the AGVs spend less time in operation, utilizing fewer resources. This efficiency gain in energy consumption is consistent across the scenarios, highlighting the positive impact of increased AGV speed on reducing energy requirements and optimizing resource utilization within the container terminal.

Upon analyzing the replications plot of the charging costs results 5.13, it is evident that these values in the scenarios with varied AGV speeds are generally comparable to those observed in the base model. However, a noteworthy observation can be made regarding Scenario 3, where a slight decrease in charging costs is apparent. This can be attributed to the increased speed of the AGVs, which enables them to complete their tasks more quickly. As a result, the AGVs spend less time in transit and require fewer charging intervals to replenish their batteries. The reduced charging costs in Scenario 3 indicate improved energy efficiency and optimization of resource utilization, leading to cost savings in the overall operation of the container terminal.

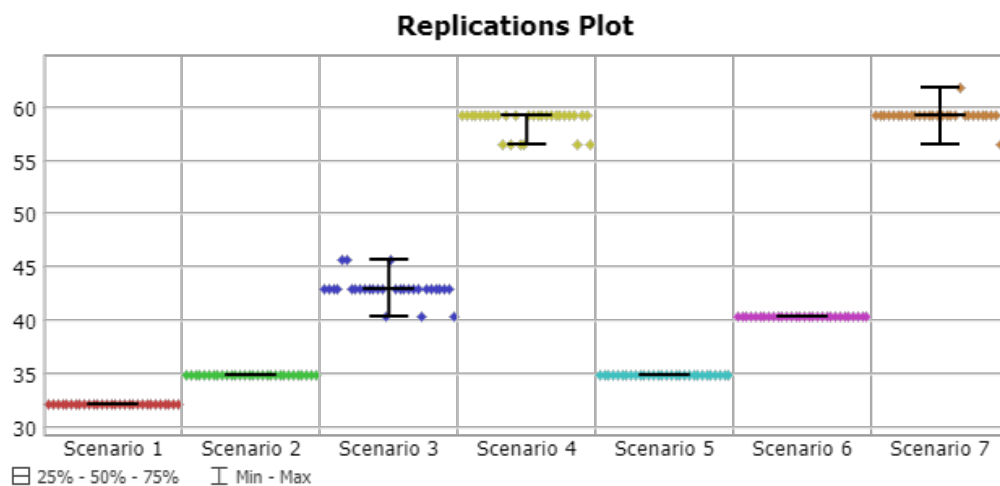


Figure 5.13: Replications Plot of Charging Cost after increasing AGVs' speed

Based on the analysis of the obtained results, it can be inferred that the augmentation of AGV speeds has contributed to enhanced operational efficiency within the container terminal. The increased speed has reduced the ship's unloading time, thereby expediting the overall process. In terms of energy consumption, the impact of this change is more prominent, primarily affecting the costs associated with energy usage. The accelerated movement of AGVs due to the speed increase has effectively minimized the time taken for AGV travel, both when loaded and unloaded. Consequently, this effect has influenced the computation of energy consumption costs, decreasing their magnitude. However, the impact on charging costs is relatively minimal, with only a slight reduction observed in Scenario 3, wherein three AGVs and one QC are employed. These

findings suggest adjusting AGV speeds can positively influence operational efficiency and energy consumption costs within the container terminal.

To comprehensively evaluate the impact of the model, the idle time of QCs serves as an important factor. The bar charts presented in figures B.31 to B.37 provide insights into the changes in QC idle time across various scenarios. In Scenarios 1, 2, and 3, a slight reduction in QC idle time is observed compared to the baseline model. However, in the remaining scenarios, the utilization of QCs remains relatively consistent with that of the base model.

Based on these observations, it can be inferred that utilizing AGVs with higher speeds is only advantageous in scenarios involving a single QC, with the exception of the scenario characterized by one QC and four AGVs. In these specific scenarios, the higher speed of AGVs enables more efficient utilization of QCs, leading to a decrease in idle time and improved operational performance. In the scenarios involving the utilization of two QCs, the advantages of increasing the AGVs' speed in terms of QC utilization are not as prominent. Analysis of the corresponding metrics reveals no notable improvement in QC utilization when AGV speed is increased. Therefore, it can be concluded that the increase in AGV speed does not significantly impact the utilization of QCs in scenarios featuring two QCs. These findings suggest that other factors or strategies should be considered to enhance the efficiency of QC utilization in such scenarios.

#### 5.4.4 Impacts of Different AGV Routes

After conducting the simulation of the seven scenarios involving the AGVs' new rectangular route, an evaluation of the obtained results was performed, focusing on performance measures and the distance traveled by the AGVs.

By restricting the available path options for the AGVs and imposing a fixed route, they are compelled to follow a predetermined trajectory. This change in the AGVs' movement pattern leads to a slight increase in the total unloading time of the ship, as demonstrated in figure 5.14.

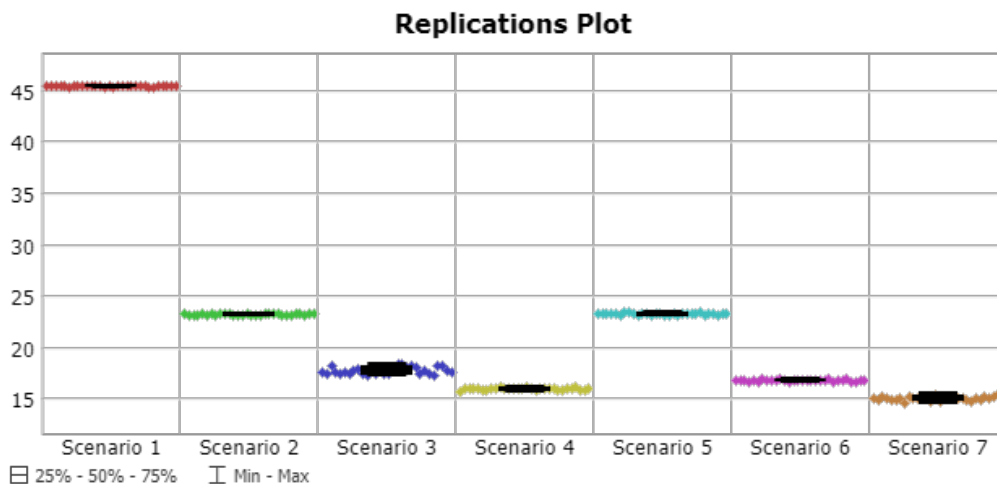


Figure 5.14: Replications Plot of Total Operation Time after the first change of AGVs' route

The total operation time increases due to a higher value of the distance traveled by the AGVs compared to the base model, as observed from figure B.38 to figure B.43. The increased distance traveled by the AGVs leads to a corresponding increase in the energy consumed by them in all scenarios, as depicted in figure 5.15.

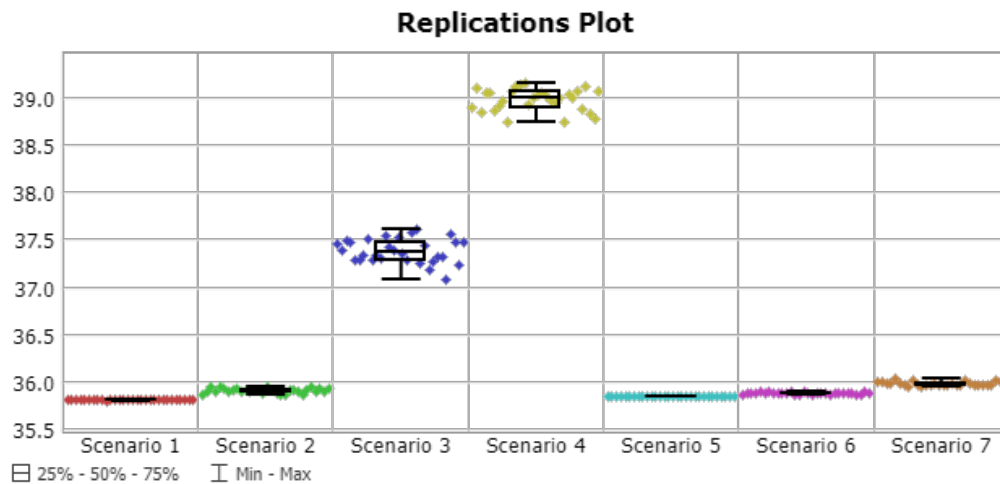


Figure 5.15: Replications Plot of Energy Consumption Cost after the first change of AGVs' route

Despite the increase in energy consumption costs of the AGVs, the charging costs remained unchanged in comparison to the baseline model, except for Scenario 4, where a slight increase was observed in figure 5.16. One possible explanation for this could be the utilization of the AGVs in Scenario 4. With only one QC and four AGVs, the AGVs may have a higher workload and more frequent tasks than other scenarios with more QCs. The increased workload can result in more frequent movements and longer operating times for the AGVs, leading to higher energy consumption and, subsequently, higher charging costs.

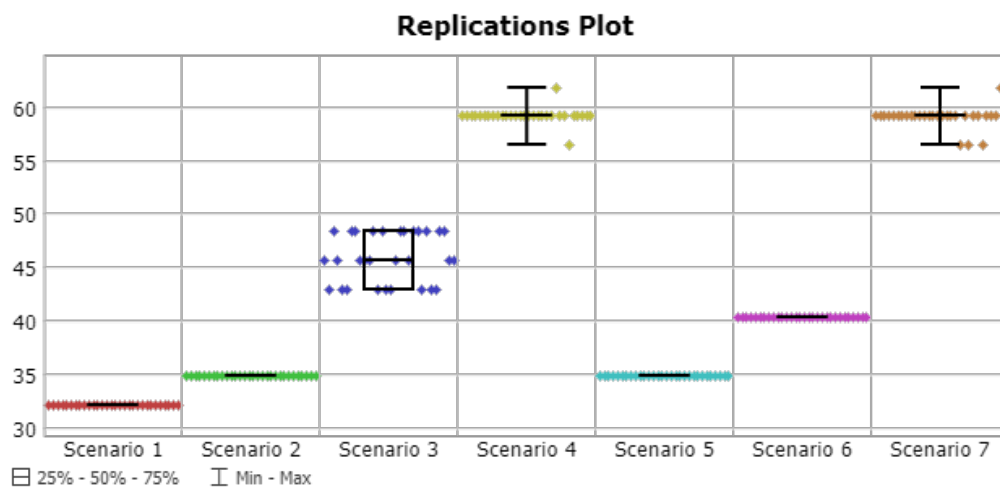


Figure 5.16: Replications Plot of Charging Cost after the first change of AGVs' route

In summary, the modification of the AGV route to the one depicted in figure 5.1 resulted in a slight increase in ship unloading time due to the extended distance traveled by the AGVs. Consequently, the costs associated with energy consumption by the AGVs significantly increased. Despite this rise in energy costs, the charging costs for the AGVs remained nearly unchanged compared to the base model.

After executing the scenarios with the rectangular route, it was modified to a route with additional path options for the AGVs, as illustrated in figure 5.2. The added path in the route of the baseline model reduces the distance traveled by the AGVs between the storage yard and the quay area and vice versa. This reduction in distance can be observed from figure B.44 to figure B.49, where it is evident that the distance traveled by the AGVs is significantly lower compared to the baseline model.

Despite this factor, the total ship unloading time undergoes minimal changes, with only a slight decrease observed in Scenarios 1, 4, and 7 (figure 5.17).

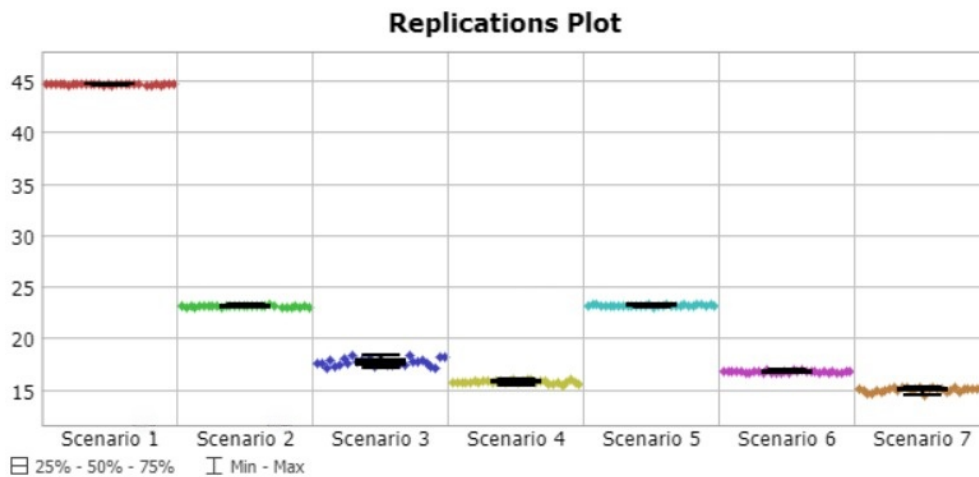


Figure 5.17: Replications Plot of Total Operation Time after the second change of AGVs' route

This slight decrease in the total operational time can be attributed to the loading/unloading time of the QCs, as this time remained unchanged. Consequently, it becomes challenging for the QCs to keep up with the early arrival of the AGVs.,

The significant reduction in the distance traveled by the AGVs positively impacted the costs associated with energy consumption. These values decreased considerably compared to the baseline case, as depicted in figure 5.18.



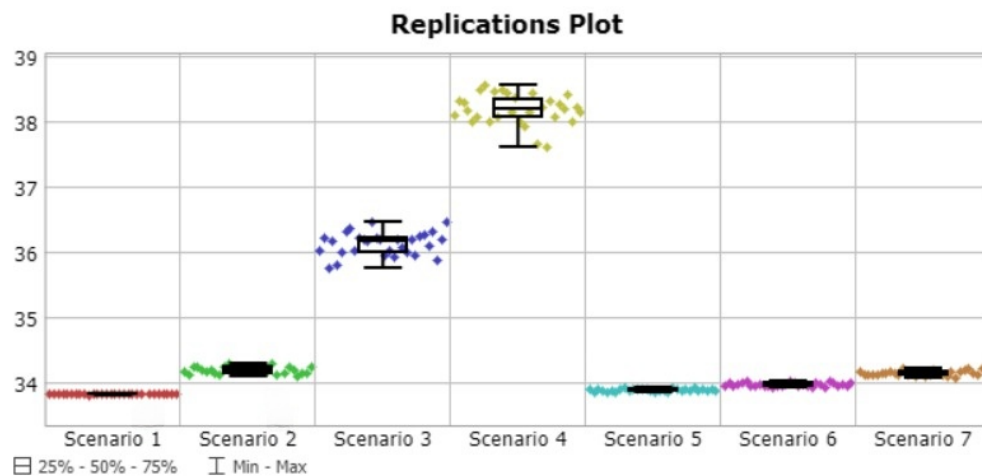


Figure 5.18: Replications Plot of Energy Consumption Cost after the second change of AGVs' route

Similar to the previously executed scenario, the charging costs obtained in the second route are mainly similar to those in the baseline case, with the exception of Scenario 6, which exhibits a slightly higher maximum value due to an outlier, as shown in figure 5.19.

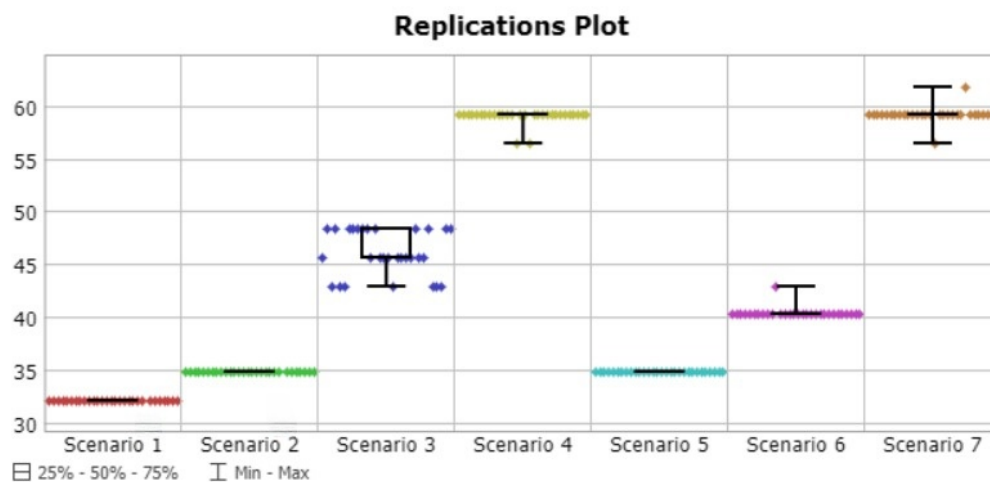


Figure 5.19: Replications Plot of Charging Cost after the second change of AGVs' route

In summary, the modification of the AGV routes significantly influences the distance traveled by the AGVs, subsequently affecting the energy consumption values. However, this alteration does not substantially impact the charging costs of the AGVs and only slightly influences the total operation time. This is primarily due to the fact that the unloading/loading times of the QCs and YC are not adjusted to accommodate the changes in AGV routes. These times are randomly generated, which may increase the AGVs' waiting times.



## **Chapter 6**

# **Conclusions and future work**

The findings related to the work completed during the course of the project are presented in this chapter. The contributions of this dissertation will be examined and analyzed to see whether the goals were achieved. In addition to findings, some recommendations for future work are also provided, bearing in mind a philosophy focused on constant progress and awareness of what is yet possible.

### **6.1 Conclusions**

The primary aim of this study was to design and develop a comprehensive FlexSim simulation model to serve as a decision-support tool for optimizing the overall performance of container terminals within seaports. The conceptual model focused explicitly on the unloading operations of ships and internal processes within container terminals, taking into consideration the increasing automation and sustainability concerns of these facilities.

The developed simulation model incorporated autonomous electric vehicles, known as AGVs, for container transport within the terminal. This choice aligned with the objectives of green ports and the growing adoption of environmentally friendly practices. The model's decision variables revolved around the quantity of equipment employed, serving as input parameters for seven simulated scenarios. These scenarios enabled the evaluation of terminal behavior under varying combinations of AGVs and QCs. The model's performance was assessed through calculated performance measures and metrics provided by FlexSim's dashboard.

To enhance the value of the research, two extensions to the base model were implemented: (1) adjustment of AGV speeds and (2) modification of AGV routes. Analysis of the results indicated that changing AGV speeds significantly impacted the duration of ship unloading and subsequent energy consumption. Additionally, it was observed that AGV speeds notably influenced the waiting time of QCs. Conversely, altering AGV routes substantially affected the distance traveled by the vehicles, consequently impacting energy costs.

The established objectives for this dissertation were successfully achieved, resulting in the implementation of a decision-support tool that helps the optimization of port operations by considering multiple performance measures and metrics within the FlexSim environment. Although the simulation model was designed for a simplified container terminal with a limited number of equipment, it can be readily customized to suit the specific characteristics of individual ports by adjusting the input parameters and leveraging other relevant features of FlexSim pertaining to AGVs.

In conclusion, the approach developed in this study lays the foundation for the future development of a methodology that enables decision-makers to proactively assess the behavior of a container terminal with the aim of optimizing its operations. This framework opens up possibilities for enhancing the efficiency and effectiveness of container terminal management through informed decision-making and strategic planning.

## 6.2 Future Work

In summary, this dissertation's results and contributions lay a solid platform for further study and innovation targeted at improving container port operations. Several topics need consideration and investigation in order to expand on current work and further enhance performance.

First, the current simulation models can be enhanced in the future. There is potential for improvement and growth even if the built FlexSim simulation model is performed as a valuable decision-support tool. Future initiatives should concentrate on including further elements and variables that affect container terminal operations. This might entail taking into account various ship types, various container sizes, and dynamic resource allocation, enabling a more thorough and accurate simulation of actual terminals.

Second, sophisticated optimization methods present potential directions for further study. The best methods for scheduling, allocating, and routing equipment inside the terminal can be found using mathematical optimization, evolutionary algorithms, or machine learning techniques. Container terminals may increase efficiency, productivity, and resource utilization by utilizing these strategies, which will improve overall performance.

Furthermore, the marine sector is becoming increasingly concerned with sustainability. The integration of more sustainable practices and green technology into container terminals should be the main topic of future study. In order to do this, it may be necessary to examine the environmental effects of various operating strategies, determine the potential of renewable energy sources, and put creative waste management and emission reduction solutions into practice. Container terminals may improve their competitiveness, lessen their environmental impact, and help create a better future by adopting sustainability.

Moreover, investigations that compare and benchmark performance are valuable tools for performance evaluation. Future research can undertake extensive studies comparing the productivity, efficiency, sustainability, and customer happiness of various terminals. Container terminals may

learn about potential areas for improvement and promote continual optimization by establishing best practices and performance standards.

By looking at these topics, academics may contribute to the continued creation of novel solutions that improve container terminal operations' productivity, efficiency, and environmental sustainability.



## Appendix A

# Simulation Model for the Case Study

### A.1 Implementation in FlexSim

#### A.1.1 3D Model

The screenshot displays the configuration window for an ASRS vehicle in FlexSim, organized into three main sections: ASRS, TaskExecuter, and Travel.

- ASRS Section:**
  - Lift Speed: 1.45 m/s
  - Extension Speed: 2.75 m/s
  - Initial Lift Height: 3.00 m
- TaskExecuter Section:**
  - Capacity: 1
  - Load Time: `triangular(30.0, 60.0, 40.0, getstrear` s
  - Unload Time: `triangular(30.0, 60.0, 40.0, getstrear` s
  - Break To: New Tasksequences Only
  - ☒ Fire OnResourceAvailable at Simulation Start
- Travel Section:**
  - Max Speed: 0.75 m/s ☐ Rotate
  - Acceleration: 1.00 m/s/s
  - Deceleration: 1.00 m/s/s
  - Flip Threshold: 180
  - Navigator: None
  - Travel offsets for load/unload tasks (dropdown menu)

Figure A.1: Relevant properties of ASRS vehicle in FlexSim

Speeds

	Max Speed	Acceleration	Deceleration
Gantry	3.70	0.40	0.40
Trolley	2	0.40	0.40
Hoist Lift	1.25	0.35	0.35
Hoist Drop	1.25	0.35	0.35

Frame

	X	Y	Z
Location	161.86	-7.29	0.00
Size	122.99	33.96	7.69

**TaskExecuter**

Capacity: 1

Load Time: `triangular(36, 102, 60, getstream(cu s`

Unload Time: `triangular(36, 102, 60, getstream(cu s`

Break To: New Tasksequences Only

☒ Fire OnResourceAvailable at Simulation Start

Figure A.2: Relevant properties of the crane in FlexSim



DefaultAGV		
	Empty	Loaded
Acceleration	2	0.50
Deceleration	2	0.50
Forward Speed		
Straight	6	3
Curved	1	1
Spur	1	1
Reverse Speed		
Straight	6	3
Curved	1	1
Spur	1	1
Battery Use (A)	208	312
Rotation Speed	30	30

Battery Cap. (AH)  Idle Use (A)  Recharge (A)

Rotate Threshold  °

Figure A.3: AGV type's features defined in FlexSim

### A.1.2 Process Flow

ProcessFlow / Ships to unload - Arrival Schedule

Arrivals  Labels

Arrival Time	Name	Quantity	id_ship	Berth	Load
0		1	1	1	1 Model.parameters.Load

Figure A.4: Ship arrivals table

### A.1.3 Parameters

Parameters

Name	Value	Display Units	Description
AGVs_type1_capacity	1		
Number_QC	2		
Number_AGV	4		
BatThresholdMin	10		
BatThresholdMax	80		
Load	250		

Figure A.5: Model's parameters

### A.1.4 Dashboard

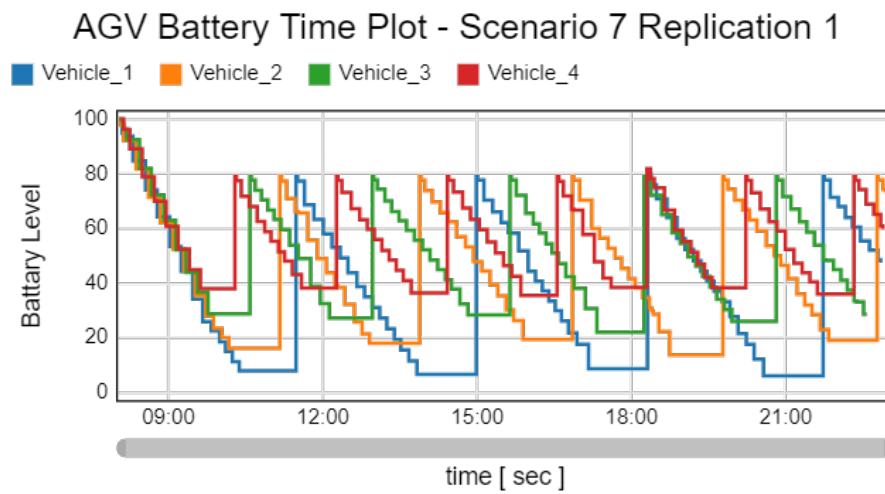


Figure A.6: Example of a time plot indicating the AGV battery during the execution of replication 1 of scenario 7

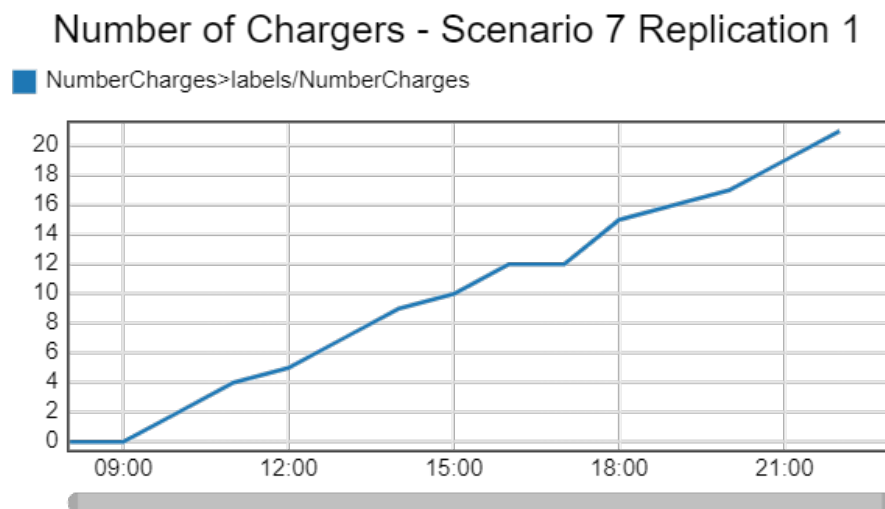


Figure A.7: Example of a time plot indicating the number of chargers of the AGVs during the execution of replication 1 of scenario 7

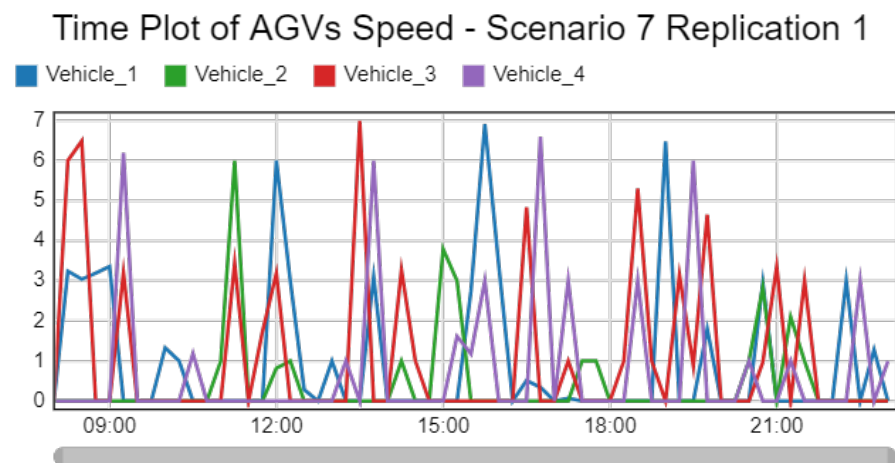


Figure A.8: Example of a time plot indicating the AGVs' speed during the execution of replication 1 of scenario 7



## Appendix B

# Results Analysis

### B.1 Design of Experiments

#### B.1.1 Extension 1 (Impacts of Different AGV Speeds)

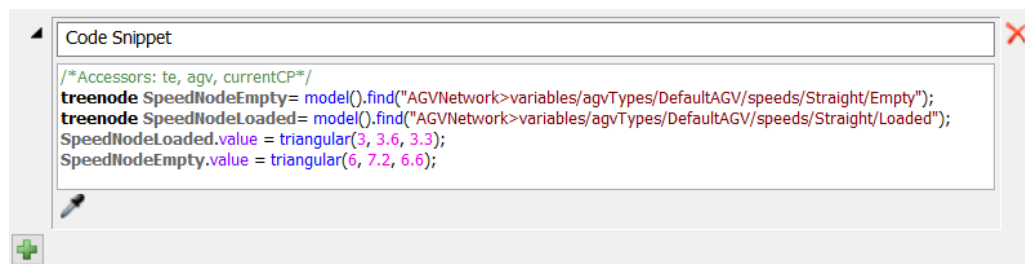


Figure B.1: Triangular distribution implemented in the AGV Network to increase the AGVs' speed by 20%

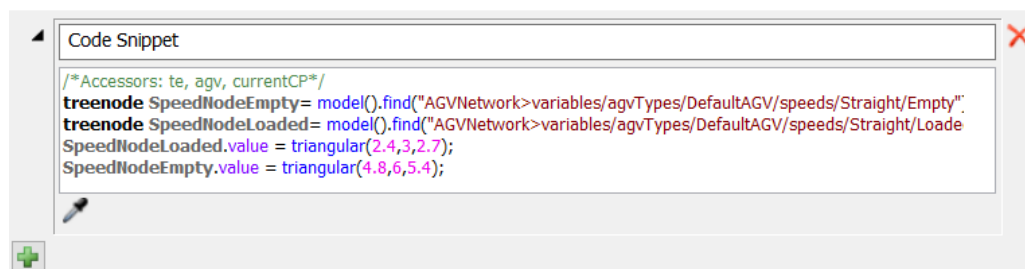


Figure B.2: Triangular distribution implemented in the AGV Network to decrease the AGVs' speed by 20%

## B.2 Experiments in FlexSim

Name: Experiment1  
 Warmup Time: 0.00 08:00:00 29/03/2023  
 Stop Time: 190800.00 13:00:00 31/03/2023  
 Replications per Scenario: 30

Parameters:
 

- ☐ AGVs\_type1\_capacity
- ☒ Number\_QC
- ☒ Number\_AGV
- ☐ BatThresholdMin
- ☐ BatThresholdMax
- ☐ Load

Scenarios:
 

	Number_AGV	Number_QC
Scenario 1	1	1
Scenario 2	2	1
Scenario 3	3	1
Scenario 4	4	1
Scenario 5	2	2
Scenario 6	3	2
Scenario 7	4	2

7    Set model to selected scenario

Figure B.3: Experimenter interface in FlexSim

## B.3 Analysis Scenarios of Base Model

Table B.1: Summary of charging cost values after the execution of the seven scenarios considering the base model

Summary		
	Mean (95% Confidence Interval)	Sample Std Dev
Scenario 1	32.2559999999999312 ± 0.00000000000000540	0.00000000000001445
Scenario 2	34.94399999999998840 ± 0.00000000000000809	0.00000000000002168
Scenario 3	45.33760000000001611 ± 0.86346603053315818	2.31266416900956129
Scenario 4	58.7775999999999252 ± 0.34699162494593472	0.92936498898905018
Scenario 5	34.94399999999998840 ± 0.00000000000000809	0.00000000000002168
Scenario 6	40.32000000000001450 ± 0.00000000000000270	0.00000000000000723
Scenario 7	59.4047999999999450 ± 0.30622795384371837	0.82018561397973300

Table B.2: Summary of energy consumption cost values after the execution of the seven scenarios considering the base model

Summary		
	Mean (95% Confidence Interval)	Sample Std Dev
<b>Scenario 1</b>	35.1766190 $\pm$ 0.0001030	0.0002759
<b>Scenario 2</b>	35.3257110 $\pm$ 0.0156929	0.0420312
<b>Scenario 3</b>	36.9913547 $\pm$ 0.0580716	0.1555360
<b>Scenario 4</b>	38.8066253 $\pm$ 0.0437761	0.1172477
<b>Scenario 5</b>	35.2077637 $\pm$ 0.0045969	0.0123121
<b>Scenario 6</b>	35.2572263 $\pm$ 0.0073142	0.0195899
<b>Scenario 7</b>	35.3867200 $\pm$ 0.0111136	0.0297661

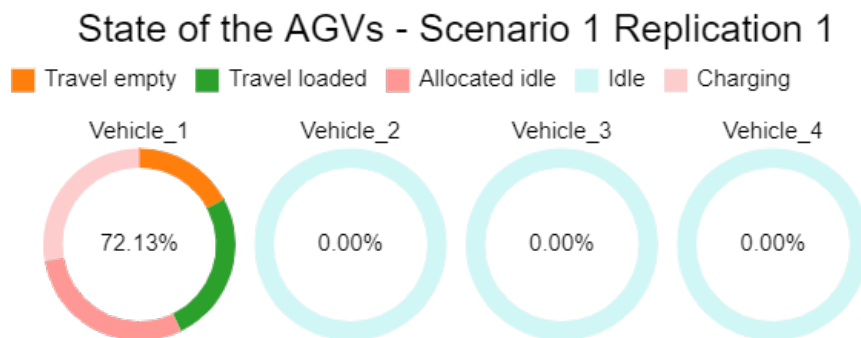


Figure B.4: Pie Chart indicating the state of the AGV during the execution of replication 1 of scenario 1

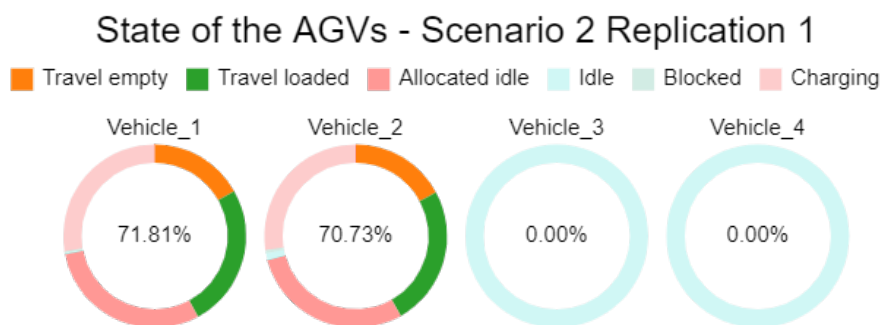


Figure B.5: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 2

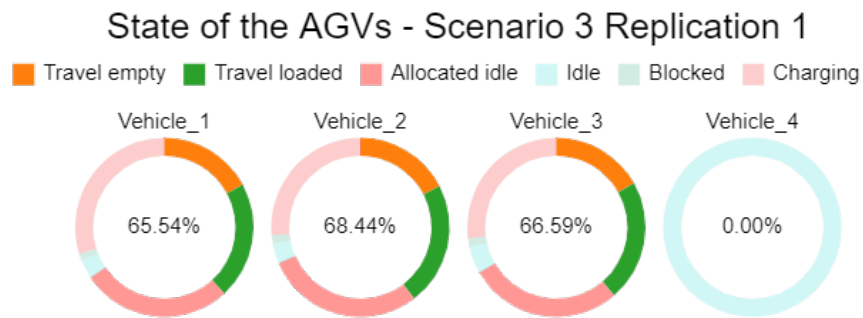


Figure B.6: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 3

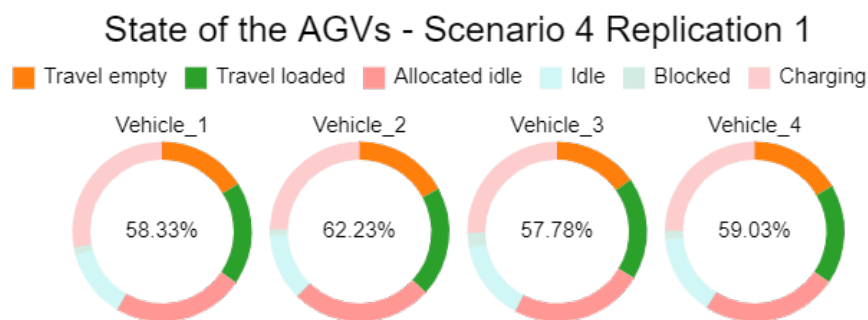


Figure B.7: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 4

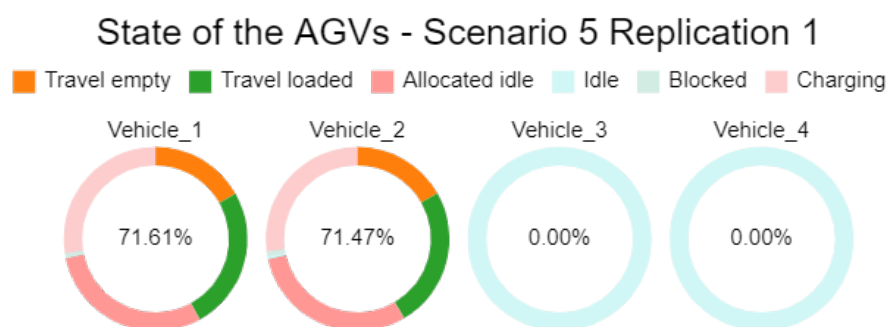


Figure B.8: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 5



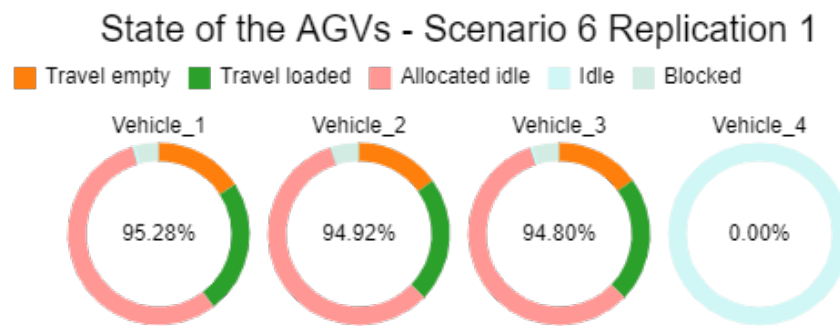


Figure B.9: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 6

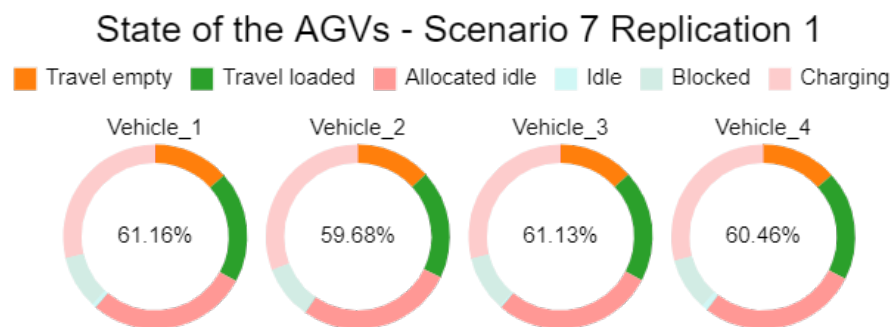


Figure B.10: Pie Chart indicating the state of the AGVs during the execution of replication 1 of scenario 7

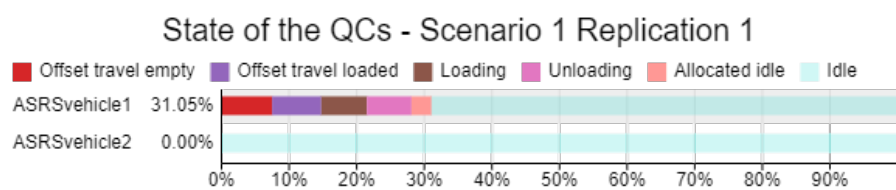


Figure B.11: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1

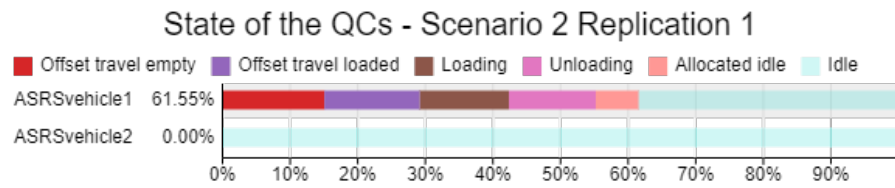


Figure B.12: Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 2

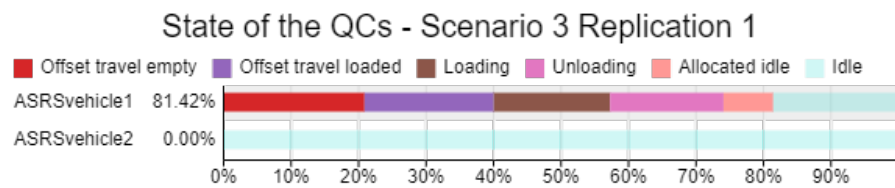


Figure B.13: Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 3

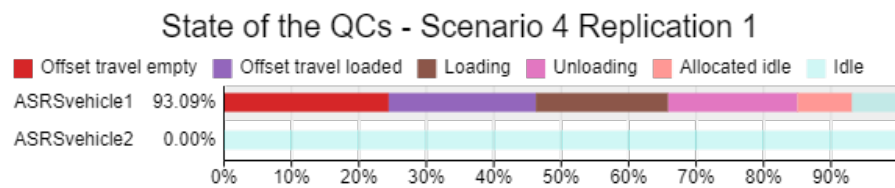


Figure B.14: Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 4

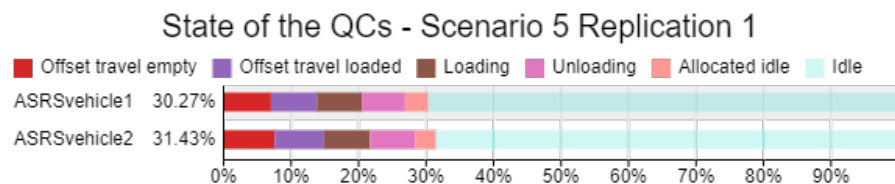


Figure B.15: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5

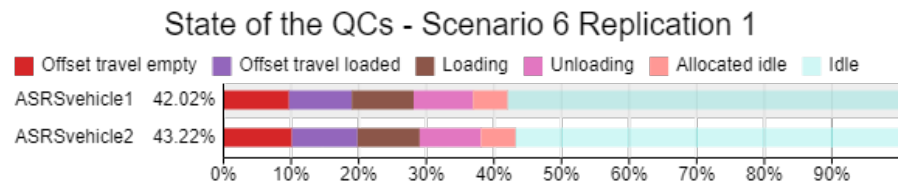


Figure B.16: Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 6

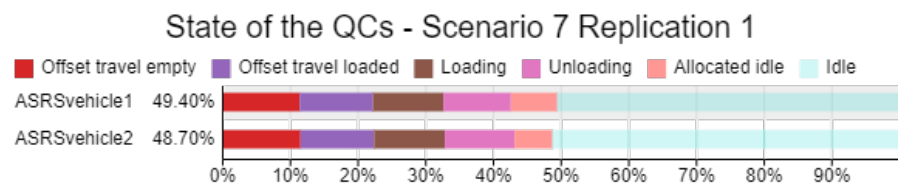


Figure B.17: Bar Chart indicating the state of the QCs during the execution of replication 1 of scenario 7

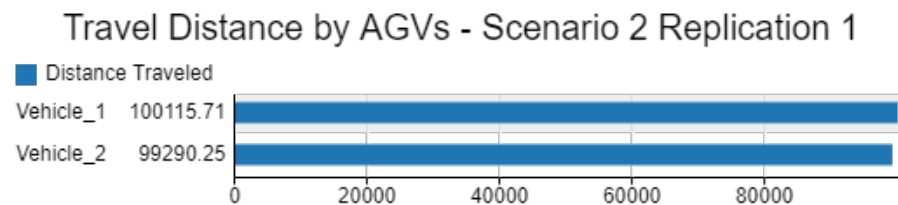


Figure B.18: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2

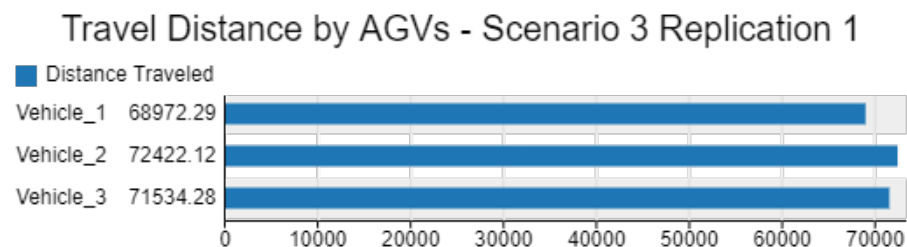


Figure B.19: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3

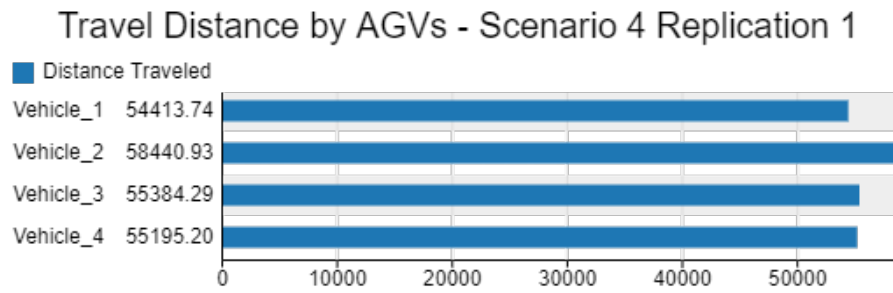


Figure B.20: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4

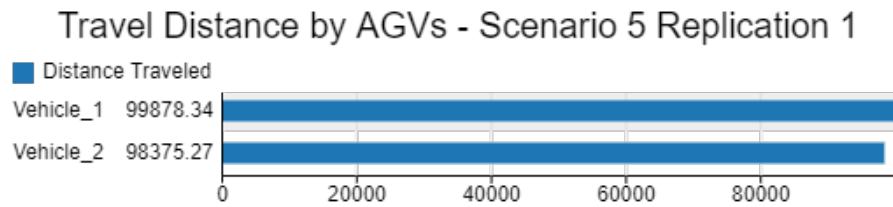


Figure B.21: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5

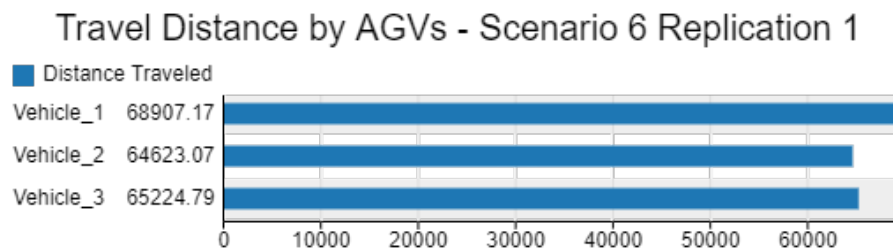


Figure B.22: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6

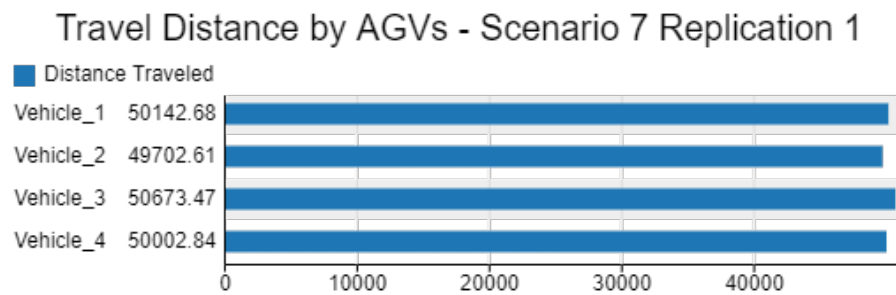


Figure B.23: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7

## B.4 Analysis Scenarios of Extension 1 (Impacts of Different AGV Speeds)

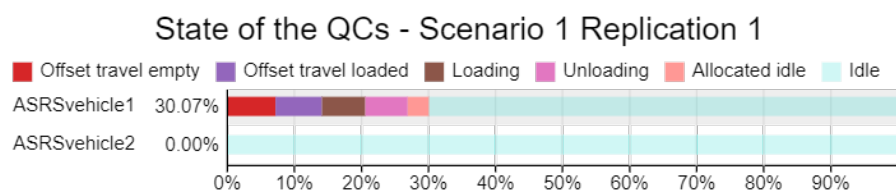


Figure B.24: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1 after decreasing the AGVs' speed

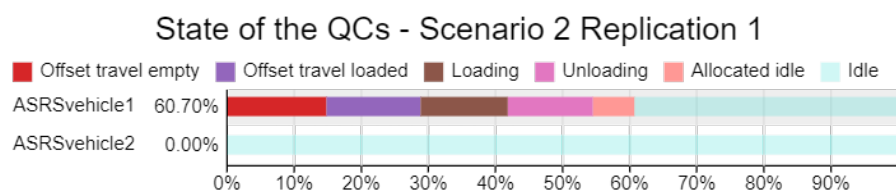


Figure B.25: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 2 after decreasing the AGVs' speed

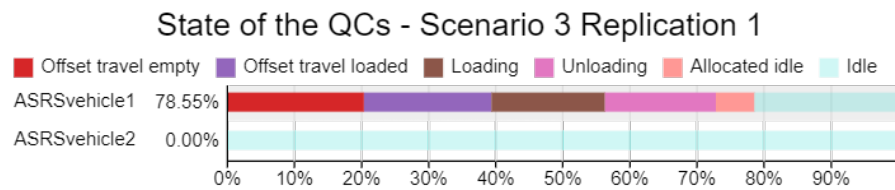


Figure B.26: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 3 after decreasing the AGVs' speed

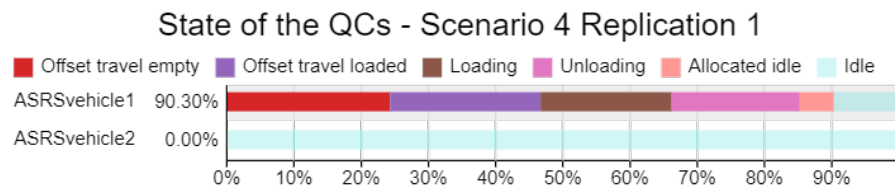


Figure B.27: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 4 after decreasing the AGVs' speed

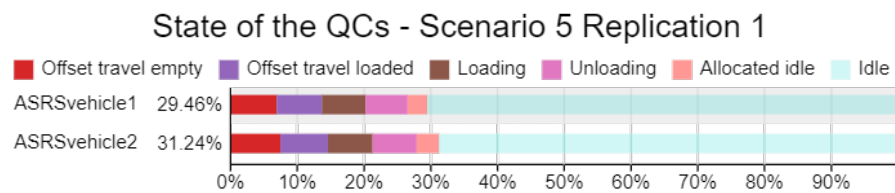


Figure B.28: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5 after decreasing the AGVs' speed

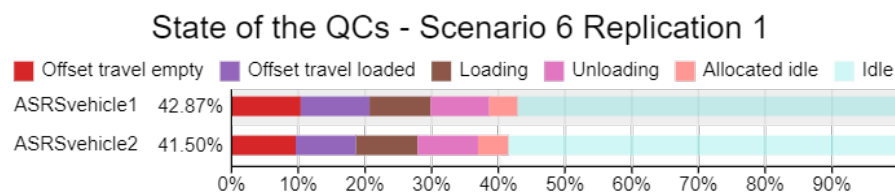


Figure B.29: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 6 after decreasing the AGVs' speed

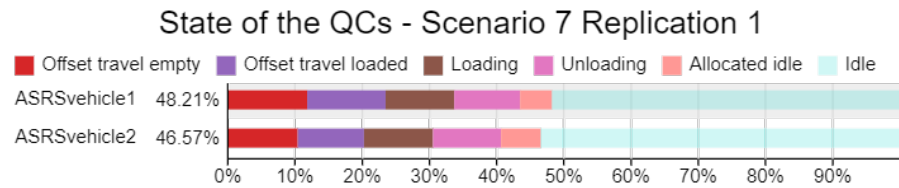


Figure B.30: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 7 after decreasing the AGVs' speed

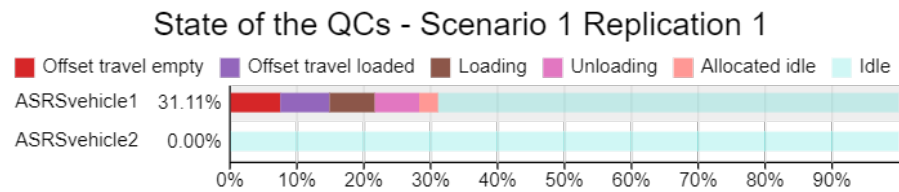


Figure B.31: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 1 after increasing the AGVs' speed

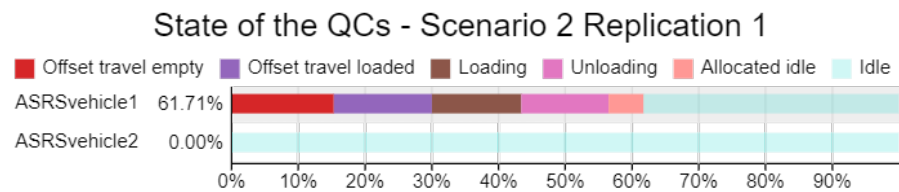


Figure B.32: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 2 after increasing the AGVs' speed

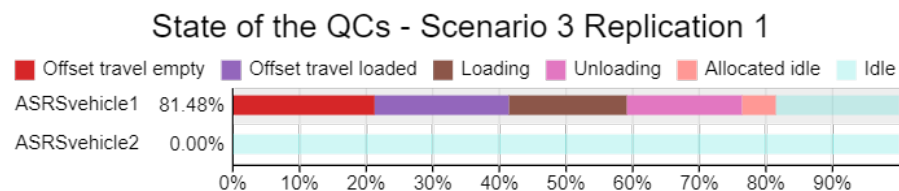


Figure B.33: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 3 after increasing the AGVs' speed

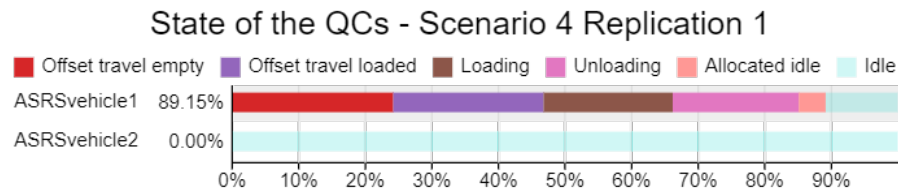


Figure B.34: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 4 after increasing the AGVs' speed

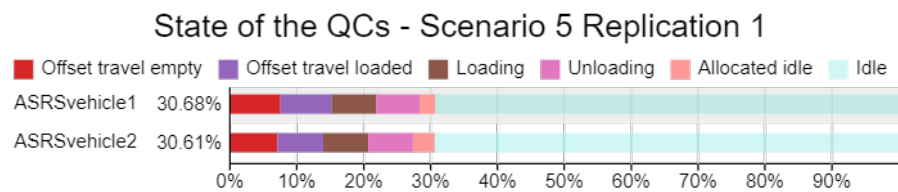


Figure B.35: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 5 after increasing the AGVs' speed

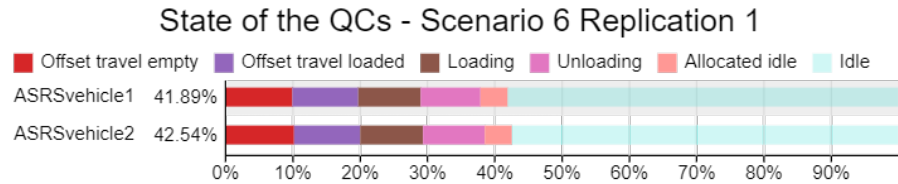


Figure B.36: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 6 after increasing the AGVs' speed

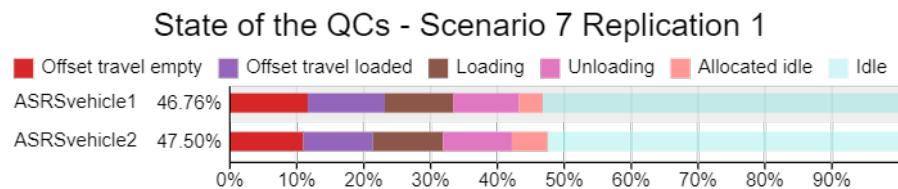


Figure B.37: Bar Chart indicating the state of the QC during the execution of replication 1 of scenario 7 after increasing the AGVs' speed



## B.5 Analysis Scenarios of Extension 2 (Impacts of Different AGV Routes)

### B.5.1 First Modification of AGVs' Route

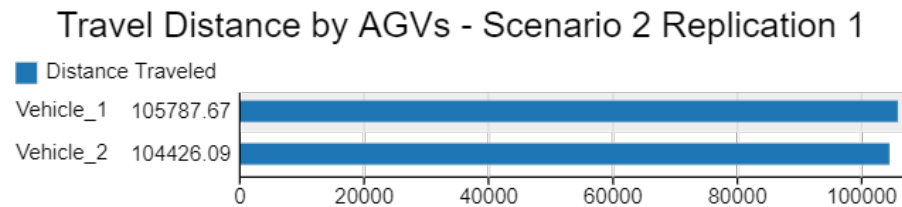


Figure B.38: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2 after the first change of the AGVs' route

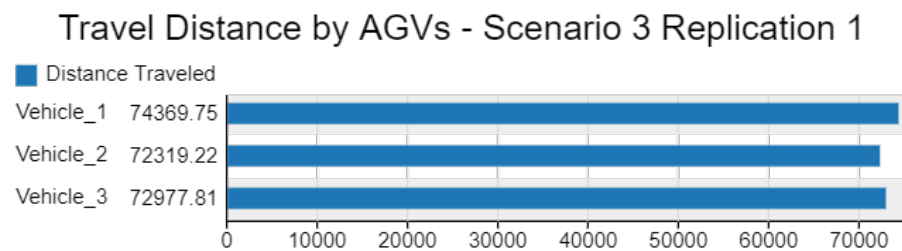


Figure B.39: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3 after the first change of the AGVs' route

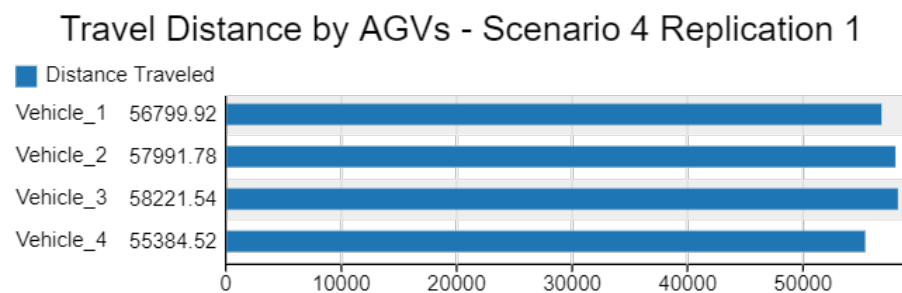


Figure B.40: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4 after the first change of the AGVs' route

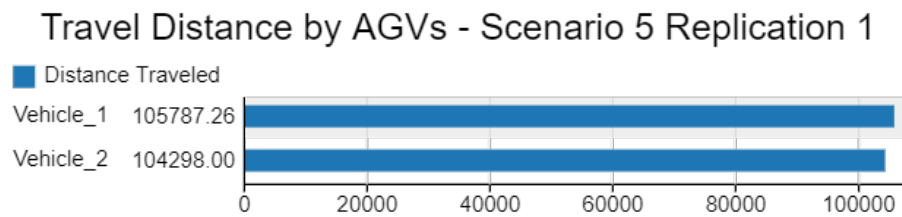


Figure B.41: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5 after the first change of the AGVs' route

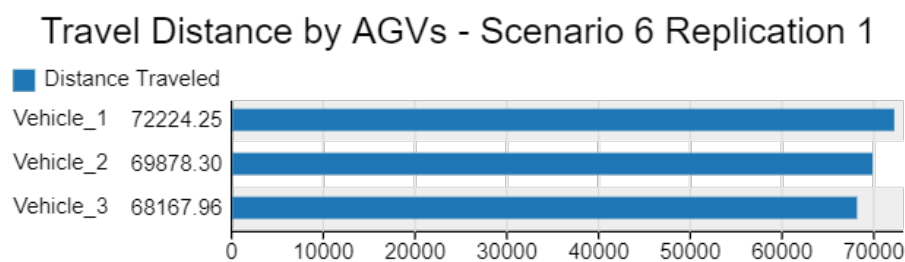


Figure B.42: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6 after the first change of the AGVs' route

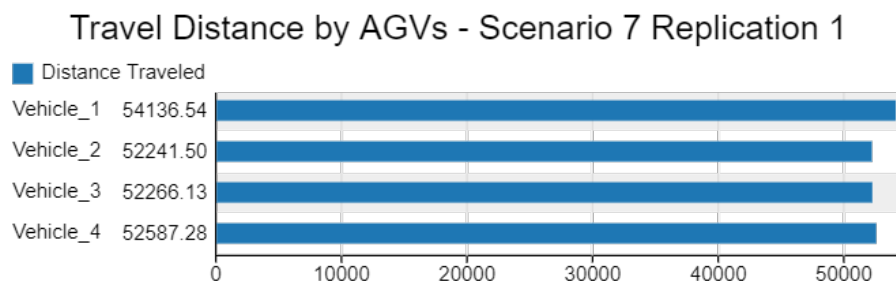


Figure B.43: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7 after the first change of the AGVs' route

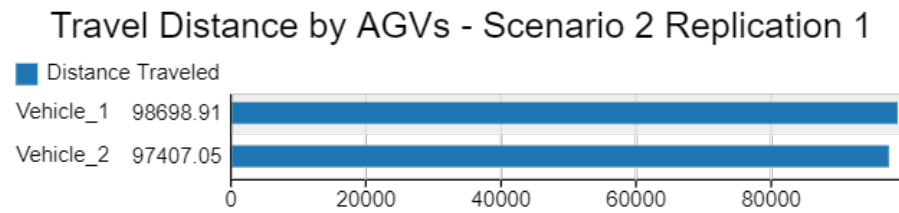
**B.5.2 Second Modification of AGVs' Route**

Figure B.44: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 2 after the second change of the AGVs' route

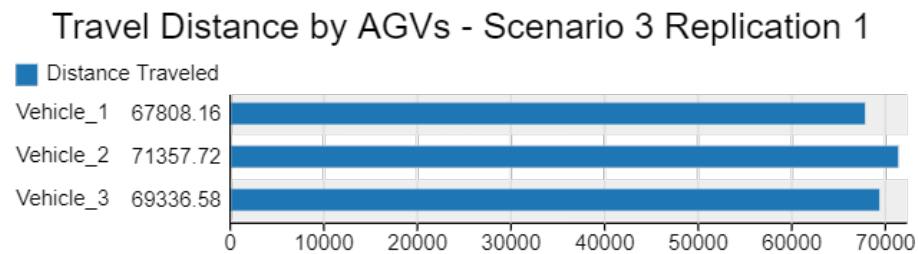


Figure B.45: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 3 after the second change of the AGVs' route

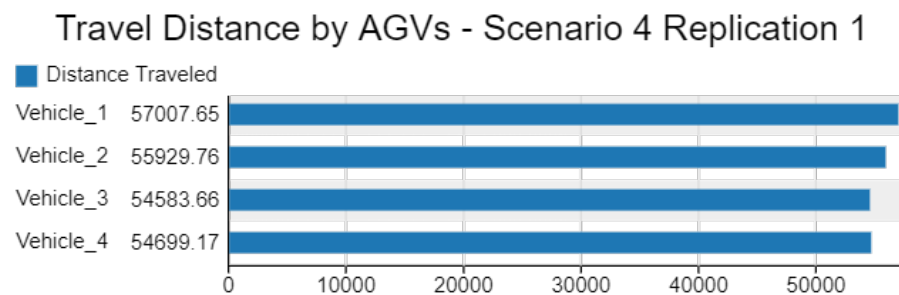


Figure B.46: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 4 after the second change of the AGVs' route

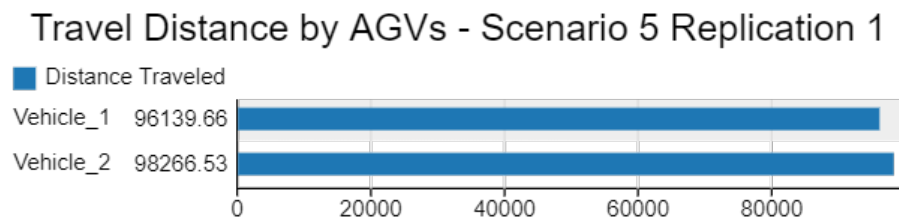


Figure B.47: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 5 after the second change of the AGVs' route

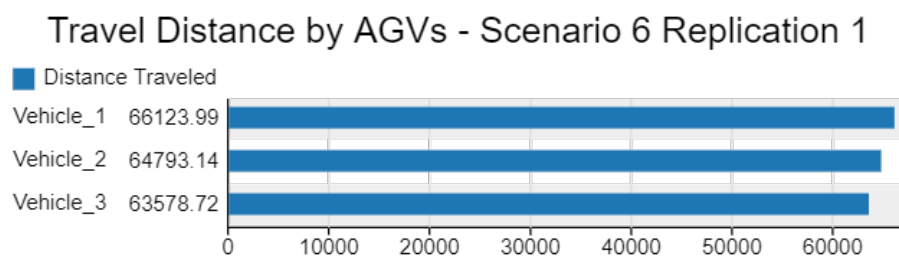


Figure B.48: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 6 after the second change of the AGVs' route

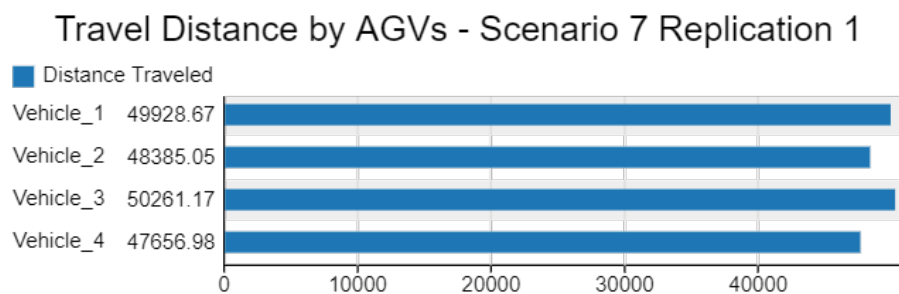


Figure B.49: Bar Chart indicating the distance traveled by the AGVs during the execution of replication 1 of scenario 7 after the second change of the AGVs' route

# References

- [1] Theo Notteboom, Athanasios Pallis, and Jean-Paul Rodrigue. *PORT ECONOMICS, MANAGEMENT AND POLICY*.
- [2] Héctor J. Carlo, Iris F.A. Vis, and Kees Jan Roodbergen. Transport operations in container terminals: Literature overview, trends, research directions and classification scheme, 7 2014. doi:10.1016/j.ejor.2013.11.023.
- [3] Ryan Finn. Container terminal st. petersburg orders 2 STS cranes from konecranes. <https://logistics-manager.com/container-terminal-st-petersburg-orders-2-sts-cranes-from-konecranes/>, January 2021. Accessed: 2023-3-17.
- [4] Brian Straight. Risk doesn't disappear just because the truck never leaves the yard. <https://www.freightwaves.com/news/risk-doesnt-disappear-just-because-the-truck-never-leaves-the-yard>, June 2021. Accessed: 2023-3-17.
- [5] Susanne Spatz. Eldorado for autonomous driverless systems. <https://www.dekra-solutions.com/2018/07/eldorado-for-autonomous-driverless-systems/?lang=en>, July 2018. Accessed: 2023-3-17.
- [6] Hamburger Hafen und Logistik AG. The world's most advanced hybrid straddle carrier. <https://hhla.de/en/media/news/detail-view/the-worlds-most-advanced-hybrid-straddle-carrier>. Accessed: June 6, 2023.
- [7] Chenhao Zhou, Byung Kwon Lee, and Haobin Li. Integrated optimization on yard crane scheduling and vehicle positioning at container yards. *Transportation Research Part E: Logistics and Transportation Review*, 138, 6 2020. doi:10.1016/j.tre.2020.101966.
- [8] Mouna Amrou, Badir Hassan, and Azedine Boulmakoul. Process mining for port container terminals: The state of the art and issues. 05 2018.
- [9] A. Bartošek and O. Marek. Quay cranes in container terminals. *Transactions on Transport Sciences*, 6:9–18, 3 2013. doi:10.2478/v10158-012-0027-y.
- [10] WorldCargo News. Innovation takes a pause. *WorldCargo News*, Month Year. Accessed: 8 06 2023.
- [11] Ji Shouwen, Luan Di, Chen Zhengrong, and Guo Dong. Integrated scheduling in automated container terminals considering agv conflict-free routing. *Transportation Letters*, 13:501–513, 2021. doi:10.1080/19427867.2020.1733199.

- [12] M. S. Gheith, A. B. El-Tawil, and N. A. Harraz. A proposed heuristic for solving the container pre-marshalling problem. pages 955–964, 2013. doi:10.1007/978-3-642-37270-4\_91.
- [13] Steel Mill Cranes. Rail mounted gantry crane, Accessed 2023. URL: <https://steelmillcranes.com/rail-mounted-gantry-crane/>.
- [14] Mohd Kamal Mohd Nawawi, Fadhilah Che Jamil, and Firdaus Mohamad Hamzah. Evaluating performance of container terminal operation using simulation. *AIP Conference Proceedings*, 1660, 2015. doi:10.1063/1.4926640.
- [15] Maurizio Bielli, Azedine Boulmakoul, and Mohamed Rida. Object oriented model for container terminal distributed simulation. *European Journal of Operational Research*, 175:1731–1751, 2006. doi:10.1016/j.ejor.2005.02.037.
- [16] Sönke Hartmann. Generating scenarios for simulation and optimization of container terminal logistics. *OR Spectrum*, 26:171–192, 2004. doi:10.1007/s00291-003-0150-6.
- [17] Mir A. Wahed, Ardeshtir Faghri, and Mingxin Li. An innovative simulation model for the operations of a multipurpose seaport: A case study from port of wilmington, usa. *International Journal of Simulation and Process Modelling*, 12:151–164, 2017. doi:10.1504/IJSPM.2017.083530.
- [18] Unctad. Unctad annual report 2018, 2018.
- [19] Carlos Jahn, Marvin Kastner, and Hannah Pache. Simulation-based optimization at container terminals: A literature review. 09 2019. doi:10.15480/882.2493.
- [20] Wayne K. Talley. *Port Economics*. Routledge, 2nd edition, 2017. doi:10.4324/9781315667720.
- [21] Mark Buzinkay. Container terminal: What is operations planning?, Apr 2023. URL: <https://www.identecsolutions.com/news/container-terminal-operations-planning>.
- [22] S. Mahdi Homayouni and Dalila B. M. M. Fontes. Energy-Efficient Scheduling of In-terminal Container Transport. In Maude Josée Blondin, João Pedro Fernandes Trovão, Hicham Chaoui, and Panos M. Pardalos, editors, *Intelligent Control and Smart Energy Management*, Springer Optimization and Its Applications, pages 155–186. Springer, July 2022. URL: [https://ideas.repec.org/h/spr/spochp/978-3-030-84474-5\\_6.html](https://ideas.repec.org/h/spr/spochp/978-3-030-84474-5_6.html), doi:10.1007/978-3-030-84474-5\_6.html.
- [23] Amir Gharehgozli, Nima Zaerpour, and Rene de Koster. Container terminal layout design: transition and future. *Maritime Economics and Logistics*, 22:610–639, 12 2020. doi:10.1057/s41278-019-00131-9.
- [24] S. Mahdi Homayouni and Dalila B.M.M. Fontes. A review of maritime operations, 2018. doi:10.1002/9781119483151.ch1.
- [25] Shawn Choo and B Eng. The crane split and sequencing problem with clearance and yard congestion constraints in container terminal ports, 2005.

- [26] Civil Engineering. Phd thesis strategies for improving import yard performance at container marine terminals author : Enrique martín alcalde phd supervisor : Dr . sergi saurí marchán. 2014.
- [27] Byung Kwon Lee and Kap Hwan Kim. Optimizing the yard layout in container terminals. *OR Spectrum*, 35:363–398, 3 2013. doi:10.1007/s00291-012-0298-z.
- [28] Gideon Mbiydenyuy. An optimization model for sea port equipment configuration case study: Karlshamn-klaipeda short sea shipping link, 2007. URL: [www.bth.se/tek](http://www.bth.se/tek).
- [29] Iris F.A. Vis and Kees Jan Roodbergen. Scheduling of container storage and retrieval. *Operations Research*, 57(2):456–467, 2009. doi:10.1287/opre.1080.0621.
- [30] Sonja Hansen. Two new hybrid rubber-tired gantry cranes (RTGs) to be installed in yidong terminal, port of shanghai. <https://corvusenergy.com/two-new-hybrid-rubber-tired-gantry-cranes-rtgs-powered-by-corvus-energy-to-be-installed-in-yidong-terminal-port-of-shanghai/>, July 2015. Accessed: 2023-3-17.
- [31] Rail mounted gantry Crane\_OverheadCraneManufacturer. <https://www.zazmae.com/Crane/14.html>. Accessed: 2023-3-17.
- [32] Chin I. Liu, Hossein Jula, and Petros A. Ioannou. Design, simulation, and evaluation of automated container terminals. *IEEE Transactions on Intelligent Transportation Systems*, 3:12–26, 2002. doi:10.1109/6979.994792.
- [33] Chao Mi, Yage Huang, Changhong Fu, Zhiwei Zhang, and Octavian Postolache. Ieee instrumentation measurement magazine vision-based measurement: Actualities and developing trends in automated container terminals, 2021.
- [34] Hang Yu, Yiyun Deng, Leijie Zhang, Xin Xiao, and Caimao Tan. Yard operations and management in automated container terminals: A review, 3 2022. doi:10.3390/su14063419.
- [35] Elif Demir, Tanzer Satir, Neslihan Dogan-Saglamtimur, and Ufuk Çalışkan. Energy efficiency in ports with a green port perspective: A conceptual framework. 03 2022.
- [36] Zhu Li, Chen Jun Feng, and Duan Jun Ya. Air Pollution and Control of Cargo Handling Equipments in Ports. *E3S Web of Conferences*, 93, 2019. doi:10.1051/e3sconf/20199302001.
- [37] Yi Chih Yang. Operating strategies of CO2 reduction for a container terminal based on carbon footprint perspective. *Journal of Cleaner Production*, 141:472–480, 2017. URL: <http://dx.doi.org/10.1016/j.jclepro.2016.09.132>, doi:10.1016/j.jclepro.2016.09.132.
- [38] Damla Kizilay and Deniz Türsel Eliiyi. A comprehensive review of quay crane scheduling, yard operations and integrations thereof in container terminals. *Flexible Services and Manufacturing Journal*, 33, 3 2021. doi:10.1007/s10696-020-09385-5.
- [39] Yun Peng, Wenyuan Wang, Ke Liu, Xiangda Li, and Qi Tian. The Impact of the allocation of facilities on reducing carbon emissions from a green container terminal perspective. *Sustainability (Switzerland)*, 10(6), 2018. doi:10.3390/su10061813.

- [40] Dayong Yu, Dong Li, Mei Sha, and Dali Zhang. Carbon-efficient deployment of electric rubber-tyred gantry cranes in container terminals with workload uncertainty. *European Journal of Operational Research*, 275(2):552–569, 2019. URL: <https://doi.org/10.1016/j.ejor.2018.12.003>, doi:10.1016/j.ejor.2018.12.003.
- [41] Jerry Banks. Introduction to simulation. *Winter Simulation Conference Proceedings*, 1:7–13, 1999. doi:10.1145/324138.324142.
- [42] Andrei Borshchev and A Filippov. From system dynamics and discrete event to practical agent based modeling: Reasons, techniques, tools. 01 2004.
- [43] Panagiotis Angeloudis and Michael G.H. Bell. A review of container terminal simulation models, sep 2011. doi:10.1080/03088839.2011.597448.
- [44] Grigoryev. Anylogic 8 in three days, 2022.
- [45] Pawel Pawlewski, Paulina Golinska, and Paul-Eric Dossou. Application potential of agent based simulation and discrete event simulation in enterprise integration modelling concepts. *ADCAIJ: Advances in Distributed Computing and Artificial Intelligence Journal*, 1:33–42, 7 2013. doi:10.14201/adcaij2012113342.
- [46] Jon Andersson. Proceedings of the 2011 winter simulation conference, wsc 2011. *Proceedings - Winter Simulation Conference*, pages 891–902, 2011.
- [47] Romão Santos, César Toscano, and Jorge Pinho de Sousa. A new simulation-based approach in the design of manufacturing systems and real-time decision making. *IFAC-PapersOnLine*, 54:282–287, 2021. URL: <https://doi.org/10.1016/j.ifacol.2021.08.033>, doi:10.1016/j.ifacol.2021.08.033.
- [48] Branislav Dragović, Ernestos Tzannatos, and Nam Kuy Park. Simulation modelling in ports and container terminals: literature overview and analysis by research field, application area and tool. *Flexible Services and Manufacturing Journal*, 29:4–34, 3 2017. doi:10.1007/s10696-016-9239-5.
- [49] Y. C. Ho and S. H. Chien. A simulation study on the performance of task-determination rules and delivery-dispatching rules for multiple-load AGVs. *International Journal of Production Research*, 44(20):4193–4222, 2006. doi:10.1080/00207540500442401.
- [50] D. Espinet F. Soriguera and F. Robuste. A Simulation Model for Straddle Carrier Operational Assessment in a Marine Container Terminal. *Journal of Maritime Research*, III(2):19–34, 2006. arXiv:arXiv:1011.1669v3.
- [51] Carlos Arango, Pablo Cortés, Luis Onieva, and Alejandro Escudero-Santana. Simulation-optimization models for the dynamic berth allocation problem. *Computer-Aided Civil and Infrastructure Engineering*, 28:769–779, 09 2013. doi:10.1111/mice.12049.
- [52] Carlos Arango, Pablo Cortés, Jesús Muñuzuri, and Luis Onieva. Simulation model for berth allocation planning in seville inland port. *International Conference on Harbour, Maritime and Multimodal Logistics Modelling and Simulation*, 1:55–60, 01 2010.
- [53] D.-H. Lee, J Cao, and Q Shi. Analysis of the container terminal traffic with productivity constraints: A simulation approach, 2007.



- [54] Pasquale Legato, Pietro Canonaco, and Rina M. Mazza. Yard crane management by simulation and optimisation. *Maritime Economics and Logistics*, 11(1):36–57, 2009. doi:[10.1057/mel.2008.23](https://doi.org/10.1057/mel.2008.23).
- [55] Carlos Arango. A simulation model for the management for containers internal transport in a seaport. *Cuadernos de Administración*, 35:95–108, 06 2019. doi:[10.25100/cdea.v35i64.7705](https://doi.org/10.25100/cdea.v35i64.7705).
- [56] OneStep Power. Container shipping. <https://www.onestepower.com/post/container-shipping>, dec 2021. Accessed: 7 june 2023.
- [57] Frank Meisel and Matthias Wichmann. Container sequencing for quay cranes with internal reshuffles. *OR Spectrum*, 32:569–591, 7 2010. doi:[10.1007/s00291-009-0191-6](https://doi.org/10.1007/s00291-009-0191-6).
- [58] Technical data typical quayside crane\* typical widespan crane\* typical feeder-panamax crane\*. URL: [www.liebherr.com](http://www.liebherr.com).
- [59] Ning Ma, Chenhao Zhou, and Aloisius Stephen. Simulation model and performance evaluation of battery-powered agv systems in automated container terminals. *Simulation Modelling Practice and Theory*, 106, 1 2021. doi:[10.1016/j.simpat.2020.102146](https://doi.org/10.1016/j.simpat.2020.102146).
- [60] Roni Permana Saputra and Estiko Rijanto. Automatic Guided Vehicles System and Its Coordination Control for Containers Terminal Logistics Application. *arXiv e-prints*, page arXiv:2104.08331, March 2021. arXiv:[2104.08331](https://arxiv.org/abs/2104.08331), doi:[10.48550/arXiv.2104.08331](https://doi.org/10.48550/arXiv.2104.08331).
- [61] Battery-electric agvs clean air in ports, 2013.
- [62] Enrique; Serrano Martínez. *Preliminary Design of an Automatic Guided Vehicle (AGV) System*. PhD thesis, 2018.
- [63] Sep 2022. URL: <https://container-news.com/hhla-completes-agv-charging-infrastructure-project-at-container-terminal-altenwerder/>.
- [64] Mohamed K. Watfa and Khaldon Al Karmadi. Connected automated guided vehicles in a smart container terminal. volume 533. Institute of Physics Publishing, 2019. doi:[10.1088/1757-899X/533/1/012029](https://doi.org/10.1088/1757-899X/533/1/012029).
- [65] Giancarlo Fortino, Man IEEE Systems, modellistica Università degli studi della Calabria. Dipartimento di ingegneria informatica, Université de technologie de Compiègne, Institute of Electrical, and Electronics Engineers. *Proceedings of the 2015 IEEE 19th International Conference on Computer Supported Cooperative Work in Design (CSCWD) : May 6-8, 2015, Calabria, Italy*.
- [66] Pablo Terán Cobo supervisor and Sergi Saurí Marchán. Optimization of yard operations in container terminals from an energy efficiency approach, 2016.
- [67] Byung Kwon Lee and Kap Hwan Kim. Performance evaluation of yard cranes in container terminals, 2006.
- [68] O. Ugurlu, Ercan Yuksekyildiz, and E. Kose. Simulation model on determining of port capacity and queue size: A case study for botas ceyhan marine terminal. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 8:143–150, 3 2014. doi:[10.12716/1001.08.01.16](https://doi.org/10.12716/1001.08.01.16).

- [69] Ahmed Hamdy. Optimization of automated guided vehicles (agv) fleet size with optimization of automated guided vehicles (agv) fleet size with incorporation of battery management incorporation of battery management. URL: [https://digitalcommons.odu.edu/emse\\_etds/169](https://digitalcommons.odu.edu/emse_etds/169), doi:10.25777/n2vs-4122.
- [70] Onur Derse and Elifcan Göçmen. Issue: 1 date, 2018.
- [71] Nordgren. Flexsim simulation environment. In *Proceedings of the 2003 Winter Simulation Conference, 2003.*, volume 1, pages 197–200 Vol.1, 2003. doi:10.1109/WSC.2003.1261424.
- [72] FlexSim. FlexSim Documentation: ASRS Vehicle, 2022. Accessed: June 16, 2023. URL: <https://docs.flexsim.com/en/20.2/Reference/3DObjects/TaskExecuters/ASRSvehicle/ASRSvehicle.html>.
- [73] Anmol Kapoor. What is dijkstra’s algorithm? here’s how to implement it with example?, Feb 2023. URL: <https://www.simplilearn.com/tutorials/cyber-security-tutorial/what-is-dijkstras-algorithm>.