Efficient Inter Terminal Container Transport using Amphibious Vehicles

A Simulation Approach

Master Thesis

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by

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Abstract

In the 21^{st} century, maritime landscape is confronted with issues such as congestion and delays due to the ever increasing maritime trade volumes. This thesis explores the possibility of utilising the concept of amphibious vehicles as a potential solution to address the issue of congestion and enabling the autonomous container terminal operations. For this research, an agent based model is developed to study the impact of amphibious vehicles on space optimization and reduction of material handling equipment within a given port region. The study analyses the performance of the proposed concept over several key performance indicators such as time taken by a handling equipment from origin to destination, container throughput, handling equipment fleet size and container demand fulfilment rate. The developed simulation model is then applied to the chosen case study of the port of Rotterdam. Additionally, the study also performs a sensitivity analysis to simulate how container demand variations affects the efficiency of logistic chains with these amphibious vehicles. This thesis highlights the effect of these amphibious vehicles on tackling problems faced by container terminals due to increased global trade. Through an extensive analysis of existing literature and developed model, this thesis provides valuable insights into the future of container terminal operations.

Keywords— Transshipment, Amphibious AGV, Inter Terminal Transport, Globalisation, Container Re-Handling Points, Agent Based Modelling, Genetic Algorithm

Preface

This thesis is the culmination of my graduation project for the Masters program in Mechanical Engineering with a specialization in Multi-Machine Engineering at Delft University of Technology. It represents the conclusion of extensive research and analysis conducted in the field of container inter-terminal transport(ITT) using amphibious vehicles.

I would like to express my sincere gratitude to all the individuals who have been instrumental in the completion of this thesis. First and foremost, I am deeply thankful to my supervisor, Dr. Jovana Jovanova. Whose guidance and support have been instrumental throughout every stage of this project. Her expertise and insights have greatly contributed towards the development and direction of the thesis. I thank her for believing in the concept of Amphibious AGVs.

I extend my deepest appreciation to Dr. Lavanya Meherishi for her invaluable feedback that has always challenged me to surpass my limits and deliver my best work. Each meeting with her was an intense and enlightening experience that helped me gain knowledge and clarity about my research goals. I would also like to express my gratitude to my chair, Prof.Dr.Ir. Dingena Schott, for her critical feedback. Her expertise and attention to detail greatly contributed to the refinement and improvement of the thesis, elevating its overall quality. Undoubtedly, this journey was not without its challenges. Yet, these challenges became opportunities for growth and refinement, ultimately shaping the trajectory of this thesis.

I would like to express my heartfelt gratitude to my family and friends. I am forever indebted to my parents for their unconditional support and their unwavering belief in me. This educational journey would not have been possible without them. I would also like to thank my brother, who has been my biggest cheerleader since my childhood. I would like to thank all my friends for supporting me throughout my Masters's phase and making life fun in this beautiful country. Lastly, I want to express my appreciation to my close friends in India who were always just a phone call away when I needed someone to talk to.

With the completion of my graduation project, my time at Delft University of Technology also officially comes to an end. Reflecting on these two years, I take great pride in knowing I have successfully navigated through this roller coaster and emerged stronger. I am thankful for the friendships I have made and the valuable life lessons I have learned. I am looking forward to the new adventures and challenges that are in stock for the future. I hope this thesis contributes towards the existing body of knowledge on container transport and serves as a valuable resource for researchers, corporate companies and policy makers in the field of transportation and logistics.

Vijay Sathya Ghiridharan
Delft, November 2023

Summary

This thesis presents an extensive research in the applicability of Amphibious Autonomous Guided Vehicles(AAGVs or Amphibious AGVs) for inter terminal container transport, addressing the identified research gap is in the field of port operations. Amphibious AGVs work exactly like standard AGVs but have the ability to traverse in water. The motive of this research is to find out if Amphibious AGVs contribute towards the operational performance of a container terminal. To do so, the following research question is formulated:

How does the use of Amphibious AGVs in the context of container port operations improve the productivity of Inter Terminal Transport(ITT)?

To answer this research question, several sub questions were explored. The first sub question is focused on identifying a suitable strategy to quantify and compare different modes of inter terminal transport. A thorough literature review was conducted to find out the suitable strategy. Through this review, it was determined that a simulation model is needed to quantify logistic chains. In order to create a realistic scenario, the utilization of the handling equipment is to be optimized. This realistic scenario is developed using agent based simulation with genetic algorithm for optimization .

The second sub question revolves around the impact of implementing Amphibious AGVs on port equipment interaction. The logistic chains were devised for various traditional handling equipment and Amphibious AGVs for container inter terminal transport from which the key performance indicator number of re-handling points was determined. This KPI is important to address the delays and the need for variety of handling equipment to establish a logistic process. It is found that AAGVs have the least amount of container re handling points due to their capability to traverse on both land and water.

The third sub question is focused on the extent of integration of Amphibious AGVs to improve port efficiency with respect to the current/traditional logistics chains. An agent based model is developed to simulate the drafted logistic chains and their performance is compared case and equipment wise for KPIs like time taken by a handling equipment from origin to destination, container throughput, handling equipment fleet size and container demand fulfilment rate. Upon using the developed model to a case study - the port of Rotterdam, across all cases, trucks and AAGVs have an edge over barges in terms of these KPIs. The performance of Trucks and AAGVs are found to be similar over a transport network.

The fourth sub question revolves around the profile of routes and scenarios that are beneficial to be handled by Amphibious AGVs. The transport network is broken into individual routes and the performance KPIs are compared for different modes of inter terminal transport. In general, the results depict that AAGVs have an edge over trucks when the distance to reach a destination is at least twice as greater than the amphibious route. AAGVs are very useful to be employed for the scenario of transport of containers from a vessel in one terminal to another vessel at the destination terminal. AAGVs also have an edge when the number of re handling points are greater for road transport.

The fifth sub question is focused on the potential amount of space that can be generated and the possible ways to utilize this additional space. It is seen that, employing Amphibious AGVs clears up the operation schedule of handling equipment that were traditionally used for transfer at re handling points. These handling equipment can be used to supplement other logistic chains. In this process, making more barge berths available by reducing the need for barges for short range inter terminal transport. Additionally a sensitivity analysis is performed to understand how these KPIs fluctuate with respect to variation in demand. This analysis depicts that AAGVs are suitable to transport a greater demand of containers over a short distance.

This thesis is aimed to closely emulate real life conditions, with certain assumptions playing a crucial role. Recommendations include applying the generic model for other ports in order to understand the efficacy of Amphibious AGVs globally, applying this to the whole route network in the port of Rotterdam and conducting a cost benefit analysis. Future research can explore sustainability aspect of AAGVs and develop a digital twin for inter terminal transport using agent based modelling. Finally, it can be said that this thesis serves as an initial exploration of the applicability of amphibious vehicles in the context of efficient port operations.

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Nomenclature

Abbreviations

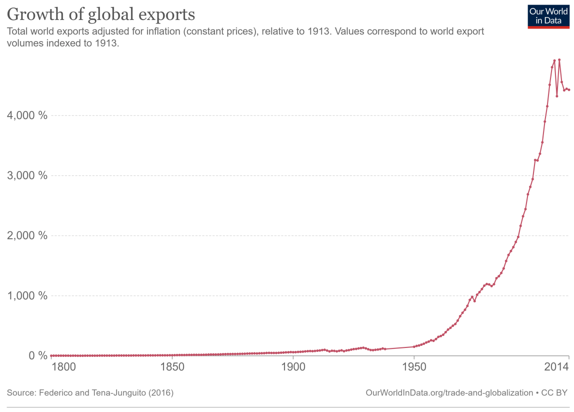
Abbreviation	Definition
AAGV	Amphibious Autonomous Guided Vehicle
AGV	Autonomous Guided Vehicle
GDP	Gross Domestic Product
APAC	Asia and Pacific
EMEA	Europe, the Middle East and Africa
AMER	North, Central and South America
TEU	Twenty Feet Equivalent Unit
ITT	Inter Terminal Transport
KPI	Key Performance Indicators
MBSE	Model Based Systems Engineering
SysML	Systems Modelling Language
OSM	Open Street Map
DOE	Design ofExperiment
P&D	Pick & Deliver
GA	Genetic Algorithm
GIS	Geographic Information System
QC	Quay Crane
ASC	Autonomous Stacking Crane
GC	Gantry Crane
FIFO	First In First Out
OCR	Optical Character Recognition
CER	Container Exchange Route
RWG	Rotterdam World Gateway
APMT MVII	APM Terminals Maasvlakte 2
ECT	Europe Container Terminals

Chapter 1

Introduction

1.1 Background and Motivation

The integration of national economies into a global economic system has been one of the most important developments of the last century. This process of integration, often called Globalization, has materialized in a remarkable growth in trade between countries. Figure 1.1, shows the value of world exports over the period 1800 to 2014. An extraordinary growth in international trade is seen in the last couple centuries. Exports in 2014 were 400 times that in 1913 [17][79]. Figure 1.2, shows how trade has grown more that proportionately with GDP. With the world economy experiencing sustained positive economic growth([117][65][24]), the changes in GDP that is offered by trade is enormous. Up to 1870, the sum of worldwide exports accounted for less than 10% of GDP. In 2014, the value of exported goods around the world is close to 25%. This shows that over the last hundred years of economic growth, there has been more than proportional growth in global trade [10][79].


Growth of global exports

Total world exports adjusted for inflation (constant prices), relative to 1913. Values correspond to world export volumes indexed to 1913.

Source: Federico and Tena-Junguito (2016)

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Figure 1.1: Growth of Global Exports, [17]


Value of exported goods as share of GDP, 1827 to 2014

Estimates correspond to merchandise export-to-GDP ratios.

Source: Fouquin and Hugot (CEPII 2016)

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Figure 1.2: GDP share of the exported goods, [10]

In an era defined by connectivity and technology, globalization stands as the beacon guiding the course of human progress. This phenomenon transcends borders, cultures, and economies, weaving a complex web of interdependence across the globe. At the heart of this transformation process lies maritime trade. The surge in globalization has resulted in an unprecedented surge in maritime commerce which reshaped economies and industries. Advancements in transportation technologies, exemplified by the containerization revolution, have played a pivotal role in the expansion of maritime trade. Containerization streamlined the process of loading and unloading cargo, drastically reducing transit times and costs. This breakthrough allowed for the efficient movement of goods on a scale previously unimaginable, catalyzing a surge in maritime commerce. Figure 1.3 exhibits the growth of world container turnover from 2013 to 2022 with a forecast till 2027. The Container throughput data is divided based on Regions namely APAC(Asia and Pacific), EMEA(Europe, the Middle East and Africa) and AMER(North, Central and South America). Starting with a overall 642 million twenty feet equivalent unit (TEU) in 2013 and increasing to 861 million TEU in 2022, world container turnover is expected to reach almost 1000 million TEU in 2027[30].

Since their introduction in the 1960s, containers represent the standard unit load concept for international freight. The transshipment of containers between different parties in a supply chain involves manufacturers, freight forwarders, shipping lines, transfer facilities, and customers. Container terminals primarily serve as an interface between different modes of transportation, e.g., domestic rail or truck transportation and deep sea maritime transport. As globally acting industrial companies have considerably increased their production capacities in Asian countries, the container traffic between Asia and the rest of

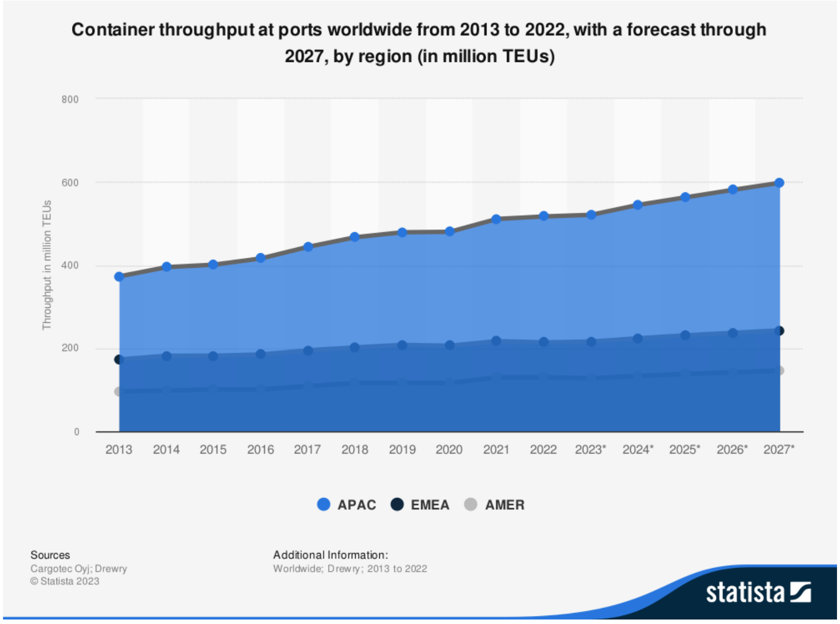


Figure 1.3: Container throughput at ports worldwide from 2013 to 2022, with a forecast through 2027 by region,[30][60]

the world has steadily increased [116]. For instance, from 1980 to 2021, the volume of international seaborne container trade increased from 0.1 billion tons to 1.95 billion tons, which is an increase almost by 2000% over 40 years[118]. Improvements in ship and maritime terminals have facilitated the flows of freight, particularly containerized traffic [101]. Weight-wise, about 80% of the world trade is carried by maritime transportation, which account for 70% of its value. About half of this trade is handled by large container ships linking producers and consumers along sea lanes. This transportation system is organized around major maritime transport gateways where continental trade converges, namely Shanghai, Hong Kong, Singapore and Busan for Pacific Asia, Rotterdam and Antwerp for Europe and Los Angeles and New York for North America, among the largest container ports in the world [89].

Containers have played a vital role in the standardisation of various Port Equipment. The Standardisation and the low cost of container boxes have made them the foremost choice of transportation means in the global international trade [8]. Containers are Unit Load Devices used for shipping in the world of Marine Transport. Container transport takes place by road, rail, inland waterway, and maritime traffic networks. The delivery of containers from the supplier to customer involves the following scope:

When a ship arrives at a terminal, the containers destined for that particular terminal and port are unloaded and then the new containers are loaded before the ship resumes its journey. This process of loading and unloading containers is called serving a vessel [71]. Vessels are served at a terminal in the port. A container terminal acts as a transshipment node in a container transport network. The container transshipment opportunities pre- and post- container terminal. An example of such container flow options are depicted in Figure 1.4.

The demand for terminals to perform such tasks with ease and efficiency is becoming greater day by day due to the increase in the fleet size of shipping companies and the increase in the carrying capacity of the new ships as a result of globalisation [109]. Due to this more containers will have to be handled by the ports. The Port authorities have issues dealing with this increase in containers due to unavailability of new space for expansion near ports.

This increasing container traffic causes congestion in ports, which cause issues like delays, reduce in efficiency and increase in costs. Congestion can lead to delays in ship movements, cargo handling, and other port operations, which can result in financial losses and reputation damage for port operators and shipping lines. Congestion can reduce the efficiency of port operations, as ships and cargo may have to wait in the harbor for longer periods, causing bottlenecks and reducing the overall throughput of the port.

As seen in the 145-year-old Suez Canal, spanning 72 kilometers, which stands as the swiftest route connection between Europe and Asia through Port Said. This strategic passage is increasingly vulnerable to congestion, prompting the Egyptian government to contemplate expansion. Container ships dominate this route, making logistics precision crucial. Any delays or congestion here could reverberate across supply chains, leading to extended transit times, elevated costs, inventory imbalances, disrupted contracts, and reputational damage. Such disruptions might even prompt a shift in shipping routes, impacting

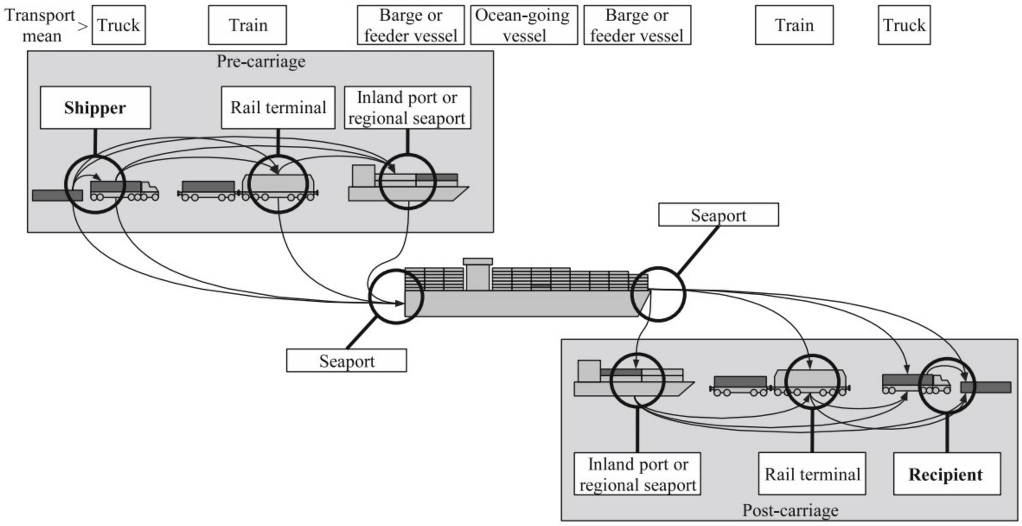


Figure 1.4: Container Transshipment Opportunities, [71]

market stability and potentially spurring regulatory changes.The consequences of congestion at the Suez Canal and Port Said for the logistics and supply chain between Europe and Asia are significant. These include the potential diversion of container ships bound for Asia/Europe towards the Cape of Good Hope and the Gulf of Guinea. Moreover, delays in cargo delivery could result in defaults on trade agreements made by shippers. This congestion may disrupt inventory levels for traders and manufacturers, either due to non-receipt of cargo or the inability to ship out goods as planned. This could lead to missed sales opportunities and incurring demurrage charges on ship charter. Additionally, there may be an increase in port costs and anchorage bills. Ultimately, these issues not only affect global trade but also have economic implications for Egypt [28]. Hence, addressing this is very important.

The operations in a container terminal are predominantly divided based on the area at which tasks are being done, namely Quay Side, Land Side and Yard Side. The Equipment used in these areas are also divided. Equipment such as Quay Cranes, Deep Sea Vessel and Barge interact with the Quay Side. While equipment such as Automated Guided Vehicle, Stacker Cranes, Fork Lifts, Reach Stackers, Straddle Carrier, Multi-Trailer System, Gantry Cranes and Yard Truck are used in the Yard Side. Equipment like Trucks and Trains are used on the Gate/land Side for Inter Terminal Transport. This interaction can be seen in Figure 1.5.

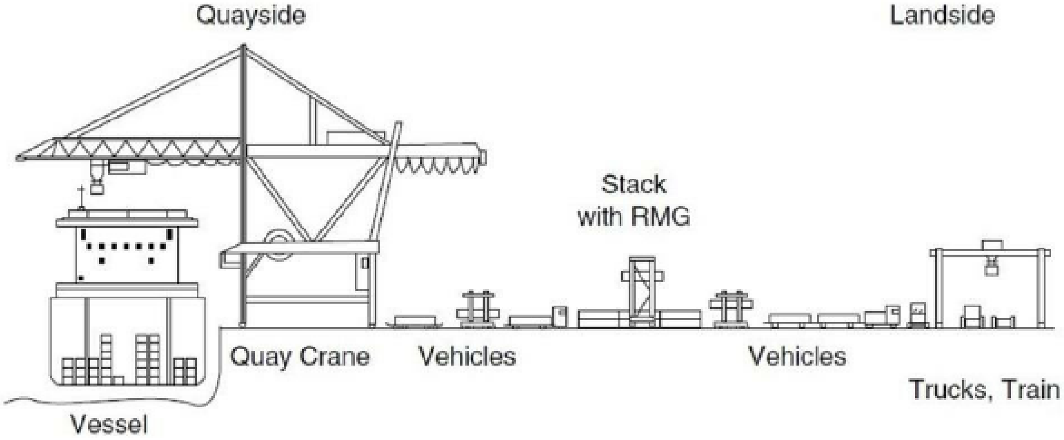


Figure 1.5: Example for Container Transshipment at the port, [22][115]

As the handling equipment are confined there is an increase in container re-handling points. Increase in re-handling points can lead to delays like:

1. Shortage of Container Handling Equipment [5]

2. Yard Congestion [106]
3. Gate Processing Delays [61]
4. Poor Inter-modal Connectivity [110]

These operational delays have significant implications on the efficiency of container Terminal. Therefore, it is crucial for terminal operators to address this. These delays can be eradicated with the help of unifying container handling equipment on all the sides. One potential solution would be a single piece of equipment that can perform all or most of the container handling operations. Based on this idea, this thesis explores the concept of amphibious vehicles.

Another Challenge for Deep Sea Ports situated on the banks of a river is hinterland transport. These Ports have a natural deep-water harbor, which allows large vessels to access the ports. These ports have an inner harbor that serves as a sheltered area for ships to dock and unload cargo. They have multiple terminals, each dedicated to handling different types of cargo, such as containers, bulk cargo, and liquid bulk cargo. These ports have an outer harbor that serves as a buffer zone between the open sea and the inner harbor, providing additional shelter for ships. The ports have road and rail connections that allow for efficient transportation of cargo to and from the hinterland. Some ports have barge connections for hinterland transport. There are also differences in the layout of these ports, reflecting their unique geographic and operational characteristics. For example, Rotterdam and Hamburg have more extensive canal and inland waterway networks[90][84][51]. Such Ports exist in all around the world and act as a gateway to connect Deep Sea Container Transport to Inland Ports. A list of Such Ports that have container Terminals can be seen in table 1.1.

Table 1.1: List of Major Ports that facilitate hinterland transport

Port	Inland Water Way
Rotterdam, NL	Located on the Rhine River Delta
Antwerp, BE	Connected to the Scheldt River
Hamburg, DE	Connected to the Elbe River
Le Havre, FR	Connected to the Seine River
Amsterdam, NL	Connected to the North Sea Canal
New Orleans, US	Located on the Mississippi River
Baltimore, US	Located on the Chesapeake Bay
Shanghai, CN	Located on the Yangtze River Delta

Thus, it can be observed that there is an Industrial scope of Improving the transshipment process. This can been seen as a research gap in the field of Port Operations. Port Operational equipment are predominantly divided based on whether if it is Movable or Immovable, Which side of the port is it used, What are the degrees of freedom and the range of tasks it can perform. For Ports like Rotterdam, Hamburg and Thessaloniki the shortest distance or the least time taking route between terminals need not always be by Land or Water. The use of an amphibious vehicle could be ideal. These Amphibious Vehicles are used in the real world for various other purposes like Amphibious Assault Vehicles and Hovercraft in the Military [1].

1.2 Amphibious AGV : A Novel Concept

Amphibious AGVs are Amphibious Vehicles which can be employed in the field of Container Terminal Operations expected to replace AGVs and barges in the context of operation. An Amphibious AGV works exactly like and AGV but with the capability of traversing on water whenever required. This novel concept was developed based on the existence of various other usage of amphibious vehicle. In an earlier report, an Amphibious Automatic Guided Vehicle (AAGV) was designed. The design of this AAGV was based on existing normal AGVs in terms of dimensions, power drives and battery features. Additionally, this AAGV has the ability to transfer from land to water, and vice versa, autonomously by various conceptual transfer systems, float steadily in calm port waters, and sail itself In the design, close attention was paid to interaction with existing port equipment and machinery to be compatible in the port without the need of expensive investments. The only investments necessary will be a system for the battery replacement system and the water-land transfer systems. The final design of the AAGV portrayed in water mode and land mode can be seen in Figure 1.6.

Table 1.2: Comparing Equipment Similar to AAGV

Material Handling Equipment	**Quay Side**	Amphibious AGV	Feeder Vessel	Barge
	Yard Side		AGV	ALV
	Land Side		Multi Trailer System	Truck

From table 1.2 it is seen that Amphibious Automated Guided Vehicle is capable of Interacting with all three sides of the port. This is capable of replacing an Automated Guided Vehicle, Multi Trailer System, Truck and Barge. On comparing table 1.2

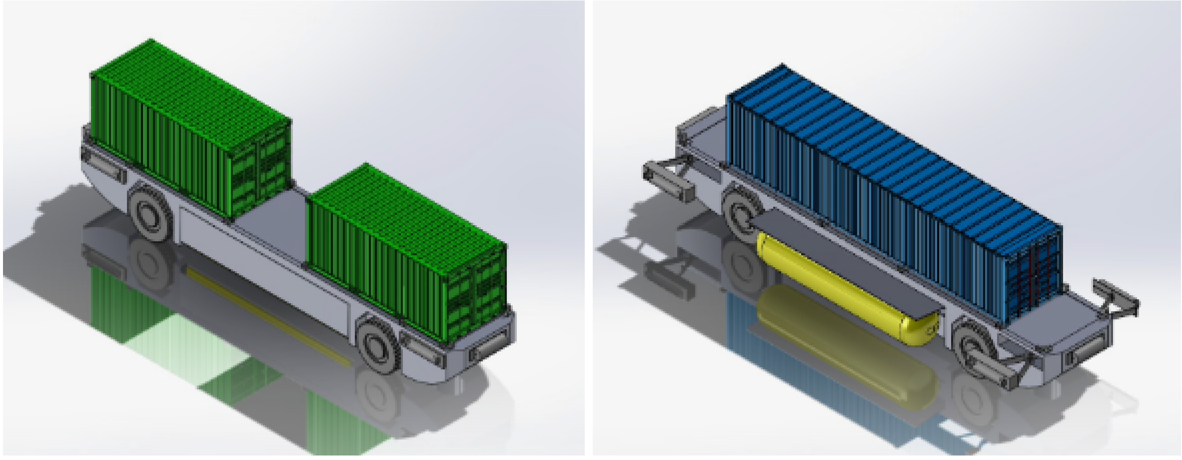


Figure 1.6: Amphibious AGV in Land Mode(left) and Water Mode(right), [11]

to the way handling equipment are confined to the side of usage, we see the potential for Amphibious AGVs to reduce the number of material handling equipment required for container transshipment.

Table 1.3: Comparison of Equipment tasks

Material Handling Equipment	Function:
Amphibious Automated Guided Vehicle	For a single Container over a Short Distance on Land and Water
Automated Guided Vehicle	For a single Container over a Short Distance on Land
Multi Trailer System	For multiple Containers over a Short Distance on Land
Yard Truck	For a single Container over a Short Distance on Land
Truck	For a single Container over Mid or Long Range Distance on Land
Barge	For multiple Containers over Mid or Long Range Distance on Water

The design specifications and performance details about Amphibious AGVs can be found in appendix.

1.3 Research Questions

From the previous sections, it can be understood that for the transport of container from one point to another there is an interaction between multiple material handling equipment. This leads to multiple container re-handling points between Quayside, Yardside and Landside equipment. With the rise in container transportation due to the ever increasing globalisation, ports need to address the issue of container storage either by creating more space or by optimizing transshipment. As highlighted in [53], Amphibious Vehicle technologies can decrease the transportation costs and this emerging technology also has far-reaching applications and implications beyond all current expectations. This leads to the following question:

How does the use of Amphibious AGVs in the context of container port operations improve the productivity of Inter Terminal Transport(ITT)?

1. What is a suitable strategy to quantify and compare different modes of ITT?
2. What is the impact of implementing Amphibious AGVs on port equipment interaction?
3. To what extent can the integration of Amphibious AGVs improve port efficiency with respect to the current logistic chains?
4. What profile of Routes and Scenarios are beneficial to be handled by Amphibious AGVs?
5. What is the potential amount of space that can be generated and what are the possible ways to utilize this additional space?

1.4 Research Methodology

Figure 1.7 outlines the research methodology employed to obtain results, compare, discuss and conclude this thesis. A literature review is first done on container Port, handling equipment and Autonomous operations to identify the issues faced. Recommendations were given on the use of various new concepts and technologies to address the issues. This review can be found in Literature Assignment - Report Number:2023.MME.8799. This research is into the applicability of Amphibious AGV for Container ITT. The research questions are devised based on this concept. Then a second literature review is performed on selecting the suitable Modelling Strategy. An extensive research on various Simulation and Optimization techniques and ultimately choosing the suitable strategy. The next step was to explore and understand how the logistic chain would change with respect to the current logistics chain for container inter-terminal transport(ITT). Then a model is developed to compare these two logistic chain based on KPIs like time, throughput, fleet size etc. After a model is developed, in order to have a quantitative comparison a case study is chosen to which this model is used. For this research the chosen case study is on the Port of Rotterdam. The KPI results are obtained and then these results are discussed. Based on these results, understandings are made and the thesis is concluded.

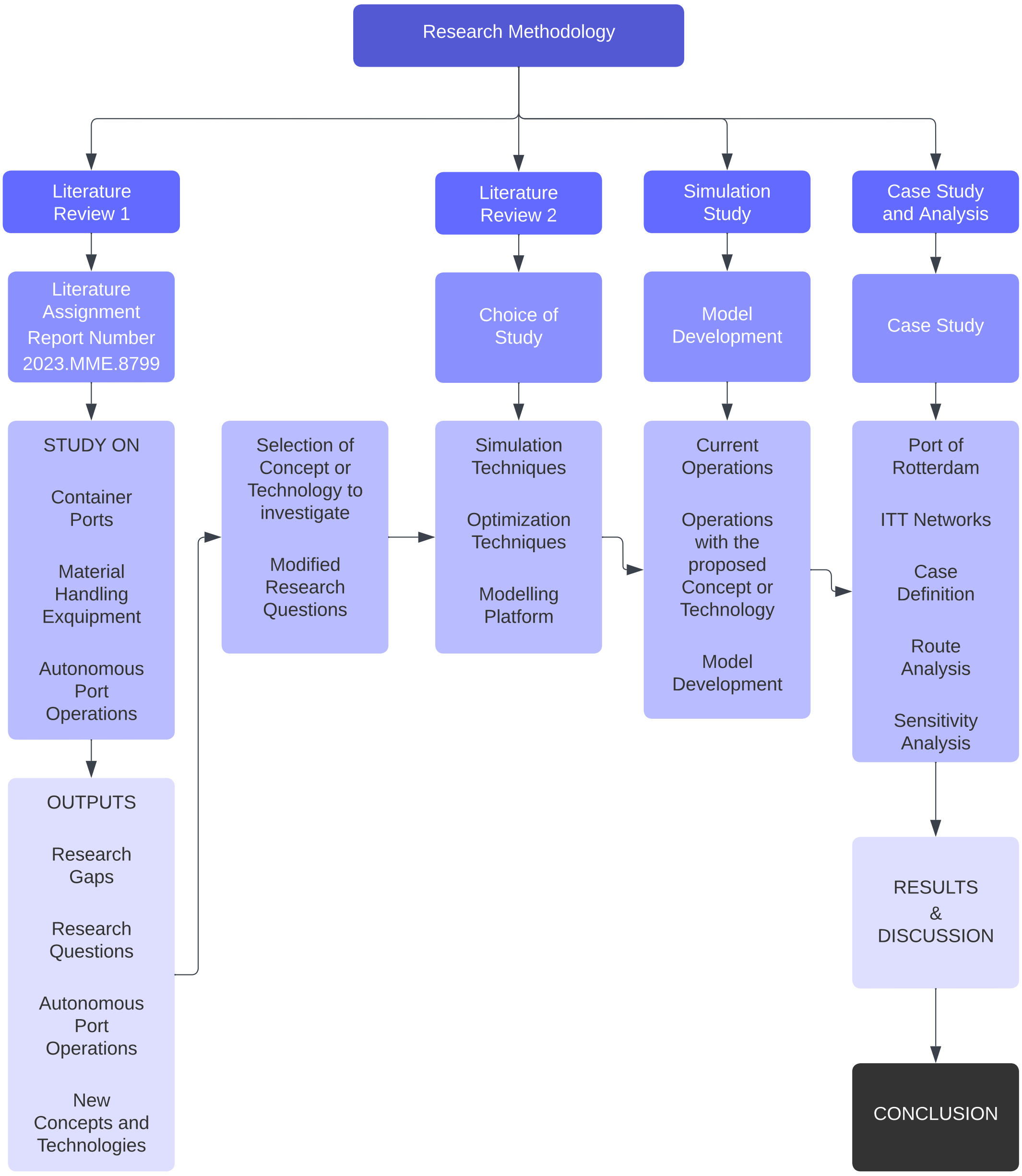


Figure 1.7: Research Flow

1.5 Structure of Report

The structure of the thesis report is as shown in Figure 1.8 and will be described as follows. Chapter 1 is the introduction where the research problem, research scope and the research questions are explained. In chapter 2, literature review is performed to choose the suitable strategy for modelling and quantifying various logistic chains to compare different modes of Inter Terminal Transport. Further in Chapter 3, the methodology of this thesis is explained. It covers information about the Scenarios and Cases that are to be simulated, followed by a explanation about the developed model. Chapter 4 is the application of the developed model to the chosen case study. Port of Rotterdam is chosen as the case study for this thesis. The Results are computed and discussed in this chapter as well. The thesis is concluded in Chapter 5, with an additional discussion on limitations and recommendations towards future research directions in this field. This figure also shows the sections in which the sub research questions are answered, culminating in the answer to the main research question.

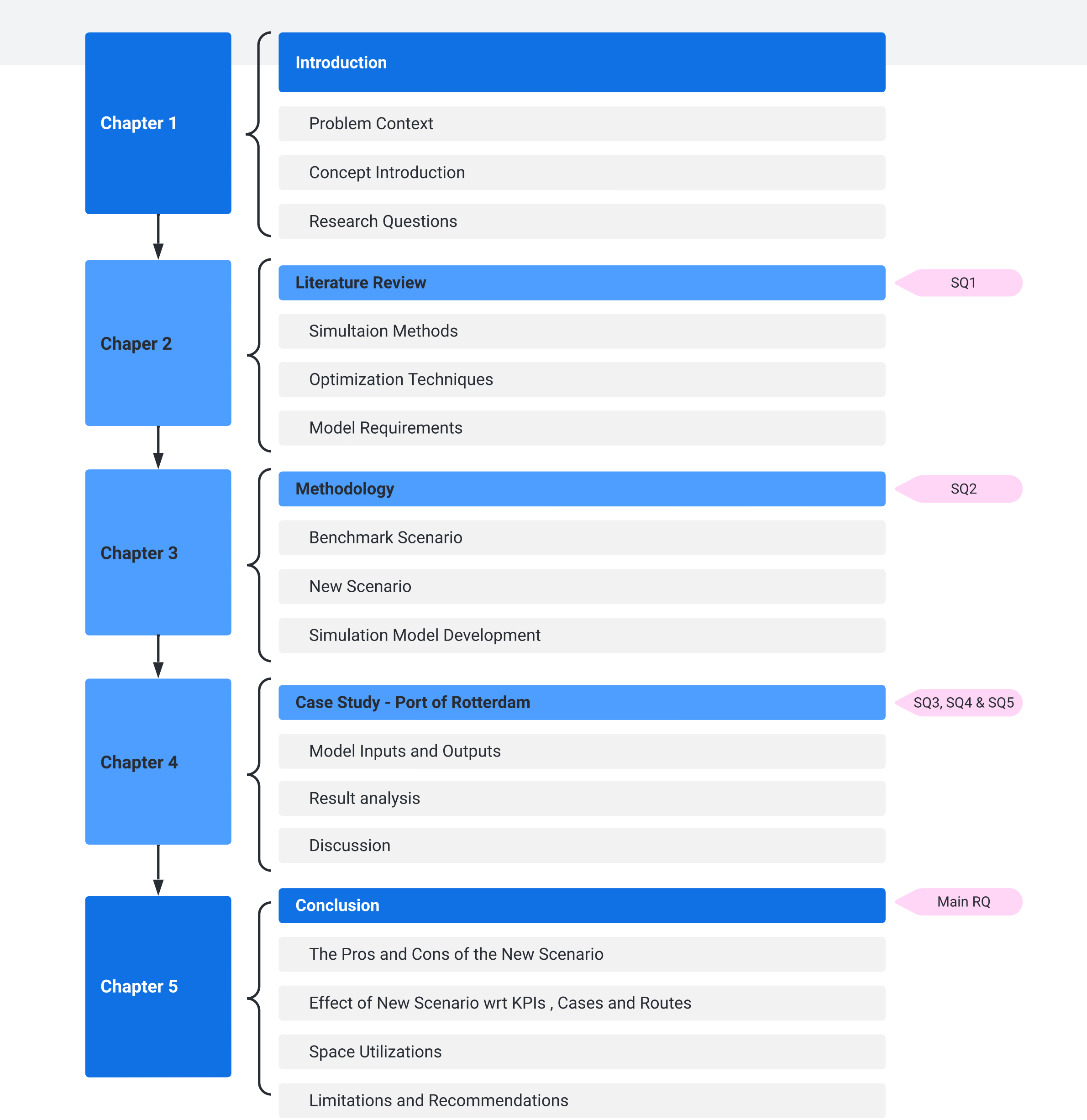


Figure 1.8: Report Outline

Chapter 2

Literature Review

In this chapter, a comprehensive exploration of modeling methodologies relevant to logistic process simulation(refer 2.1), vehicle routing(refer 2.1.1), process optimization(refer 2.2), fleet sizing and fleet utilization(refer 2.2.1) has been conducted through a thorough literature review. Various scholarly sources in these domains have been analyzed to identify prevalent methods, their applications, and their effectiveness in addressing similar research questions. The choice of modeling methodology for this research will be informed by the insights gleaned from existing literature, ensuring a well-informed decision aligned with the established practices and proven effectiveness in similar studies. This study is crucial as it can help understand the required problem solving strategy to help quantify the performance of various logistics chains and obtain the required Key Performance Indicators (KPIs) that are required to compare logistic processes.

2.1 Simulation

The design of a process has to be evaluated for it's performance before it's implementation the real world. This can be evaluated with the help of a simulation tool. Simulation is a cost effective mechanism to evaluate process design [67]. If the system is required to mimic real time processes(like ITT) in terms of interaction, Agent Based Model should be used. Agent Based Models are used to simulate autonomous agents with their actions and interactions to observe the effects on the whole network, instead of traditional models that only simulate system-wide behaviours [55]. Model based Systems Engineering (MBSE) is another way of understanding interaction between various stakeholders [95].

In paper [100], Systems Modelling Language (SysML) is used to define a model based planning process for Manufacturing System Planning (MSP). A similar Model Based Systems Engineering (MBSE) approach could be adapted for logistic processes. Modeling in SysML provides two key advantages. Firstly, it establishes a shared understanding through a domain-specific language, presented in a clear and easily comprehensible graphical format. Secondly, beyond mere structural depiction (which can be achieved with flow charts or similar visual aids), the model also facilitates analysis, enhancing its utility [59]. There are quite some challenges of using MBSE as well. It deviates from traditional MSP methods, potentially leading to resistance. Expertise in MBSE and SysML is essential, and SysML's abstract graphical elements may limit accurate representation. Modeling and evaluating design variants is not explicitly covered. Larger scope models can be confusing, especially if created by non-experts. Standardized libraries for manufacturing entities are not available.

As an ITT system changes state instantaneously, a discrete event simulation can also be used. Discrete event simulation offers a quantitative representation of real-world phenomena. It simulates the dynamics of the real world event by event. This method provides a comprehensive understanding of process operations, identifies queue formations, and assesses the potential impact of proposed enhancements on overall system performance [55]. Discrete event simulation has found widespread application in complex logistical and production systems. It has been instrumental in analyzing operations in bulk terminals [13], enhancing warehouse efficiency [96], and optimizing production schedules [92]. In the context of ports, discrete simulation has predominantly been employed in studying container terminals. From a modeling perspective, the transfer system in a container terminal shares similarities with the ITT system, employing vehicles for the transportation of containers between specific origins and destinations. In discrete event simulations, a fundamental component is the operation routine responsible for overseeing the event calendar and simulation clock [80]. The specifics of this routine are contingent upon the underlying worldview and can be structured around events, activities, or processes [96].

2.1.1 Vehicle Routing

Vehicle routing using Open Street Map (OSM) is a process that aims to find the most efficient routes for a fleet of vehicles to visit a set of locations. OSM contributes towards a more precise representation of real-time routes or probable routes and how they are affected by the local geography. This can be instrumental in various applications like logistics, delivery services, ride-sharing, and more. The process involves two key steps: Data Preparation and Route Planning.

Obtaining precise map data from Open Street Map (OSM) is the initial step in vehicle routing. This data, rich in geographic details, can be sourced from official channels or specialized providers. Geo coding converts addresses into coordinates, facilitating accurate location identification. Pre processing refines the data, extracting key information like road networks and traffic rules [29].

The pre-processed data is transformed into a graph, where nodes represent intersections and edges signify roads. This graph forms the basis for route calculation. Utilizing routing algorithms like Dijkstra's or A* [98], the system identifies the most efficient path between locations. Constraints like one-way streets, vehicle type, and time windows are integrated, ensuring practical routes. These steps lay the foundation for more advanced optimization and deployment [29].

2.1.2 Model Requirement

Simulation is a powerful tool for cutting costs and increasing throughput at ports and container terminals. It enables deep insight and provides a risk-free environment to develop plans. Port and terminal simulation can be used for detailed internal logistics analysis, decision support, risk mitigation, and disruption response. Upon careful examination of these methodologies, it is evident that agent-based modeling presents several advantages for addressing the specific research problem. As noted in [64], one key strength of agent-based modeling over other simulation approaches like systems dynamics and discrete event simulation lies in its ability to account for well-defined behaviors and decisions of actors, dynamic strategic interactions, and relationships between actors, along with spatial components. Furthermore, agent-based models do not necessitate a constant state of equilibrium, a departure from economic models. They can also incorporate the bounded rationality often observed in real-life scenarios. However, it is important to acknowledge the limitations of this method. For instance, in cases where the model lacks equilibrium, a single definitive solution may not emerge. Nonetheless, this mirrors the inherent complexity of the real world. Another constraint is that, depending on the complexity and volume of interactions modeled, practical limitations may arise regarding the number of agents that can be effectively simulated on a standard computer [87].

2.2 Optimization

There are two algorithms for solving problems: exact and approximation algorithms. Exact algorithms are guaranteed to identify and verify an optimal solution and prove its optimality for the required condition or show that no feasible solution exists. If optimal solutions cannot be computed quickly enough in practice, it is common to trade the guarantee of optimality for efficiency. The assurance of finding optimal solutions is sacrificed to get very good solutions by using approximate algorithms in a reasonable amount of time [105]. There are two types of Exact Algorithms: Design of Experiment (DOE) and Mathematical Iterative search. DOE efficiently uncovers factor effects and interactions. Its factorial designs and Response Surface Methodology enhance data-driven decision-making in engineering, manufacturing, and research [73]. Mathematical Iterative Search focuses on optimizing an objective function through iterative exploration of the solution space. This algorithms is applied to incrementally adjust variables until an optimal solution is achieved. This method excels in scenarios where precise solutions are challenging or the objective function is noisy [120]. Examples of DOE are Taguchi Method[18], Factorial Design[56] and Response Surface Design methodology[75] and examples of Mathematical iterative search are Dynamic Programming[88], Non-linear Programming and Linear Programming [119]. The Approximation algorithms are used to are Little faster than exact algorithms. These algorithms are divided into Meta-Heuristics and Problem Specific Search. Examples of Meta-Heuristics searches are Genetic Algorithm[122], Simulated Annealing[82] and Tabu Search[57] and examples of Problem Specific Search are Greedy Algorithm[74] and Randomized Rounding algorithm[25][104].

2.2.1 Fleet Sizing and Utilisation

Routing strategies and rules play a crucial role in determining the number of Material handling Equipment required in a system, along with factors like Pick & Deliver (P&D) locations. This consideration, commonly referred to as fleet sizing, is based on various parameters such as transport load demands, time constraints, AGV capacity, speed, routing, traffic management, assignment, and P&D locations, as outlined in [114]. Paper [111] emphasized the significance of response time in fleet size calculations, aiming to minimize idle travel time until the next pickup [114]. This reduction in non-value-added time contributes to an overall decrease in total transport time. Paper [114] further examined the minimization of the maximum response time with strategically positioned waiting points in an AGV system. They conducted a comparative analysis between a single loop pattern and mathematical model, noting that computational time increased with model size, and genetic algorithms could be optimized using the mathematical model [112][97].

2.2.2 Model Requirement

Optimizing utilization is a critical endeavor in resource-constrained environments, as it directly impacts efficiency and productivity across various domains. One potent approach to this challenge is the application of Genetic Algorithms (GAs), which draw inspiration from the process of natural selection to navigate complex solution spaces. They evolve a population of solutions, guided by a fitness function, through selection, crossover, and mutation operations. GAs excel in global search, adaptability, and robustness, making them versatile for various optimization problems [43][4][31]. Their applications range from resource allocation and manufacturing optimization to transportation and logistics [16]. By harnessing the evolutionary principles underlying natural selection, Genetic Algorithms offer a competitive advantage in achieving maximum efficiency and productivity. Their impact is evident in resource allocation, production process optimization, and transportation and logistics, underscoring their significance in the modern landscape of optimization methodologies.

2.3 Discussion and Conclusion

Based on the model requirements, it is understood that Agent based simulation with Genetic algorithm optimization is required to design and evaluate logistic processes. A software platform has to be chosen in order to implement the chosen mechanism. The leading platforms that are used to model and evaluate logistics process are AnyLogic[2] and Arena[3]. Both these platforms offer a combination of Agent Based Modelling and Genetic Algorithm based optimization. There is also a need to declare Geographic locations and mimic real time routes, there is a need to use Open Street Maps [78]. The GIS map feature is very crucial to model the scenarios as per the chosen Case Study as seen in Chapter 4. This feature is missing in Arena. A comparison between Arena and AnyLogic can be seen in table 2.1.

Table 2.1: Modelling Platform Comparison, [2][3]

Feature	AnyLogic	Arena
Company	The AnyLogic Company	Rockwell Automation
Simulation Types	Discrete-event, Agent-based, System Dynamics	Discrete-event, Agent-based
Modeling Capabilities	Wide range of modeling paradigms including agent-based, discrete event, and system dynamics.	Primarily focused on discrete-event modeling.
Industry Applications	Manufacturing, Logistics, Supply Chain, Healthcare, Transportation, Energy, etc.	Manufacturing, Supply Chain, Service Operations, Healthcare, etc.
Language	Proprietary modeling language and Java for advanced customization.	No built-in programming language.
3D Modeling	Supports 3D visualization and modeling.	Primarily 2D modeling.
Optimization	Built-in optimization tools.	Limited optimization capabilities.
Output Analysis	Comprehensive output analysis tools and data visualization capabilities.	Offers a range of output analysis tools.
Documentation	Extensive documentation, tutorials, and user forums.	Comprehensive documentation and user community.
Licensing	Personal Learning Edition has a limit of 10 agents per simulation.	Student Version has a limit of 100 entities.
Cross-Platform	Windows, Linux, macOS	Windows
Support	Technical support available through the vendor.	Technical support available through Rockwell Automation.

From Table 2.1, a decision can be made that the most suitable modelling platform for this research is AnyLogic. AnyLogic offers the a GIS interface through OSM which enables the usage of the real time routes in order to ensure the reality of ITT is mimicked properly. Agent based modelling helps in understanding the interaction between multiple material handling equipment required to establish the process. Genetic algorithm optimization is used to optimize the process as accurate as possible at the least time possible. These selections for simulation, optimization and platform are used to build a digital twin for the futuristic process of ITT as shown in Chapter 3.

Chapter 3

Methodology

This chapter delves into understanding the cases that are to be modelled, optimized and simulated. This chapter introduces the benchmark scenario which highlights the current logistic chains for container ITT. In order to understand this scenario more in depth, four cases are developed based on situation and requirement. These four cases are compared based on their benchmark current logistic chains and the new logistics chains employing Amphibious AGVs. In order to have quantifiable data to compare Agent Based Modelling is used to model these logistic chains. All these Models are done on AnyLogic: Personal Learning Edition 8.8.3.

3.1 Benchmark: The Current Logistic Chain

This section sheds light on how logistics operations are being carried currently. Figure 3.1 shows a pictorial representation of a general process. When a deep sea vessel arrives on the quay side, it is moored at the quay and then the vessel is served with the help of a quay crane(s). These containers are then transferred to the yard with the help of an AGV. Once the AGV arrives at the yard, the stacking crane helps in arranging the container in the yard. If the container has a truck as a land side agent, the ASC places the container on the truck. If the container has a barge as a land side agent, the AGV picks up the container from the stack with the help of ASC and takes it to the barge quay where a quay crane loads the container onto a barge. If the container has a rail as a land side agent, the AGV picks up the container from the stack with the help of ASC and transfers to the Rail GC where the container is loaded onto a train.

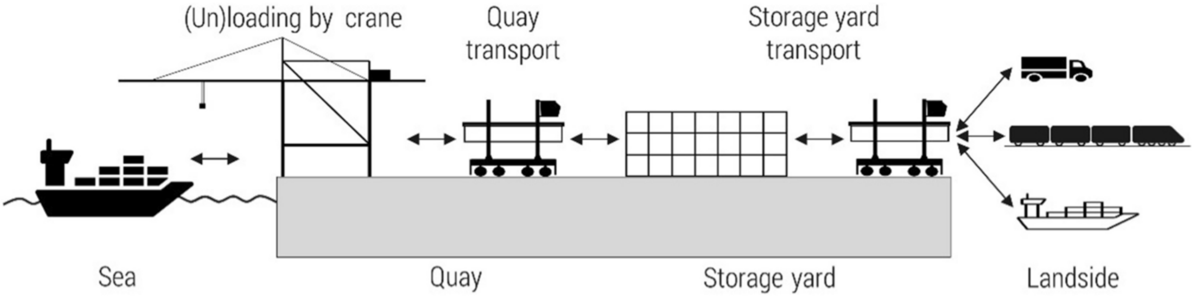


Figure 3.1: Container Re-Handling Points, [7]

In order to understand the container handling process between terminals in depth, the logistic chain design is split into four cases. The cases are as follows:

1. Container Transport from Storage to Storage (SS)
2. Container Transport from one Vessel to another Vessel (VV)
3. Container Transport from Storage to a Vessel (SV)
4. Container Transport from a Vessel to Storage (VS)

These logistic chains help in understanding the number of container **Re-Handling Points** involved in order to fulfill a particular process based on the case. The following subsections delve into the four cases and their respective sub cases based on the mode of inter terminal handling equipment.

3.1.1 Case SS: Container Transport from Storage to Storage

This is a scenario where the logistics chain is designed in order for a container to get from the storage yard of a container terminal to the storage yard of another terminal. Every scenario is explained with logistic chains for each sub case. The boxes in yellow depict the handling equipment used for horizontal movement or transportation of containers and the boxes in red depict the container handling equipment used for transfer of containers. This diagram key is common for all logistic chain in this research. The sub cases are explained as follows

Case SS-T

The Container from the yard is handled by the Autonomous Stacking Crane and placed on a Truck. This Truck Travels by road, passing the land side gate and reaches the other terminal's storage yard. The Autonomous Stacking Crane unloads the container from this truck and is stacked in the Storage Yard. The logistic chain is shown in figure 3.2. There are two Container Re-Handling Points in this logistic chain.

Figure 3.2: Storage to Storage Transfer with a Truck

Case SS-B

The Container from the yard is handled by the Autonomous Stacking Crane and placed on an AGV. This AGV travels from the Yard Area to the Barge Quay of the same terminal. Upon it's arrival in the Quay Area a Quay Crane handles the Container and loads it onto the barge. Upon the barge being optimally loaded, it sets sail to the required terminal following the barge route shown in figure 4.2 and 4.3. Then it arrives at the destination terminal. The Barge is Moored and then the containers are unloaded with the help of a Quay Crane. The Quay Crane places the container on an AGV for it's transfer to the storage yard. Once the AGV arrives at the yard area, the Autonomous Stacking Crane handles the container and stacks it in the Storage Yard. The logistic chain is shown in figure 3.3. There are four Container Re-Handling Points in this logistic chain.

Figure 3.3: Storage to Storage Transfer with a Barge

3.1.2 Case VV: Container Transport from one Vessel to another Vessel

This is a scenario where the logistics chain is designed in order for a container to get from a Vessel at a container terminal to another Vessel docked at another container terminal. This is like FIFO(First In First Out) for Containers or Kiss and Ride of the Container with respect to the terminal.

Case VV-T

The Container is unloaded by a Quay Crane from the vessel and placed on an AGV. This AGV then helps in the transport of container from the Deep Sea Quay to the Yard Area. This Container from the yard is handled by the Autonomous Stacking Crane and placed on a Truck. This Truck Travels by road, passing the land side gate and reaches the other terminal's storage yard. The Autonomous Stacking Crane unloads the container from this truck and is moved to the other side and placed on an AGV. This AGV transports the container form the Yard Area to the Deep Sea Quay, where a Quay crane handles the container and loads it onto a vessel. The logistic chain is shown in figure 3.4. There are four Container Re-Handling Points in this logistic chain.

Figure 3.4: Vessel to Vessel Transfer with a Truck

Case VV-B

The Container is unloaded by a Quay Crane from the vessel and placed on an AGV. This AGV travels from the Deep Sea Quay Area to the Barge Quay of the same terminal. Upon it's arrival in the Quay Area a Quay Crane handles the Container and loads it onto the barge. Upon the barge being optimally loaded, it sets sail to the required terminal following the barge route shown in figure 4.2 and 4.3. Then it arrives at the destination terminal. The Barge is Moored and then the containers are unloaded with the help of a Quay Crane. The Quay Crane places the container on an AGV for it's transfer to the Deep Sea Quay. Once the AGV arrives at the Deep Sea Quay, the Quay Crane handles the container and loads it onto the Vessel. The logistic chain is shown in figure 3.5. There are four Container Re-Handling Points in this logistic chain.

Figure 3.5: Vessel to Vessel Transfer with a Barge

3.1.3 Case SV: Container Transport from Storage to a Vessel

This is a scenario where the logistics chain is designed in order for a container to get from the Storage Yard of a container terminal to a Vessel docked at another container terminal. This scenario is the Kiss and Ride of the container at destination.

Case SV-T

The Container from the yard is handled by the Autonomous Stacking Crane and placed on a Truck. This Truck Travels by road, passing the land side gate and reaches the other terminal's storage yard. The Autonomous Stacking Crane unloads the container from this truck, takes it to the pther side of the yard and drops it on an AGV. This AGV takes this container till the Deep Sea Quay from where a Quay Crane picks up the container and loads the Vessel. The logistic chain is shown in figure 3.6. There are three Container Re-Handling Points in this logistic chain.

Figure 3.6: Storage to Vessel Transfer with a Truck

Case SV-B

The Container from the yard is handled by the Autonomous Stacking Crane and placed on an AGV. This AGV travels from the Yard Area to the Barge Quay of the same terminal. Upon it's arrival in the Quay Area a Quay Crane handles the Container and loads it onto the barge. Upon the barge being optimally loaded, it sets sail to the required terminal following the barge route shown in figure 4.2 and 4.3. Then it arrives at the destination terminal. The Barge is Moored and then the containers are unloaded with the help of a Quay Crane. The Quay Crane places the container on an AGV for it's transfer to the Deep Sea Quay. Once the AGV arrives at the deep sea quay, the Quay Crane handles the container and loads it onto the Vessel. The logistic chain is shown in figure 3.7. There are four Container Re-Handling Points in this logistic chain.

Figure 3.7: Storage to Vessel Transfer with a Barge

3.1.4 Case VS: Container Transport from a Vessel to Storage

This is a scenario where the logistics chain is designed in order for a container to get from a Vessel at a container terminal to the Storage Yard of another terminal. This scenario is the Kiss and Ride of the container upon arrival.

Case VS-T

The Container is unloaded by a Quay Crane from the vessel and placed on an AGV. This AGV then helps in the transport of container from the Deep Sea Quay to the Yard Area. This Container from the yard is handled by the Autonomous Stacking Crane and placed on a Truck. This Truck Travels by road, passing the land side gate and reaches the other terminal's storage yard. The Autonomous Stacking Crane unloads the container from this truck and stacks it in the storage yard. The logistic chain is shown in figure 3.8. There are three Container Re-Handling Points in this logistic chain.

Figure 3.8: Vessel to Storage Transfer with a Truck

Case VS-B

The Container is unloaded by a Quay Crane from the vessel and placed on an AGV. This AGV travels from the Deep Sea Quay Area to the Barge Quay of the same terminal. Upon it's arrival in the Quay Area a Quay Crane handles the Container and loads it onto the barge. Upon the barge being optimally loaded, it sets sail to the required terminal following the barge route shown in figure 4.2 and 4.3. Then it arrives at the destination terminal. The Barge is Moored and then the containers are unloaded with the help of a Quay Crane. The Quay Crane places the container on an AGV for it's transfer to the storage yard. Once the AGV arrives at the yard area, the Autonomous Stacking Crane handles the container and stacks it in the Storage Yard. The logistic chain is shown in figure 3.9. There are four Container Re-Handling Points in this logistic chain.

Figure 3.9: Vessel to Storage Transfer with a Barge

3.2 Container Transport by AAGV

This section sheds light on how the logistics chain would look if Amphibious AGVS are used in the same scenarios as discussed in section 3.1.

3.2.1 The New Logistics Chain

Case SS-A: Container Transport from Storage to Storage

The Container from the yard is handled by an Autonomous Stacking Crane and placed on an Amphibious AGV. This Amphibious AGV drives on road from the Yard Area to the Ramp of that particular terminal. While on the ramp the AAGV inflates it's side pods and changes into water mode. This AAGV upon entering the water moves to the ramp of the destination terminal.

When on this ramp the AAGV deflates and comes back to Land Mode. Upon entering the Quay, the AAGV then drives to the Storage Yard where the Container is picked by an Autonomous Stacking Crane and stacked in the yard. The logistic chain is shown in figure 3.10. There are two Container Re-Handling Points in this logistic chain.

Figure 3.10: Storage to Storage Transfer with an AAGV

Case VV-A: Container Transport from one Vessel to another Vessel

The Container is unloaded from the vessel with the help of a Quay Crane and is placed on an Amphibious AGV. This Amphibious AGV drives on road from the Deep Sea Quay to the Ramp of that particular terminal. While on the ramp the AAGV inflates it’s side pods and changes into water mode. This AAGV upon entering the water moves to the ramp of the destination terminal. When on this ramp the AAGV deflates and comes back to Land Mode. Upon entering the Quay, the AAGV then drives to the Deep Sea Quay where the Container is picked by a Quay Crane and loaded onto a vessel. The logistic chain is shown in figure 3.11. There are two Container Re-Handling Points in this logistic chain.

Figure 3.11: Vessel to Vessel Transfer with an AAGV

Case SV-A: Container Transport from Storage to a Vessel

The Container from the yard is handled by an Autonomous Stacking Crane and placed on an Amphibious AGV. This Amphibious AGV drives on road from the Yard Area to the Ramp of that particular terminal. While on the ramp the AAGV inflates it’s side pods and changes into water mode. This AAGV upon entering the water moves to the ramp of the destination terminal. When on this ramp the AAGV deflates and comes back to Land Mode. Upon entering the Quay, the AAGV then drives to the Deep Sea Quay where the Container is picked by a Quay Crane and loaded onto a vessel.The logistic chain is shown in figure 3.12. There are two Container Re-Handling Points in this logistic chain.

Figure 3.12: Storage to Vessel Transfer with an AAGV

Case VS-A: Container Transport from a Vessel to Storage

The Container is unloaded from the vessel with the help of a Quay Crane and is placed on an Amphibious AGV. This Amphibious AGV drives on road from the Deep Sea Quay to the Ramp of that particular terminal. While on the ramp the AAGV inflates it’s side pods and changes into water mode. This AAGV upon entering the water moves to the ramp of the destination terminal. When on this ramp the AAGV deflates and comes back to Land Mode. Upon entering the Quay, the AAGV then drives to the Storage Yard where the Container is picked by an Autonomous Stacking Crane and stacked in the yard. The logistic chain is shown in figure 3.13. There are two Container Re-Handling Points in this logistic chain.

Figure 3.13: Vessel to Storage Transfer with an AAGV

3.3 Simulation Model

From all the information in Chapter 2, AnyLogic is chosen as the suitable modelling tool. Simulation modeling helps answer questions with verifiable statistics and visual feedback. AnyLogic can capture the dynamics of business processes without compromise, including internal logistics of ports and terminals[83]. AnyLogic offers a simulation platform, where Agent Based Modelling can be done using GIS (Geographic information system) Map. Agent Based Modelling is chosen in this scenario as it helps in modelling a real time chain and understand the behaviour and interaction of agents. The GIS Map helps finding routes using OSM(Open Street Map). It also has the option of using Genetic Algorithm for the optimization experiment. In order to model the logistic chain, the process modelling library is used.

3.3.1 Model Requirements

This Subsection sheds light on the expected outputs and required inputs of the Simulation Model. Figure 3.14 represents the inputs and outputs of the simulation model.

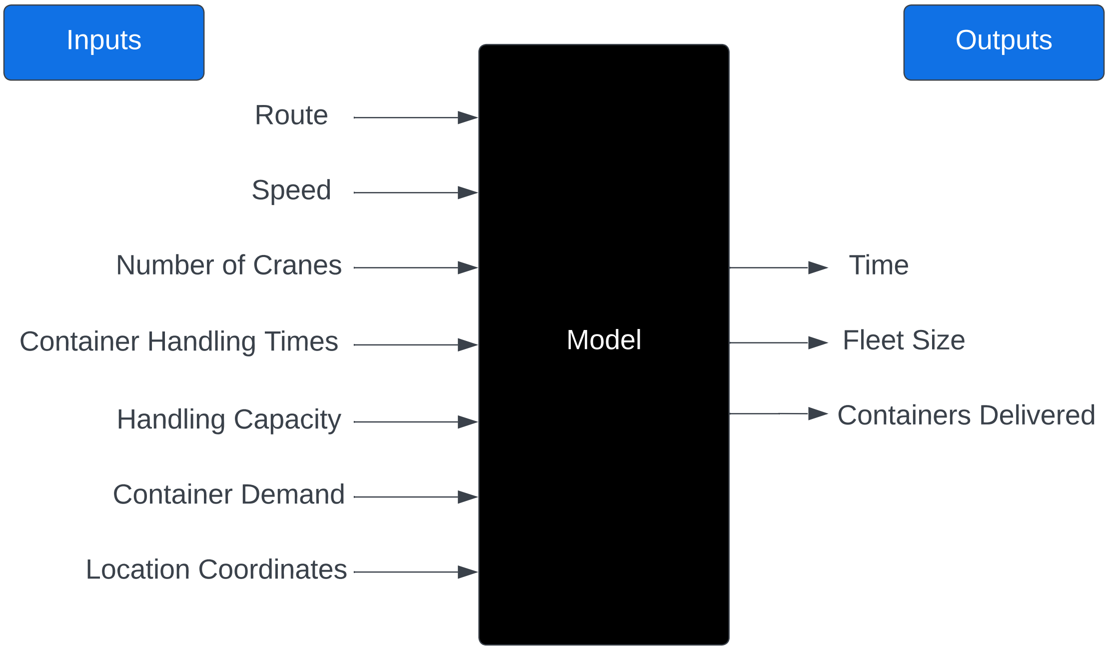


Figure 3.14: Inputs and Outputs of the Simulation Model

3.3.2 Stakeholder Agents

The list of agents that act as stakeholders in the logistic process that is to be modelled. These Agents are not always used in all simulations. These are used based on the presence in the given process. The various agents are:

Yard

The Yard Agent helps to specify the central location of the storage yard area where the process of stacking happens. This agent is used as with a prefix of Mother and Customer to identify the flow of containers. Containers flow from the Mother to the

Customer. The Mother is a single agent while the Customer is a population of agents. This is a static agent confined to it's coordinates.

Deep Sea Quay

The Deep Sea Quay Agent helps to specify the central location of the Deep Sea Quay Cranes where the loading and unloading process happens.This agent is used as with a prefix of Mother and Customer to identify the flow of containers. Containers flow from the Mother to the Customer. The Mother is a single agent while the Customer is a population of agents. This is a static agent confined to it's coordinates.

Barge Quay

The Barge Quay Agent helps to specify the central location of the Barge Quay Cranes where the loading and unloading of Barge happens.This agent is used as with a prefix of Mother and Customer to identify the flow of containers. Containers flow from the Mother to the Customer. The Mother is a single agent while the Customer is a population of agents. This is a static agent confined to it's coordinates.

AAGV Ramp

The AAGV Ramp Agent helps to specify the location of the AAGV where the process of transfer of AAGVs from land to water and vice versa happens. This agent is used as with a prefix of Mother and Customer to identify the flow of containers. Containers flow from the Mother to the Customer. The Mother is a single agent while the Customer is a population of agents. This is a static agent confined to it's coordinates.

Truck

The truck agent is designed to mimic the characteristics, attributes, and behaviors of a real-world truck. This includes factors such as capacity and speed. Truck agent interacts with various other agents within the Model like the Yard. This is a population of Agents and the location is confined to the Mother Yard. This a moving agent and it travels to and from a static agent as declared in the logistic process.

Barge

The barge agent is designed to mimic the characteristics, attributes, and behaviors of a real-world barge. This includes factors such as capacity and speed. Barge agent interacts with various other agents within the Model like the Barge Quay. This is a population of Agents and the location is confined to the Mother Barge Quay. This a moving agent and it travels to and from a static agent as declared in the logistic process.

AGV

The AGV agent is designed to mimic the characteristics, attributes, and behaviors of a real-world AGV. This includes factors such as capacity and speed. Truck agent interacts with various other agents within the Model like the Yard, Deep Sea Quay and Barge Quay. This is a population of Agents and the location is confined either to the Mother Yard, Mother Deep Sea Quay, Customer Barge Quay or Customer Yard based on the model scenario. This a moving agent and it travels to and from a static agent as declared in the logistic process.

AAGV

The AAGV agent is an experimental agent. It mimics real life factors of truck, barge and AGV such as capacity and speed. AAGV agent interacts with various other agents within the Model like the Yard. This is a population of Agents and the location is confined either to the Mother Yard or Mother Deep Sea Quay. This a moving agent and it travels to and from a static agent as declared in the logistic process.

Order

The Order agent is used to describe a demand for a process to be created. This agent is also responsible for assigning the orders to the vehicles to mimic the concept of the vehicle carrying the container. Here, the order agent depicts a 40 foot container(2 TEU). This does not have a confinement or representation in the GIS space but is a significant part of the process model.

3.3.3 Variables and Parameters

The Variables and Parameters of the model are:-

- Speed(Truck, Barge, AGV and AAGV)
- Container Handling Times(Quay Crane, ASC, On Ramp and Mooring)
- Capacity(Truck, Barge, AGV and AAGV)
- Container Demand(per day)
- Number of Cranes serving(Vessel and Barge)

These Parameters and Variables are used as inputs at various stages in the model.

3.3.4 State Chart Model

State Chart Model in AnyLogic is used to initiate a process. The state first enters to normal work where the terminals are at a base state where there is no requirement for Inter Terminal Transport. Then at a defined rate, the state changes from normal work to wanting details.

$$\text{Transition Rate} = \frac{\text{Container Demand}}{\text{Capacity of Material Handling Equipment}} \tag{3.1}$$

The wanting details state is a state which triggers the requirement for Inter Terminal Transport. The process of sending an order happens in this state. A new order object is created and then the order is sent to the Terminal from where the container originates in the process model. Post the order is delivered at the respective destination, a message is sent to the state chart model from the process model. Upon the receipt of this message, the state changes back to normal work. The model is as seen in figure 3.15.

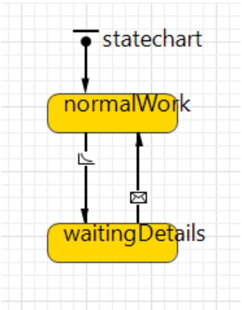


Figure 3.15: State Chart Model

3.3.5 Process Model

Process models in AnyLogic use mathematical representations to study how things move through systems. Diagrams with nodes and connections are used to show stages and steps. The entities, go through different states as per flow like moved to or being loaded. The chances of moving between states follow specific rules as mentioned in the action block of each process block. The Process blocks used to simulate this process are as listed in table 3.1.

Table 3.1: Process Model Blocks used to model the scenarios

Blocks	Usage
Resource Pool	Provides resource units that are seized and released by agents
Enter	Inserts agents created in the State Chart into the Process Model
Resource Task Start	Defines the start of the flowchart branch modeling the task process for resource units
Delay	Delays the agent by a certain time
Move To	Moves an agent from its current location to the new location
Seize	Seizes the number of units of the specified resource required by the agent
Release	Releases the resource unit previously seized by the agent
Resource Task End	Defines the end of the flowchart branch modeling the task process for resource units
Sink	Destroys the incoming agents

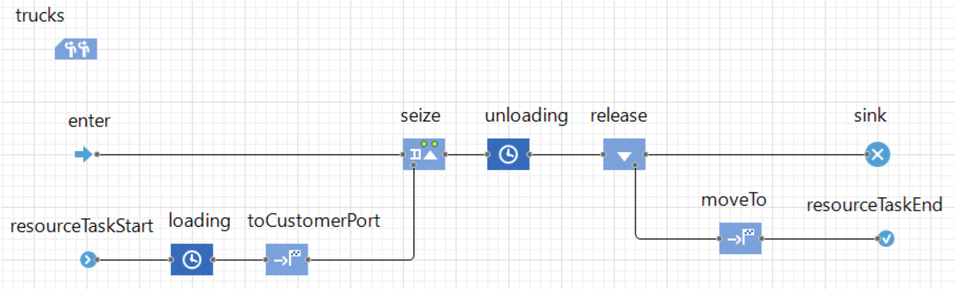


Figure 3.16: Process Model of a Truck delivery

Figure 3.16 depicts how the process blocks explained in table 3.1 are used to model a logistic chain. Here is a process model to mimic a basic logistic chain of *'Using a truck to deliver a container from a port to the Customer port(s)'*. The enter block takes the demand requirement order as a message rate from the State Chart Model (refer Subsection 3.15). This created demand is then seized by the seize block. At the same time a parallel process is created with a resource Task Start and the resource set assigned is the resource pool of trucks as shown above. The resource pool contains information like the agent that is the resource, speed and number of units. Then this resource task undergoes the process of container loading for which a delay block is used. The time taken is triangularly distributed [72] and the values vary for different handling equipment.

$$DelayTime = triangular(min, max, mode) \tag{3.2}$$

Where,

- Min - The minimum amount time taken for a particular process
- Max - The maximum amount time taken for a particular process
- Mode - The most likely amount of time taken for the process

This kind of distribution is used for unloading and barge mooring times as well. When delay block is used to represent an AAGV Ramp, it is uniformly distributed.

$$DelayTime = uniform(min, max) \tag{3.3}$$

Where, min is the minimum amount of time taken and max is the maximum amount time taken for a particular process. The difference in choice of distribution is based on the availability of data on average equipment handling times. Handling equipment like Quay Crane and Stacking Cranes have this data available as they are in operation currently. While data for Amphibious AGV ramp is based on theoretical values, hence a mode cannot be expected. Post the loading process the vehicle with the container is said to move towards the destination using the move To block. After it reaches the destination the order is assigned to the loaded vehicle in seize block. It accesses the client property of the truck object and retrieves the customer property of the order, then assigns the customer to the client property. Then this vehicle unloads as per the delay block at the destination and send a message "Delivered!" back to the State Chart Model. Then this vehicle is released from the order at the release block. The order is terminated at the sink block. The vehicle moves back to the assigned area or the initial location using the move To block, and upon arrival the vehicle which was the resource task is destroyed at resource task end. The Output from the model are container input, container output and the average **Time** taken to transport a container. Time is measured with time measure start and time measure end blocks placed before the loading process and after the release block respectively in the parallel process, shown in appendix. The graph illustrates the time distribution and the average time.

3.3.6 Optimization Experiment

An optimization experiment is required to ensure efficient usage of the resource units. To ensure this efficient usage, utilization of the resource unit has to be optimized. Utilization can be defined as:

$$\text{Utilization Rate} = \frac{\text{Number of Resource Units Being Used}}{\text{Total Number Of Resource Units}} \times 100 = \frac{\text{Demand(D)}}{\text{Fleet Size(V)}} \times 100[\%] \tag{3.4}$$

Therefore a Genetic Algorithm optimization is used to set agent utilization to a maximum of 85%. This percentage is assumed to be the upper limit of the operating window to ensure resource redundancy in unexpected situations.

Table 3.2: Indices, Sets, Parameters and Decision Variable

Indices and Sets	
i	Index of cases (i) $\forall i \in I$ = {SS-T, SS-B, SS-A, VV-T, VV-B, VV-A, SV-T, SV-B, SV-A, VS-T, VS-B, VS-A}
Parameters	
D_i	Number of resource units used in case i $\forall i \in I$
V_i	Total number of resource units in case i $\forall i \in I$
Decision Variable	
U_i	Utilization rate of resource unit in case i $\forall i \in I$ and $U_i = \frac{D_i}{V_i}$

Objective Function:
The objective function is to maximize the utilization of the total number of resource units in the system.

$$\text{Maximize} \quad U_i \quad \forall i \in I \tag{3.5}$$

Main Constraint:
This constraint ensures that the utilization rate is maintained lesser than or equal to the chosen optimality of 85%.

$$U_i \leq 85\% \quad \forall i \in I \tag{3.6}$$

Additional Constraint 1:
This constraint ensures that the demand parameter is lesser than the fleet size parameter. This is because the number of resource units used has to be lesser than the total number of resource units.

$$D_i \leq V_i \quad \forall i \in I \tag{3.7}$$

Additional Constraint 2:
This constraint ensures that the decision variable lies between 0 and 100%.

$$U_i \in [0, 100][\%] \quad \forall i \in I \tag{3.8}$$

Additional Constraint 3:
This constraint ensures that the demand parameter is always a natural number.

$$D_i \in N \quad \forall i \in I \tag{3.9}$$

Additional Constraint 4:
This constraint ensures that the fleet size parameter is always a natural number.

$$V_i \in N \quad \forall i \in I \tag{3.10}$$

Where,

- N is the set of natural numbers; N→ $[1, \infty)$
- Percentage is a positive real number

The objective is to maximize the truck utilization while ensuring it does not exceed 85%. This optimized value is used as the input to number of units that is in the resource for the given process. This optimized value is computed as the output for **Fleet Size**.

3.3.7 Data Analysis

The outputs of the simulation, as shown in Figure 3.14 are post processed to obtain KPIs such as throughput and fulfillment rate. This post processing is as shown in subsections as follows.

Throughput

Throughput is the rate at which a material moves through a system per unit time. Here, the material is a container and the throughput is computed as follows

$$\text{Throughput} = \frac{\text{Number of Containers at Sink}}{\text{Total Time of the System}} \times 2[\text{TEU per hour}] \tag{3.11}$$

Fulfillment Rate

Fulfillment rate is the ratio between containers that passed through the system with respect to the number of containers that were supposed to pass.

$$\text{Fulfillment Rate} = \frac{\text{Number of Containers at Sink}}{\text{Container Demand}} \times 100[\%] \tag{3.12}$$

The performance of a logistic chain is used to compare the efficiency of various logistic chains. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size and greater fulfillment rate. The order of Importance of this KPI is as follows

$$\text{Fulfillment Rate} \geq \text{Throughput} > \text{Fleet Size} >> \text{Time} \tag{3.13}$$

3.4 Conclusion

Within this chapter, an elaborate simulation model using agent based simulation with genetic algorithm optimization is modeled using AnyLogic. The model is subjected to thorough verification and validation processes with real time data for the benchmark scenarios, confirming its readiness for subsequent experimentation. In order to truly assess the model, a case study is chosen and additionally a comprehensive evaluation can only be achieved through experimentation. This application will be carried out in the next chapter using the Port of Rotterdam as a case study. The next chapter also focuses on the execution of experiments like route analysis and sensitivity analysis.

Chapter 4

Port of Rotterdam - a case study

This chapter is the application of the methodology described in Chapter 3 for one of the world's largest and busiest ports. For this research the Port of Rotterdam is chosen due to it's unique geography, the need for it to handle greater capacities and it's pivotal role in the maritime world. The Port of Rotterdam has solved the problem of space requirement due to the increasing transport quantities for now by expanding into the North Sea [21]. The Maasvlakte 2 expansion project involved creating a new land area of 2,000 hectares and extending the port's container terminal into the sea, adding 20 million TEUs of container storage capacity [62]. The expansion project also included the construction of a new deep-sea quay, which can accommodate the largest container ships in the world, improving the port's competitiveness and efficiency [107]. To increase the efficiency of port operations and as well as the speed of Container Storage, the port of Rotterdam has employed a container smart scanning technology. The Mobile OCR system enables seamless flow of Container information into the system. Keeping track of the containers arrival and exit. This Bar code has information such as the origin, allocated yard for storage, destination etc. This system can also take other information that will be useful for the logging of the terminal with respect to container liability.The performance of an OCR engine is critically dependent on the image-capturing sub-system. The image-capturing units must include an optical and illumination solution to produce images of the container ID number with sufficient quality (focus, resolution, contrast, and uniformity), under all operating and ambient conditions (sunlight, sun glare, night time, adverse weather conditions and dirt-covered numbers)[23]. The port of Rotterdam has seen unprecedented growth in the post COVID Era. In the pre- COVID era the port of Rotterdam saw an influx of 7.7 million TEU while an outgoing metric of 7.1 million TEU. On an average 2017-2019 saw a handling of 15 million TEU. In the post COVID boom, this figure is expected to reach 20 million TEU by 2025 and possibly earlier with Europe becoming a major trans-shipment hub. This is from the projected data of the 5 deep-sea terminals, 3 short sea terminals present more inland and the empty depots at Port of Rotterdam. Figure 4.1 shows the various terminals in the port of Rotterdam and figure 4.2 depicts the rail and Barge connectivity between these terminals. These figures further depict the unique geography of the Rhine delta.

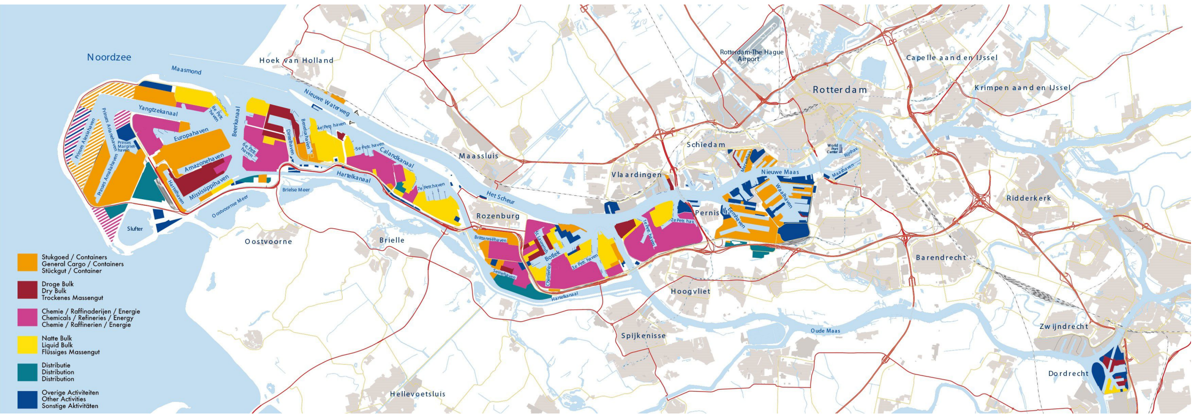


Figure 4.1: Map of the Port of Rotterdam, [69]

This port is not just a hub for container traffic but also for bulk cargo, chemicals and oil & petroleum products. Port of Rotterdam handles a significant volume of bulk cargo, including commodities like coal, iron ore, grains, and ores. Specialized terminals for dry and liquid bulk ensure efficient handling and storage of these goods. Rotterdam is known for its oil refining and distribution capabilities, the port manages a substantial portion of Europe's oil imports. It houses refineries, storage tanks, and terminals for the handling of crude oil and petroleum products. The port also has dedicated terminals for handling liquid chemicals, offering specialized facilities for the safe and efficient handling of hazardous goods. The Port of Rotterdam also

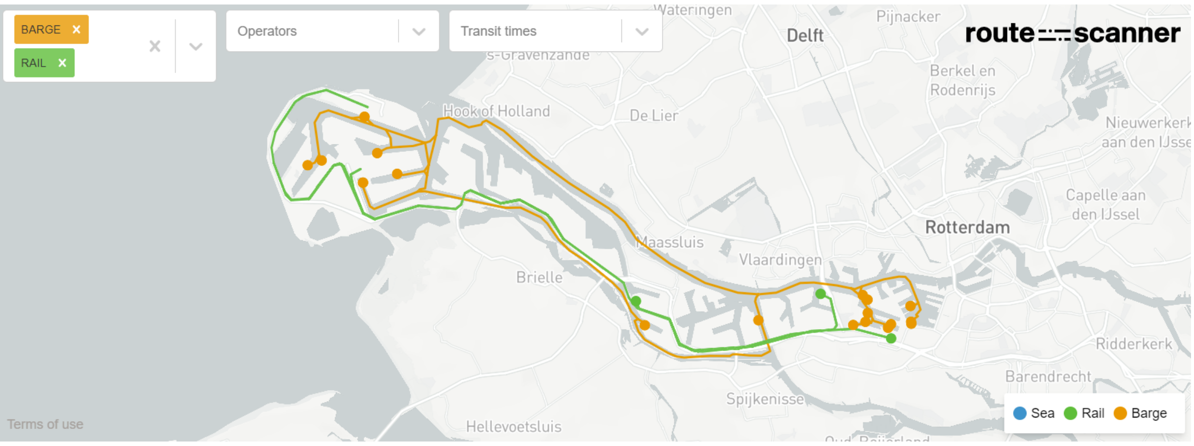


Figure 4.2: Container Transport in the Port of Rotterdam, [52]

comprises of various inland terminals and dry ports using road, rail and barge as the main modes of ITT. Rotterdam also provides a wide range of distribution and storage facilities for various types of cargo.

4.1 Deep Sea Terminals at Rotterdam

The Port of Rotterdam is one of the world's largest and busiest ports, serving as a critical gateway for European trade and commerce. To meet the growing demands of global shipping and trade, the Port of Rotterdam initiated the ambitious Maasvlakte 2 project, which represents a significant expansion of its infrastructure and capacity. Maasvlakte 2 includes state-of-the-art container handling terminals, such as the APM Terminals Rotterdam and the Rotterdam World Gateway terminal. These terminals are equipped with modern technology and equipment to handle the largest container vessels in the world, making Rotterdam a key hub for containerized cargo in Europe. The expansion project also included deepening and widening of the navigation channels, allowing access to larger vessels with drafts of up to 23 meters. This deepwater access is crucial for accommodating the ever-increasing size of container ships[77]. Figure 4.3 shows the barge and rail connectivity to and from the Container Terminals in Maasvlakte. Figure 4.4 depicts the geography of this area. There is a need for transfer of containers between the terminals, this can be seen in figure 4.5. In order to meet this requirement of 1803 containers in 2021, The Container Exchange Route was Developed (See Subsection 4.1.1). This is expected to increase the efficiency of container transport by road.

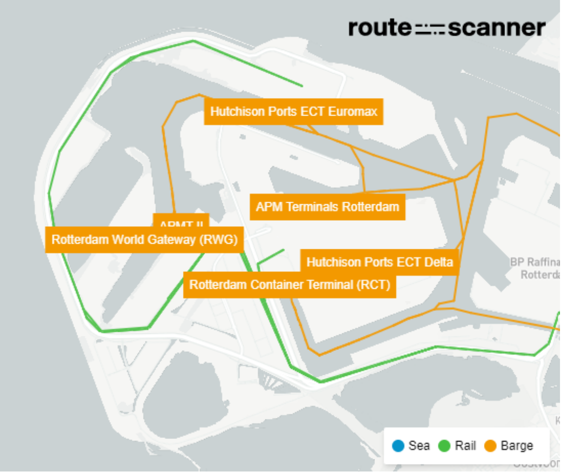


Figure 4.3: Transport Routes in Maasvlakte, [52]

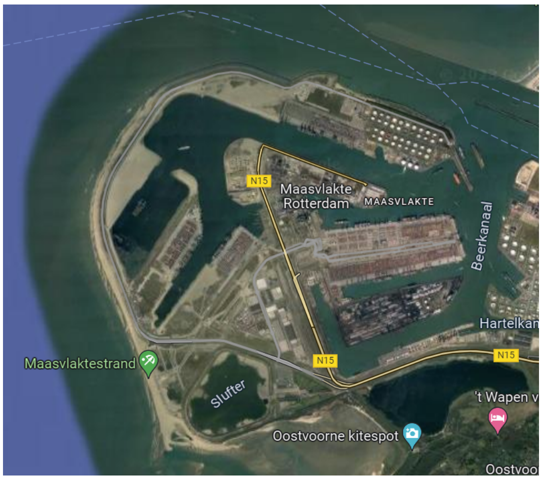
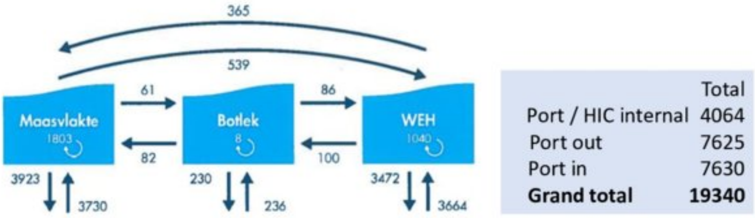


Figure 4.4: Maasvlakte Satellite view, [32]

As per figure 4.5, 1803 containers were handled between the Deep Sea Terminals of the Maasvlakte in 2014 [99]. The 2030 Projections for this demand is as shown in table 4.1.



	Total
Port / HIC internal	4064
Port out	7625
Port in	7630
Grand total	**19340**

Figure 4.5: Number of Containers Handled per day in Rotterdam, [99][113]

Table 4.1: Projected Demand Scenario in Maasvlakte 1 and 2 for 2030, [26][96][58]

Container Handlled between the terminals of Maasvlakte in 2030				
Scenario	TEU/year	TEU/day	Containers/day	Average Containers/day
High Demand Scenario	3340000	9151	4576	3761
Reduced Demand	2150000	5890	2945	

More details about the scenarios can be found in [26] and [96]. For a neutral Scenario the average of a High Demand Scenario and Reduced Demand Scenario is Assumed. The Average demand per day is 7522 TEU/day. Which is 3761 Containers/day assuming that all containers are of 2 TEU each. The focus of this research is to evaluate whether the use Amphibious AGVs is beneficial over Truck and Barge for Container ITT in ports like Rotterdam. As Amphibious AGV is still at a conceptual stage and has not been made in real life, it is anticipated that these Amphibious AGVs can be made operational by 2030.

4.1.1 Container Exchange Route

Rotterdam has five independent deep sea container terminals and offers Europes largest container cluster. The logistics on the terminals and between the ports container facilities should be as efficient as possible. That is why the Rotterdam Port Authority is introducing the Container Exchange Route; the largest, most advanced container exchange system of its kind. Container throughput here amounts to more than 15 million TEUs annually. Developments such as the planned expansion of container terminals on the Maasvlakte mean that the limits have not yet been reached.

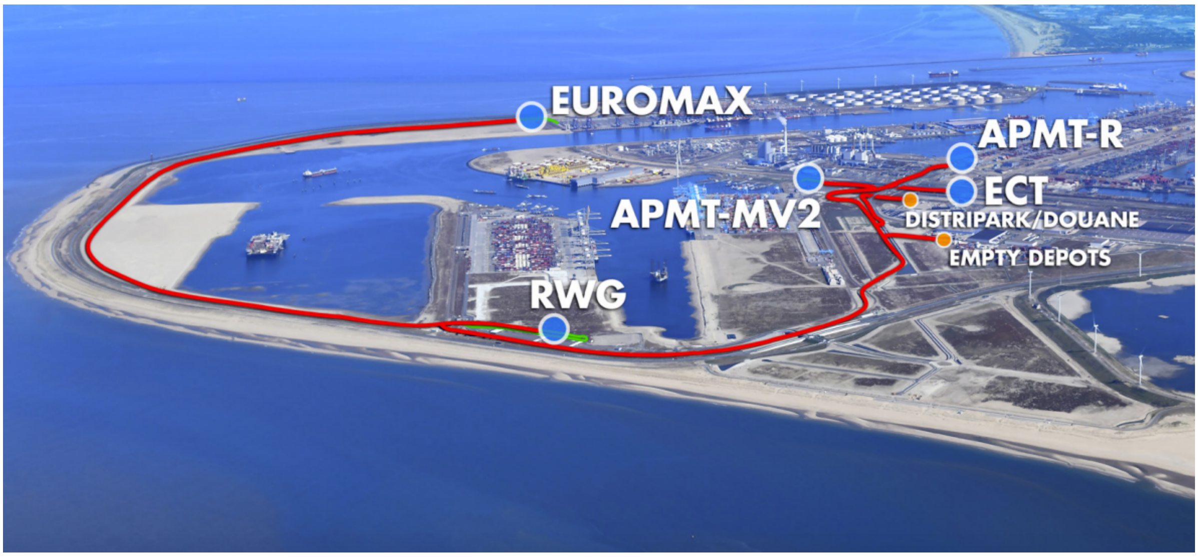


Figure 4.6: Container Exchange Route, [12]

The Container Exchange Route (CER) is a 17-kilometre-long closed road network that will connect a large proportion of the Maasvlakte's terminals, depots and distribution centres, and the State Inspection Terminal. Manned vehicles will transport containers to and from their destinations via this network. The CER is making a major contribution to security, integrity, efficiency and sustainability in the Port of Rotterdam. The routes will reduce delays. The companies using the CER will make the handling of containers smoother. That will deliver time savings, better road safety and lower emissions [12].

4.1.2 Major Deep Sea Terminals in Rotterdam

To summarise the container terminals at Rotterdam, the major set of deep sea terminals can be seen at the first point of entry into the Netherlands near the Hoek van Holland. The report will discuss the major access points for the following terminals, those which saw the highest container handling activity.

- Rotterdam World Gateway (flanked by Princess Amaliahaven and Alexiahaven)
- APM Maasvlakte, Hutchinson ECT Delta and Hutchinson Delta 2 - Amazonehaven and Europahaven, Princess Magriet Haven
- Euromax Hutchinson (Yangtzekanaal)

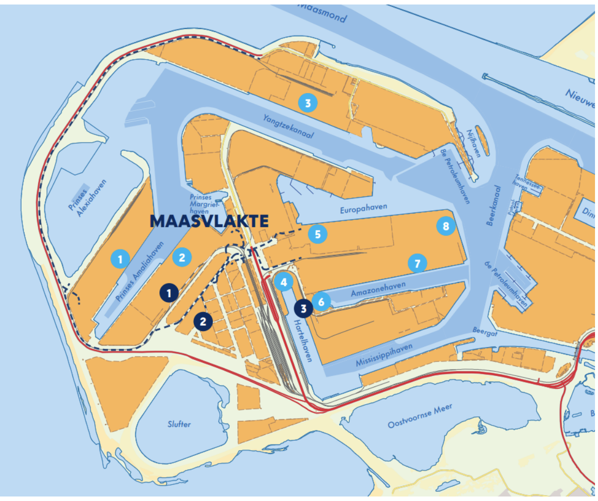


Figure 4.7: Terminals in Maasvlakte[Terminals are mentioned in Sky Blue], [102]

Container Terminals in Maasvlakte	
1	Hutchinson Ports ECT Euromax
2	Rotterdam World Gateway
3	APM Terminals Maasvlakte 2
5	APM Terminals Rotterdam/Hutchinson Ports Delta 2
7	Hutchinson Ports ECT Delta

Table 4.2: List of Deep sea Terminals in Maasvlakte, [102]

Hutchinson Ports ECT Euromax

Hutchinson Ports ECT Euromax is a major container terminal located in the Port of Rotterdam, Netherlands. It is operated as a joint venture between Hutchinson Ports and ECT (Europe Container Terminals), two of the world's leading port operators. The terminal plays a crucial role in the global supply chain, serving as a gateway to Europe and facilitating the movement of goods between continents. The terminal is situated on the Maasvlakte peninsula, which is an extension of the Port of Rotterdam. This strategic location allows for easy access to the North Sea, making it a key hub for international trade. It is one of the largest and most technologically advanced container terminals in Europe. It has a handling capacity of over 3 million TEUs per year. The layout of this terminal can be seen in figure 4.8 and the location in Maasvlakte can be seen by referring figure 4.7 with table 4.2. This terminal offers inland connectivity through Road, Rail and Barge[108].

Table 4.3: Specifications of Hutchinson Ports ECT Euromax, [36]

Specifications	
Number of Deep Sea Berths	1
Number of Quay Cranes	16
Number of Stacking Cranes	29

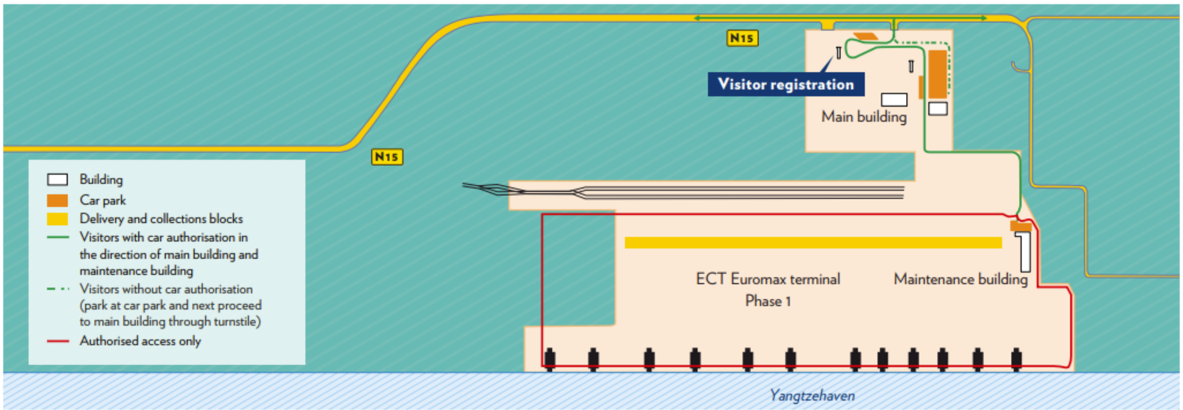


Figure 4.8: Layout of Hutchinson Ports ECT Euromax, [50]

Rotterdam World Gateway

Rotterdam World Gateway (RWG) is a prominent container terminal located in the Port of Rotterdam, Netherlands. It is known for its advanced technology and efficient operations, contributing significantly to the global supply chain. It is a prominent container terminal located in the Port of Rotterdam, Netherlands. It is known for its advanced technology and efficient operations, contributing significantly to the global supply chain. Rotterdam World Gateway is a joint venture between various international partners. APL, MOL, HMM, CMA CGM and DP World[81]. RWG is one of the largest and most technologically advanced terminals in Europe. It has a handling capacity of over 2.35 million TEUs annually. The layout of this terminal can be seen in figure 4.9 and the location in Maasvlakte can be seen by referring figure 4.7 with table 4.2. This terminal offers inland connectivity through Road and Barge[121].

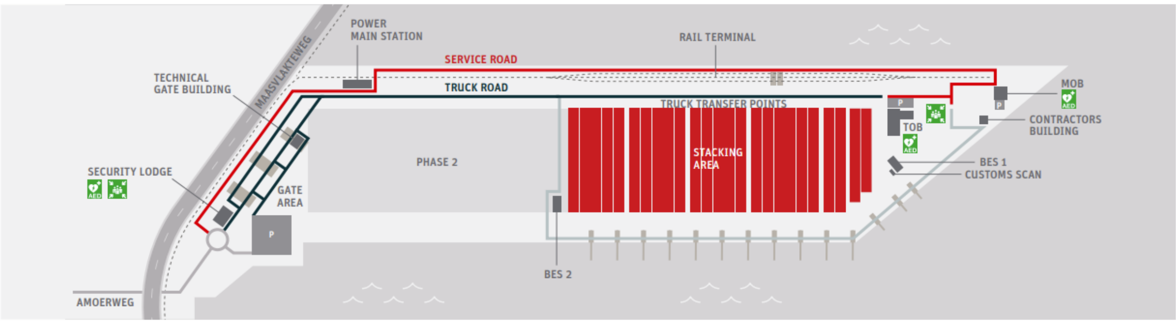


Figure 4.9: Layout of Rotterdam World Gateway, [91]

Table 4.4: Specifications of Rotterdam World Gateway, [37]

Specifications	
Number of Deep Sea Berths	1
Number of Quay Cranes	16
Number of Stacking Cranes	25

APM Terminals Maasvlakte 2

APM Terminals Maasvlakte 2 (APMT MVII) is a state-of-the-art container terminal located on the Maasvlakte 2 expansion area in the Port of Rotterdam, Netherlands. As part of the APM Terminals global network, it is known for its advanced technology and efficiency in handling containerized cargo. This location provides direct access to the North Sea, making it a crucial gateway for international trade. APM Terminals, a subsidiary of the Maersk Group, owns and operates the Maasvlakte 2 terminal. Maersk is one of the world's largest shipping and logistics companies[66], and APM Terminals is a global terminal operator with a network of facilities around the world[44]. The terminal is capable of processing over 2.7 million TEUs annually. Its size and efficiency contribute significantly to the Port of Rotterdam's overall capacity. The layout of this terminal can be seen in figure 4.10 and the location in Maasvlakte can be seen by referring figure 4.7 with table 4.2. This terminal offers inland connectivity through Road, Rail and Barge[63].

Figure 4.10: Layout of APM Terminals Maasvlakte 2, [93]

Table 4.5: Specifications of APM Terminals Maasvlakte 2, [33]

Specifications	
Number of Deep Sea Berths	1
Number of Quay Cranes	13
Number of Stacking Cranes	27

Hutchinson Ports Delta 2

Hutchison Ports Delta II is strategically located on the Delta peninsula at the Maasvlakte in the Port of Rotterdam. The facilities of Hutchison Ports Delta II are geared to the fast and efficient handling of the largest container vessels, as well as feeders and barges. The whole of Northwest Europe can be reached directly from the terminal by barge, rail and truck[46]. This Terminal was previously owned by APMT and called APMT Rotterdam. The layout of this terminal can be seen in figure 4.11 and the location in Maasvlakte can be seen by referring figure 4.7 with table 4.2. This terminal offers inland connectivity through Road, Rail and Barge[45].

Table 4.6: Specifications of Hutchinson Ports Delta 2, [68]

Specifications	
Number of Deep Sea Berths	1
Number of Quay Cranes	14
Number of Stacking Cranes	-

Hutchinson Ports ECT Delta

Hutchison Ports ECT Delta, located on the North Sea coast near Rotterdam close to the main shipping routes, is one of Europes largest container terminals capable of handling the latest generation of ultra large container vessels without any restrictions. It is operated as a joint venture between Hutchinson Ports and ECT (Europe Container Terminals), two of the world's leading port operators[48]. The layout of this terminal can be seen in figure 4.12 and the location in Maasvlakte can be seen by referring figure 4.7 with table 4.2. This terminal offers inland connectivity through Road, Rail and Barge[47].

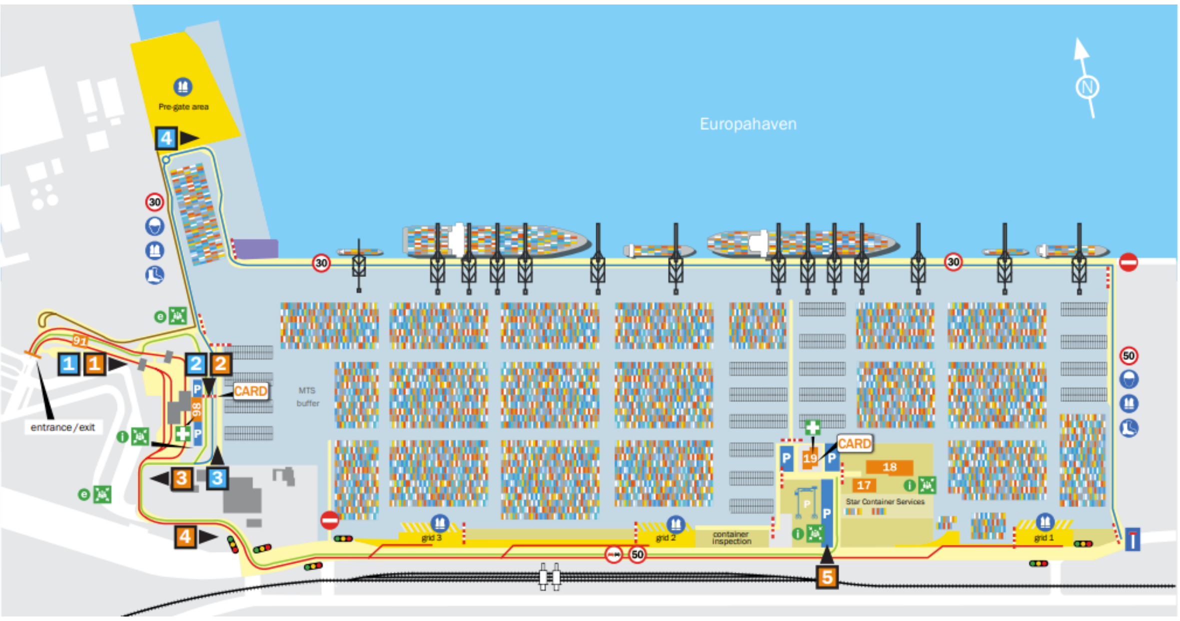


Figure 4.11: Layout of Hutchinson Ports Delta 2, [45]

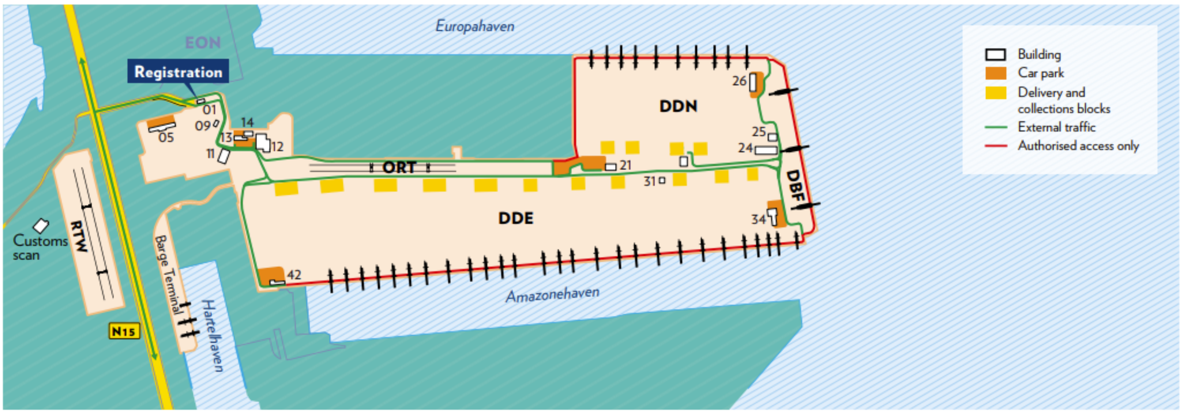


Figure 4.12: Layout of Hutchinson Ports ECT Delta, [49]

Table 4.7: Specifications of Hutchinson Ports ECT Delta, [35]

Specifications	
Number of Deep Sea Berths	2
Number of Quay Cranes	34
Number of Stacking Cranes	134

4.2 AAGV transfer systems location descriptions

In this section, the exact locations of all the transfer points are explained. Transfer location refers to the location of a ramp to be accessed by the Amphibious AGV. The type of ramp used is a passive ramp. A passive ramp provides access to the Amphibious AGV to get from land to water and vice versa. These ramp locations are designed based on the current policy limitations of terminal handling equipment, hence the requirement of ramp for every terminal. The establishment of an AAGV corridor would reduce the investment costs for multiple ramps.

Hutchinson Ports ECT Euromax

On the South-East side of the terminal there is some empty space next to the LNG facility at Azieweg. This empty space is assumed to be utilised for the construction of a passive ramp for the access of Amphibious AGV as shown in figure 4.13. This area is also seen to have a gradual decrease in altitude which could act as a natural slope.

Figure 4.13: AAGV water/land transfer location at Euromax terminal, [41]

Rotterdam World Gateway

On the North side of the terminal there is some empty space. This empty space is assumed to be utilised for the construction of a passive ramp for the access of Amphibious AGV as shown in figure 4.14. This area is assumed as we see that there is a gradual decrease in altitude here which could serve like a natural ramp.

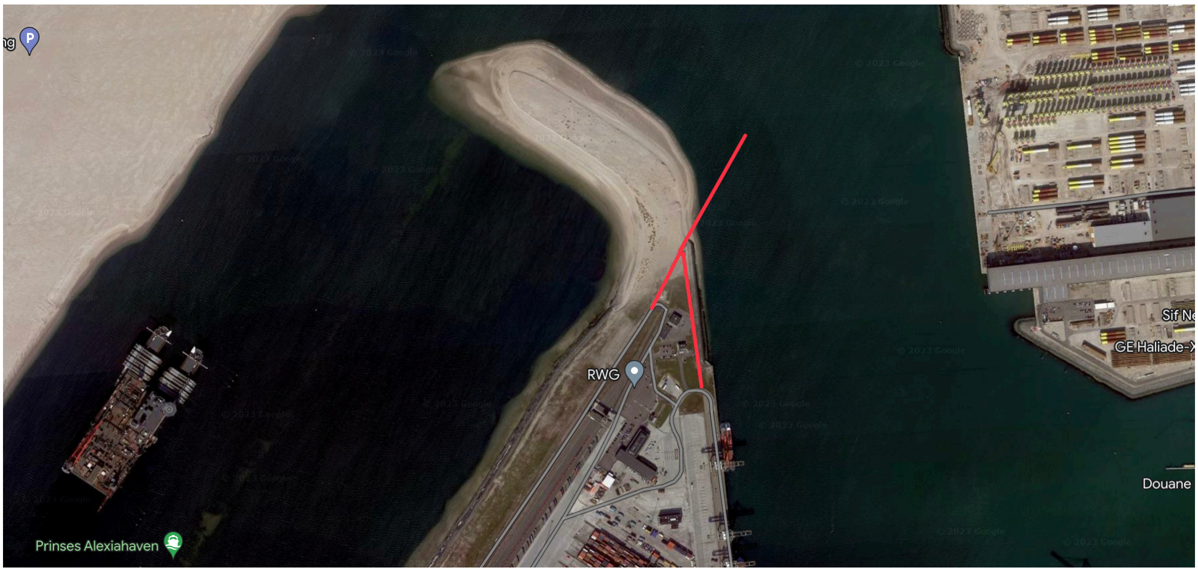


Figure 4.14: AAGV water/land transfer location at Rotterdam World Gateway, [42]

APM Terminals Maasvlakte 2

On the South-West side of the terminal there is some empty space. This empty space is assumed to be utilised for the construction of a passive ramp for the access of Amphibious AGV as shown in figure 4.15. This location is chosen even though there is space available on the North-East side is because of APMT's future plan of having a new terminal adjacent to this on the south side[85]. Hence, a common ramp system could be used to optimize investment costs.

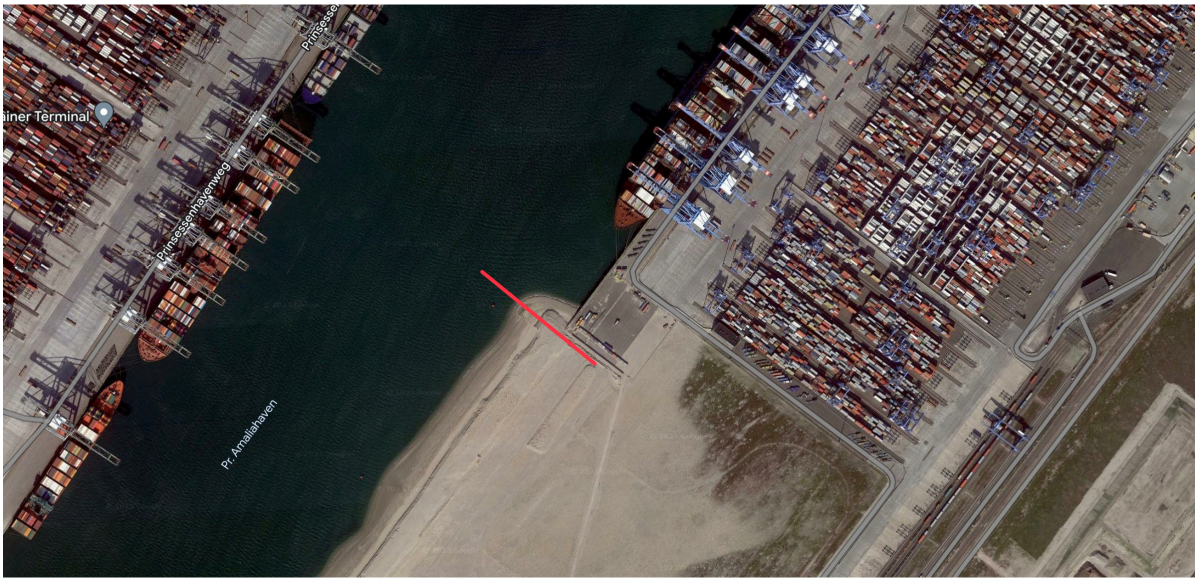


Figure 4.15: AAGV water/land transfer location at APMT Maasvlakte 2, [38]

Hutchinson Ports ECT Delta

On the North-West side of the terminal there is some empty space. This empty space is assumed to be utilised for the construction of a passive ramp for the access of Amphibious AGV as shown in figure 4.16. This area is assumed as we see that there is a gradual decrease in altitude here which could serve like a natural ramp.

Figure 4.16: AAGV water/land transfer location at ECT Delta, [39]

Hutchinson Ports Delta 2

On the North-West side of the terminal there is some empty space. This empty space is assumed to be utilised for the construction of a passive ramp for the access of Amphibious AGV as shown in figure 4.16. This area is almost the same place as that of the Hutchinson Ports ECT Delta Ramp. A Common Ramp could be used to optimize investment costs.

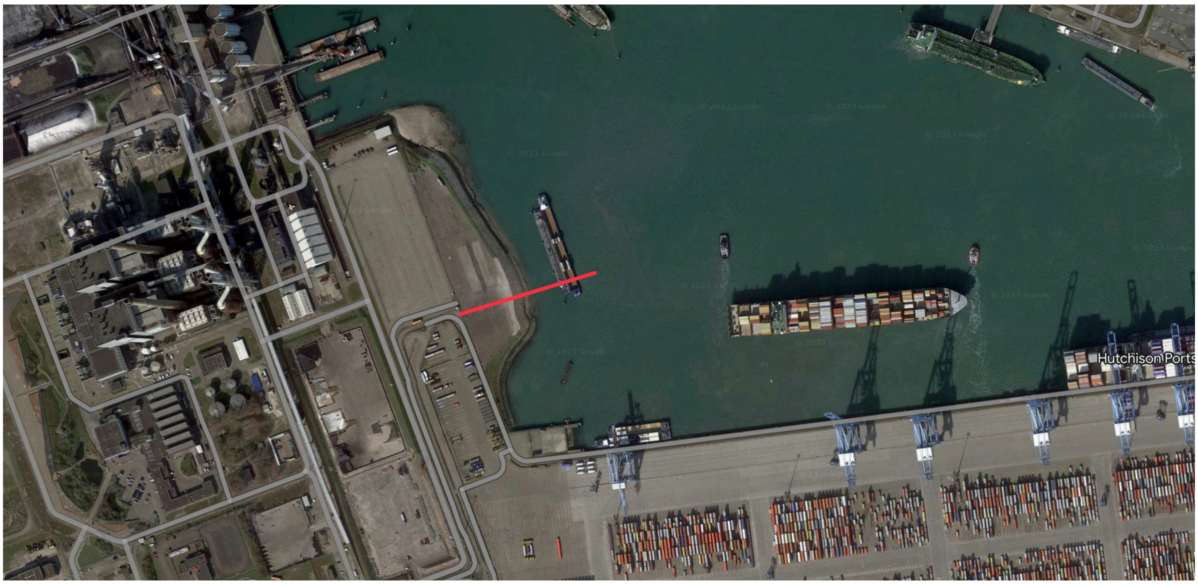


Figure 4.17: AAGV water/land transfer location at ECT Delta 2, [40]

Ramp Dimensions

In order to determine the dimension of the ramp, the following specifications as seen in table 4.8 are required. Assuming that the Quay Height, Depth of Water and Speed of AGV on Ramp are uniform and constant for all container terminals in Maasvlakte.

Table 4.8: Ramp Parameters

Parameter	Value
Quay Height	29 meters[76]
Depth of Water	17 meters[20]
Speed of AAGV on Ramp	9 Kmph[14]
Ramp Inclination	3°[14]

$$RampWidth = WaterModeAAGVWidth * NumberofLanes + 50\%(Buffer) = 5.54*2+50\% = 16.62m \approx 17m \tag{4.1}$$

More Information on the specifications of the Amphibious AGV can be found in the appendix.

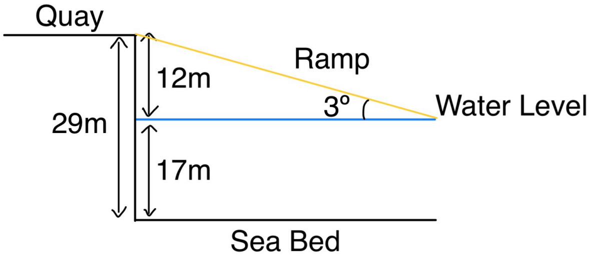


Figure 4.18: Ramp Representation

From Figure 4.18,

$$\sin 3^\circ = \frac{12m}{RampLength}$$

$$RampLength = \frac{12m}{\sin 3^\circ} = 229m \tag{4.2}$$

The Calculated Ramp length is 229 meters.

$$TimetakenbyAAGVonRamp = \frac{RampLength}{SpeedofAAGVomRamp} = \frac{229m}{9Kmph} = \frac{229m}{9000m/h} = 0.025h = 1.53min \quad (4.3)$$

The time taken by each AAGV on the ramp is approximately 1.53 minutes.

4.3 Variables and Parameters

This Section has the information about all the types of Input data that is to be used in this model to receive the desired output. In table 4.9, we can see the complete list of required data and their values.

Table 4.9: List of Inputs for the Simulation

Parameter		Value
Speed	Truck	60 Kmph
	Barge	13 Kmph[94]
	AGV	11 Kmph[86]
	AAGV	12 Kmph
Handling Time per Container	Quay Crane	1-3 minutes[6]
	ASC	1-3 minutes[54][6]
Time on Ramp for each AAGV		1.5-2.5 minutes (Refer 4.2)
Time Taken for Mooring a Barge		20-90 minutes[103]
Quantity	Truck	2 TEU
	Barge	200 TEU[19]
	AGV	2 TEU
	AAGV	2 TEU
Container Input per day		3761 Containers(Refer Table 4.1)
Number of Quay Cranes Serving	Deep Sea Vessel (Post Panamax and above)	6 Cranes[34]
	Barge	1 Crane[34]

4.4 Location of Agents

This section provides an overview on the location of agents in the major terminals of Maasvlakte. An overview of these terminals can be found in subsection 4.1.2. The main agents are Storage Yard, Deep Sea Quay, Barge Quay and Ramp. These agents are marked with blue, yellow, green and red GIS pins respectively in figure 4.19. The central location of the Storage Yard is used as the GIS point location of the Storage Yard agent. The central location of the the Deep Sea Berths is used as the GIS point location of the Deep Sea Quay agent and the central location of the Barge Berths is used as the GIS point location of the Barge Quay agent. The location of the ramps agent is based on the information in section 4.2.

Figure 4.19: Location of Agents

Figure 4.20: Terminal Locations

Figure 4.20 provides a satellite view of the terminal locations in Maasvlakte. Marked in black is Hutchinson Ports ECT Euromax, in red is Rotterdam World gateway, in blue is APM Terminals Maasvlakte 2, in purple is Hutchinson Ports Delta 2 and in green is Huthinson Ports ECT Delta. Correlating Figures 4.19 and 4.20 provides an insight on the location of the agents terminal wise.

4.5 Results and Discussion

This section presents and discusses the results obtained from the simulation model for the case of Container ITT between the Deep Sea Terminals of Maasvlakte, Rotterdam. These results are presented case wise along with the interaction of agents and the handling process. Every process is simulated for a runtime of 24hours. The data obtained are all based on a single day scenario. In order to establish Multi Modal Transport network keeping in mind the capacity of the student version of AnyLogic, split simulation method is adapted where every mode is simulated separately. But the linear chain is computed exactly for 24 hours. For the ease of computing results it is assumed that the container demand is equal in all container terminals. The results are discussed case-wise in subsections 4.5.1, 4.5.2, 4.5.3 and 4.5.4, then followed by a common discussion and then the sensitivity analysis. The benchmark logistics chain is compared with the new logistics chain in each case. All the simulations in this thesis were performed using a 12th Gen Intel(R) Core(TM) i7-1260P 2.10 GHz with a 16 GB RAM (64-bit operating system, x64-based processor) laptop.

4.5.1 Case SS: Yard To Yard

Yard to Yard Case is synonymous with Storage to Storage Case. Here, a set of containers have to be transported from the Storage Yard of Hutchinson Ports ECT Euromax to the Storage Yard of the other Four Terminals. This transport requirement can be fulfilled by either using Truck, Barge or Amphibious AGV as the primary equipment of ITT. To compare and understand the results, this case is first explained with respect to the mode of Inter Terminal Transport and then followed by a discussion on the results.

Case SS-T

When using a Truck as the main equipment for Inter Terminal Transport for Case SS, the container flow is as shown in figure 4.21. The Truck agent interacts with the Yard Agent of Hutchinson Ports ECT Euromax where it picks up containers from there and drops it at the storage yard of either of the 4 Terminals based on the order allocation.

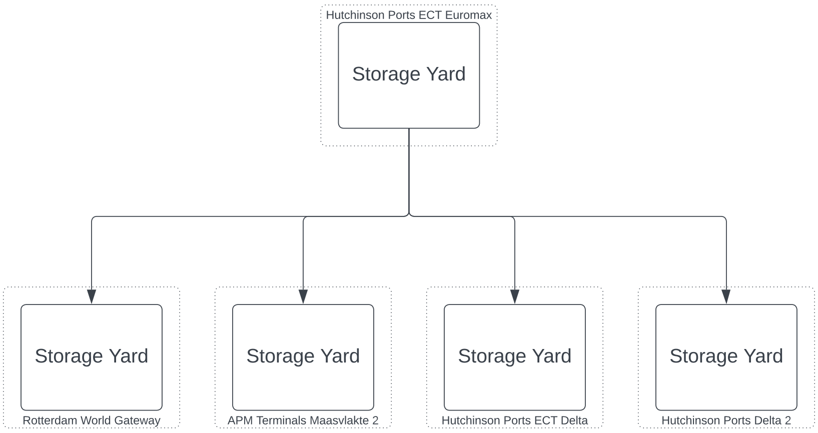


Figure 4.21: Container Flow between agents, Case SS-T

Case SS-B

When using a Barge as the main equipment for Inter Terminal Transport for Case SS, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 3 simulation chains namely A, B and C(as shown in figure 4.22). Chain A consists of the process where agent AGV interacts with the storage yard of Hutchinson Ports ECT Euromax and transports containers to the Barge Quay of the same terminal. Chain B consists of the process where the agent Barge interacts with the Barge Quay of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Barge Quay of either of the 4 Terminals based on the order allocation. Chain C consists of the agent AGV interacting with the Barge Quay of one of the 4 terminals where it picks up containers and drops it at the Storage yard within the same terminal.

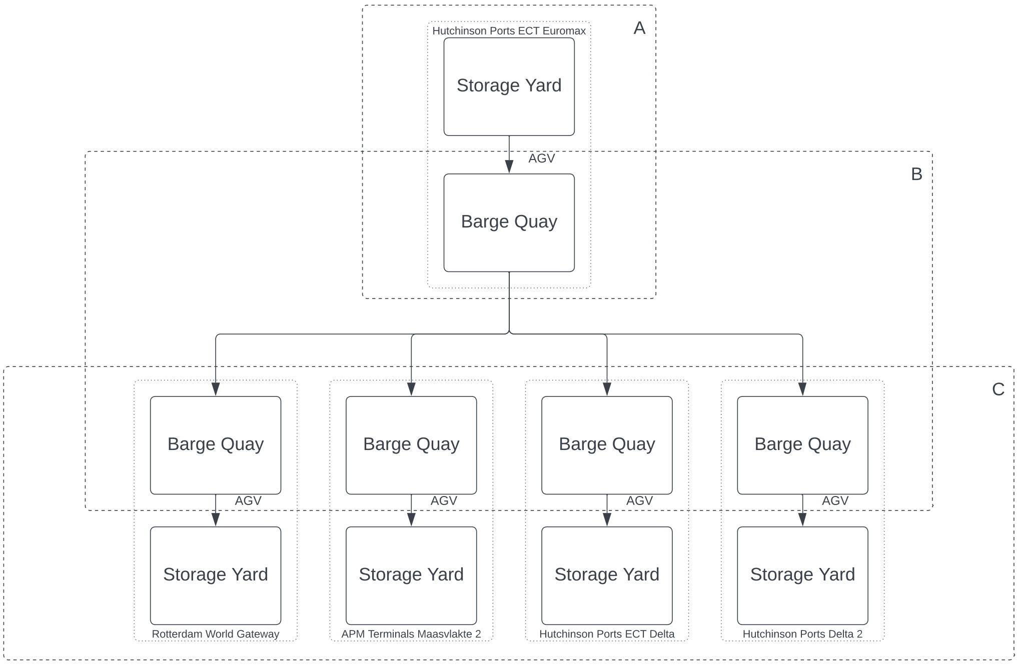


Figure 4.22: Container Flow between agents, Case SS-B

Case SS-A

When using a Amphibious AGV as the main equipment for Inter Terminal Transport for Case SS, the container flow is as shown in figure 4.23. The AAGV agent interacts with the Yard Agent of Hutchinson Ports ECT Euromax where it picks up containers from there, travels on land and enters the sea through the AAGV Ramp. Then it travels on water till it reaches the AAGV Ramp, enters land again and drops the container off at the Storage Yard of one of the for terminals based on order allocation.

Results and Discussion

The Simulation results are divided based on the sub cases of case SS. Figure 4.24 compares the time taken to transport a container, throughput, total fleet size and fulfillment rate of cases SS-T, SS-B and SS-A. The least time to transport a container from a storage yard to the storage yard of another terminal is seen in case SS-T. By transporting containers using Truck the time saving is almost 50% compared to that of using AAGVs as seen in Case SS-A. In case SS-B, it takes 472.09 minutes to transport 100 containers (200 teu). This time difference between case SS-T or SS-A and case SS-B is due to the difference in container handling capacities, mooring requirement of barges and the need of supplementary logistic chains with AGVs to complete the process in case SS-B. The time difference between case SS-T and SS-A is because of multiple factors like speed limitation of AAGV in water, speed limitation of AAGV in land (within terminal) and development of container exchange route (CER) for Trucks with greater speed limits. The throughput of case SS-T and SS-A are very comparable with each other, case SS-T having the edge over Case SS-A by 3 teu/hr. The Throughput of case SS-B is almost 30% lower than that of case SS-T and SS-A. Throughput helps in understanding the container handling capacity of the logistic chain. Throughput helps in understanding the trend of the Fulfillment rate. As shown in Figure 4.24, Fulfillment rates of cases SS-T, SS-A and SS-B are 94.92%, 93.96% and 67.56% respectively. From fulfillment rate and throughput it can be understood that the logistic chains are more efficient in Case SS-T and SS-A compared to SS-B by 25% and case SS-T having an edge over case SS-A by a little less than 1%. Fleet Size in case SS-A are considerably high than compared to that of case SS-T or SS-B. Case SS-T and SS-B are closely similar with 112 (trucks) and 121 (barges+AGVs) respectively. The Cases SS-T, SS-A and SS-B have 2, 2 and 4 container re-handling points respectively. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size, greater fulfillment rate and least amount of container re-handling points. Upon comparing SS-T, SS-A and SS-B on this basis it can be found that the performance of logistic chain between case SS-T and SS-A is close other

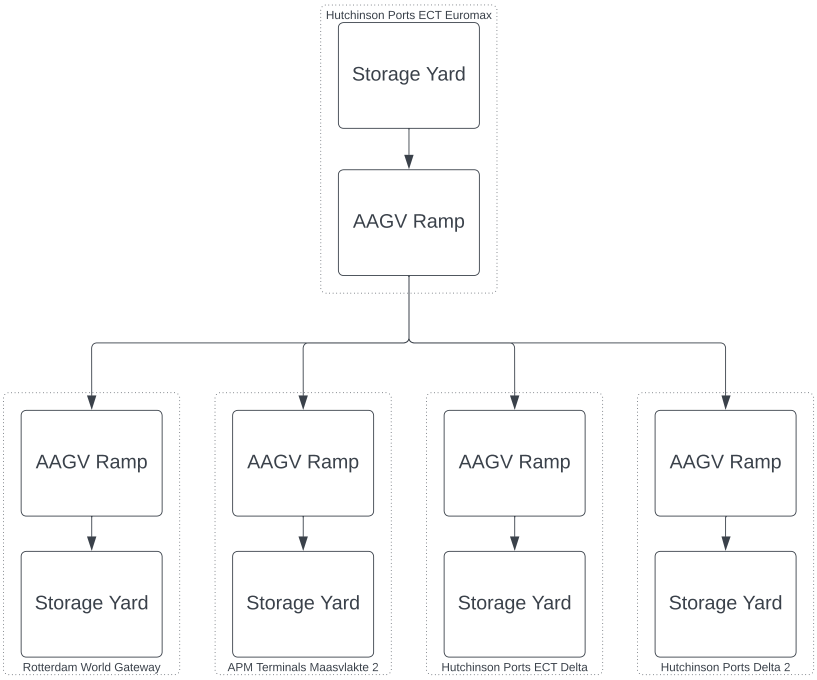


Figure 4.23: Container Flow between agents, Case SS-A

than that of fleet size. In order to understand this scenario closely, a route breakdown is done to analyze how these results differ for individual routes. This analysis is beneficial to see if the effect of average/approximation plays a vital role in the results shown in Figure 4.24.

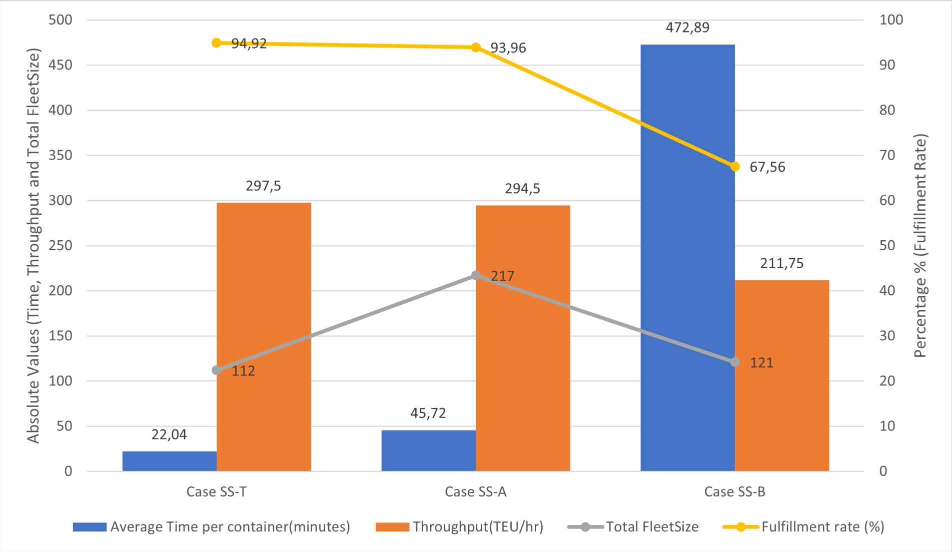


Figure 4.24: KPIs: Time, Throughput, Fleet Size and Fulfillment Rate

In order to model this system the Container Demand is also divided by the number of receiving terminals.

$$\text{New Container Demand} = \frac{\text{Container Demand}}{4} = \frac{3761}{4} \approx 940 \tag{4.4}$$

This is used across all cases to compute the results for route analysis. Figure 4.25 depicts the results of the case SS route wise. Four routes are compared for cases SS-T and SS-A. The 4 routes compared are:

- Hutchinson Ports ECT Euromax to Rotterdam World Gateway,
- Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2,
- Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2 and
- Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta

The container flow is as shown in Figures 4.21, 4.22 and 4.23, but is made linear or broken down separately. These results are depicted in Figure 4.25. It is observed that the trend of case SS-T having better performance of logistic chain over case SS-A is similar for all routes other than Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2 and Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta. For route Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2, it is observed that case SS-A has greater fulfillment rate than case SS-T by over 2%. The throughput is also greater by 2.5 teu/hr. But this advantage on fulfillment rate and throughput comes at the cost of the fleet size of case SS-A being greater than 2 times the fleet size of case SS-T. For route Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta, it is observed that case SS-A has greater fulfillment rate than case SS-T by over 0.3%. The throughput is also greater by 0.25 teu/hr. But this advantage on fulfillment rate and throughput comes at the cost of the fleet size of case SS-A being greater than 1.8 times the fleet size of case SS-T.As we see that there was a slightly different output than that of 4.24, this result is affected by the averaging/approximation effect.

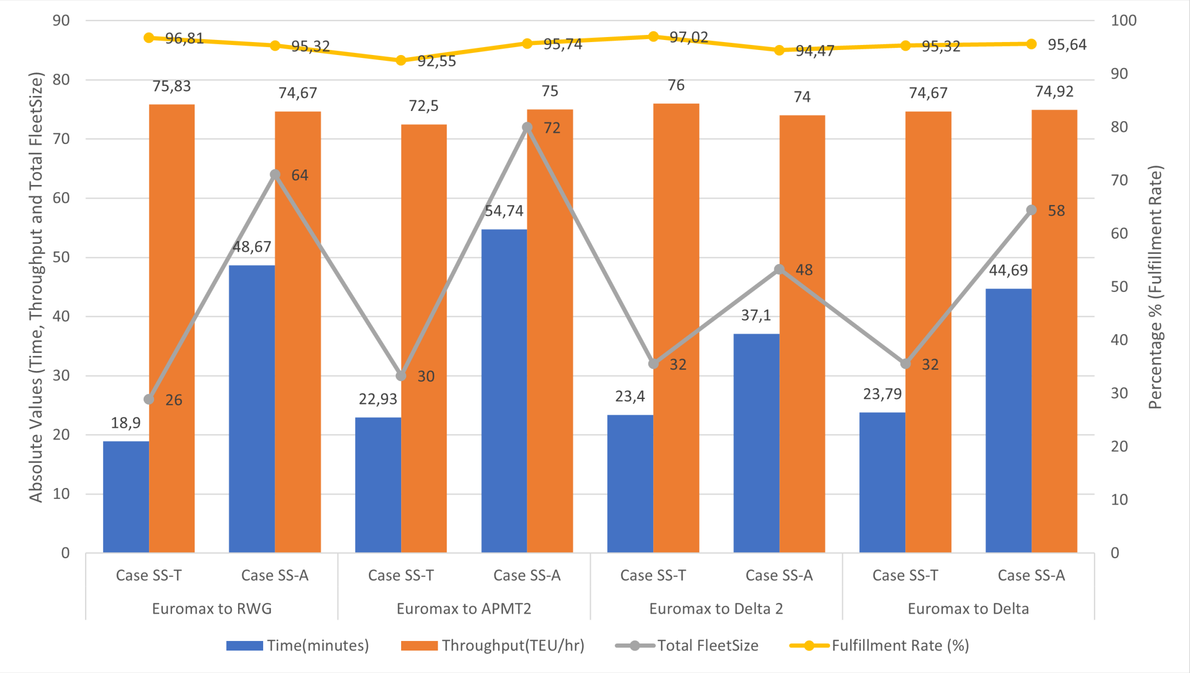


Figure 4.25: Route wise Analysis

This anomaly can be understood by referring Figures 4.19 and 4.20, it can be seen that the distance between the yard location of Hutchinson Ports ECT Euromax and the yard location of APM Terminals Maasvlakte 2 is greater by using the road than the AAGV route. This difference is also because of the need of Amphbious AGVs to navigate from the storage yard to the AAGV ramp of the terminal using the AGV lines before it enters the sea to traverse to the other terminal and the need to use the AAGV ramp and then use the AGV lanes to get to the storage yard. The difference in their routes can been seen in the appendix. From these results it can be seen that Case SS-T would be the most suitable due to the already available truck fleet, available infrastructure (CER) and lower fleet size. Even though case SS-A has an edge over case SS-T for 2 routes, it would be more efficient to use case SS-T, Truck as the main handling equipment for Inter Terminal Transfer (ITT). In order to transfer a few containers in priority, case SS-T/truck is the best option as it takes the least amount of time.

4.5.2 Case VV: Quay To Quay

Quay to Quay Case is synonymous with Vessel to Vessel scenario. Here, a set of containers have to be transported from a Deep Sea Vessel at Hutchinson Ports ECT Euromax to other Vessels at each of the other Four Terminals. This transport requirement can be fulfilled by either using Truck, Barge or Amphibious AGV as the primary equipment of ITT. To compare and understand the results, this case is first explained with respect to the mode of Inter Terminal Transport and then followed by a discussion on the results.

Case VV-T

When using a Truck as the main equipment for Inter Terminal Transport for Case VV, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 3 simulation chains namely A, B and C(as shown in figure 4.26). Chain A consists of the process where agent AGV interacts with the Deep Sea Quay of Hutchinson Ports ECT Euromax and transports containers to the Storage Yard of the same terminal. Chain B consists of the process where the agent Truck interacts with the Storage Yard of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Storage Yard of either of the 4 Terminals based on the order allocation. Chain C consists of the agent AGV interacting with the Storage Yard of one of the 4 terminals where it picks up containers and drops it at the Deep Sea Quay within the same terminal.

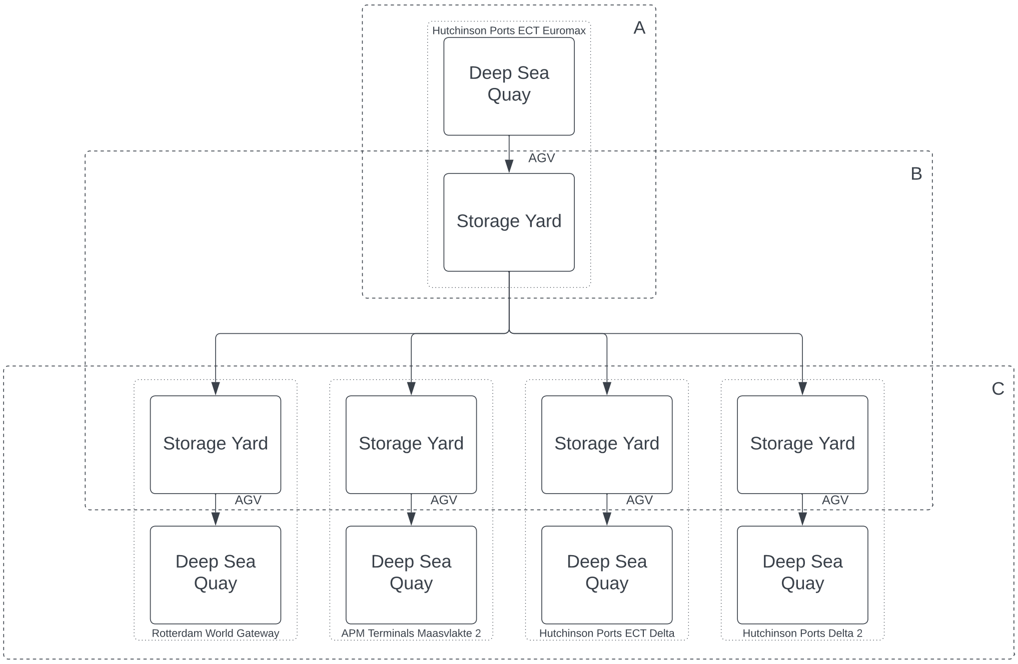


Figure 4.26: Container Flow between agents, Case VV-T

Case VV-B

When using a Barge as the main equipment for Inter Terminal Transport for Case VV, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 3 simulation chains namely A, B and C(as shown in figure 4.27). Chain A consists of the process where agent AGV interacts with the Deep Sea Quay of Hutchinson Ports ECT Euromax and transports containers to the Barge Quay of the same terminal. Chain B consists of the process where the agent Barge interacts with the Barge Quay of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Barge Quay of either of the 4 Terminals based on the order allocation. Chain C consists of the agent AGV interacting with the Barge Quay of one of the 4 terminals where it picks up containers and drops it at the Deep Sea Quay within the same terminal.

Case VV-A

When using a Amphibious AGV as the main equipment for Inter Terminal Transport for Case VV, the container flow is as shown in figure 4.28. The AAGV agent interacts with the Deep Sea Quay Agent of Hutchinson Ports ECT Euromax where it picks up containers from there, travels on land and enters the sea through the AAGV Ramp. Then it travels on water till it reaches the AAGV Ramp, enters land again and drops the container off at the Deep Sea Quay of one of the for terminals based on order allocation.

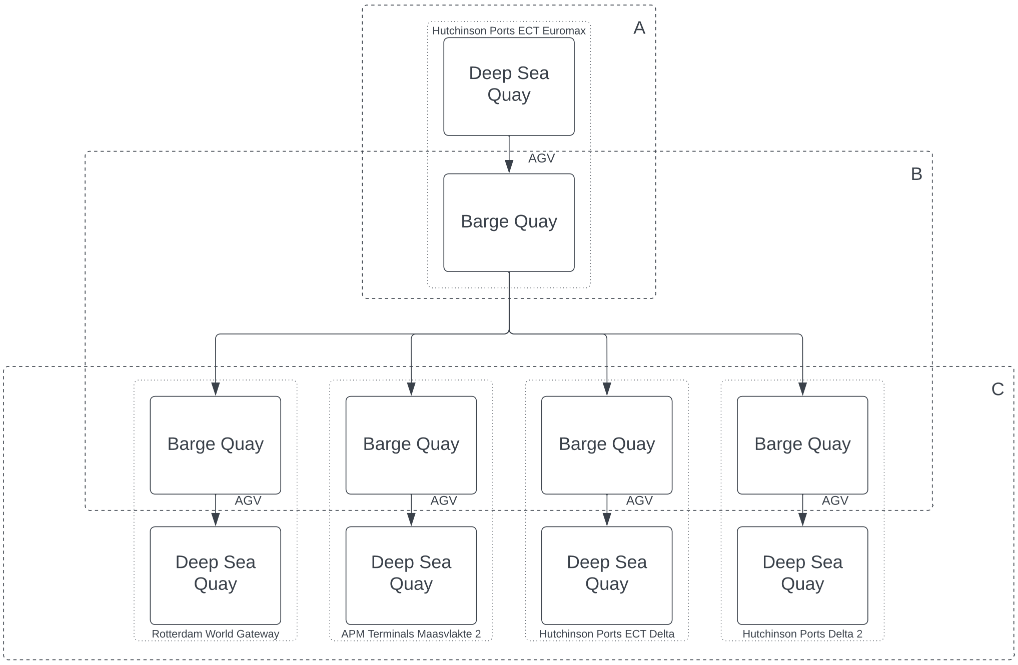


Figure 4.27: Container Flow between agents, Case VV-B

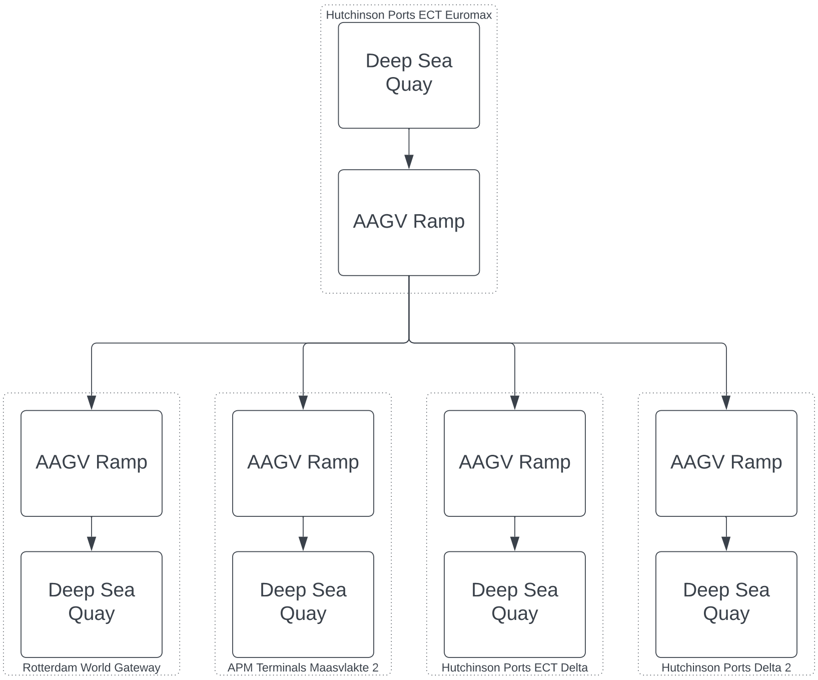


Figure 4.28: Container Flow between agents, Case VV-A

Results and Discussion

The Simulation results are divided based on the sub cases of case VV. Figure 4.29 compares the time taken to transport a container, throughput, total fleet size and fulfillment rate of cases VV-T, VV-B and VV-A. The least time to transport a container from a vessel to a vessel that is berthed in another terminal is seen in case VV-T. By transporting containers using Truck the time saving is almost 20% compared to that of using AAGVs as seen in Case VV-A. In case VV-B, it takes 473.47 minutes to transport 100 containers (200 teu). This time difference between case VV-T or VV-A and case VV-B is due to the difference in container handling capacities, mooring requirement of barges and the need of supplementary logistic chains with AGVs to complete the process in case VV-B. The time difference between case VV-T and VV-A is because of multiple factors like speed limitation of AAGV in water, speed limitation of AAGV in land (within terminal) and development of container exchange route (CER) for Trucks with greater speed limits. The throughput of case VV-T and VV-A are very comparable with each other, case VV-A having the edge over Case VV-T by almost 21 teu/hr. The Throughput of case VV-B is almost 30% lower than that of case VV-A. Throughput helps in understanding the container handling capacity of the logistic chain. Throughput helps in understanding the trend of the Fulfillment rate. As shown in Figure 4.24, Fulfillment rates of cases VV-T, VV-A and VV-B are 88.99%, 95.64% and 64.37% respectively. From fulfillment rate and throughput it can be understood that the logistic chains are more efficient in case VV-A compared to VV-T by 7% and VV-B by 31%. Fleet Size in case VV-A are considerably high than compared to that of case VV-T or VV-B. Case VV-T, case VV-A and case VV-B have a fleet size of 186 (trucks+AGVs), 231 (AAGVs) and 121 (barges+AGVs) respectively. The Cases VV-T, VV-A and VV-B have 4, 2 and 4 container re-handling points respectively. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size, greater fulfillment rate and least amount of container re-handling points. Upon comparing VV-T, VV-A and VV-B on this basis it can be found that the performance of logistic chain between case VV-T and VV-A is close, where case VV-T has the edge over fleet size while all the other KPIs are better for Case VV-A. In order to understand this scenario closely, a route breakdown is done to analyze how these results differ for individual routes. This analysis is beneficial to see if the effect of average/approximation plays a vital role in the results shown in Figure 4.29.

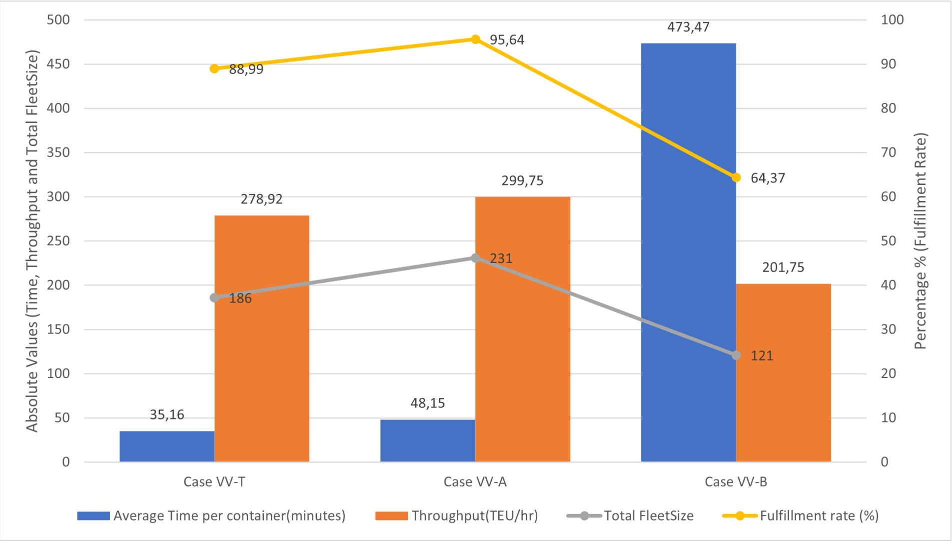


Figure 4.29: KPIs: Time, Throughput, Fleet Size and Fulfillment Rate

The container flow is as shown in Figures 4.26, 4.27 and 4.28, but is made linear or broken down separately. These results are depicted in Figure 4.30. It is observed that the trend of case VV-A having better performance of logistic chain over case VV-T is similar for all routes. The trend of case VV-T having an edge over case VV-A in terms of the KPI fleet size is similar for all routes other than the route Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2. For this route, it is observed that case VV-A has greater fleet size than case VV-T but just by 2 handling equipment. The throughput and fulfillment rate are also greater than by almost 16 teu/hr and 21% which is a lot more than the results in Figure 4.29. As the output is just slightly different than that of 4.29, this result is not affected greatly by the averaging/approximation effect.

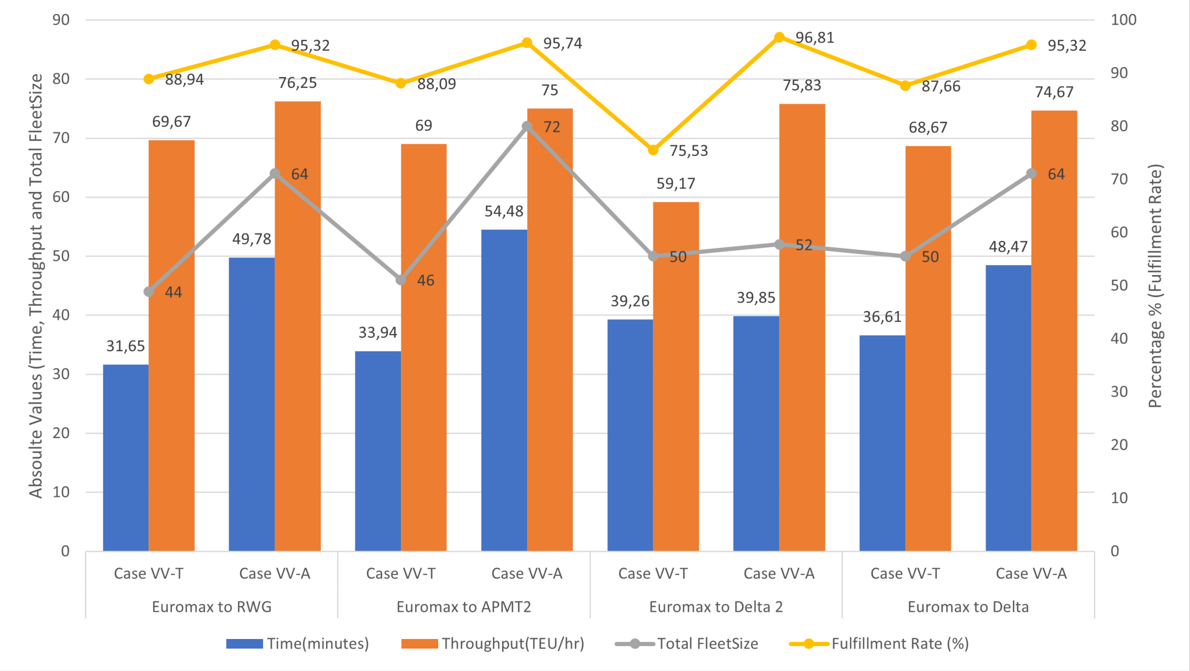


Figure 4.30: Route wise Analysis

This anomaly can be understood by referring Figures 4.19, 4.20, 4.8 and 4.11, it can be seen that the distance between the deep sea quay location of Hutchinson Ports ECT Euromax and the deep sea quay location of Hutchinson Ports Delta 2 is greater by using the road than the AAGV route. The difference is also due to the need of supplementary logistic chain that are required to complete case VV-T. The distances between the deep sea quay and the yard area of both the terminals are to be fulfilled by AGVs. The difference in their routes can been seen in the appendix. From these results it can be seen that Case VV-A would be the most suitable due to it's high efficiency with respect to throughput and fulfillment rate. Even though case VV-T has an edge over case VV-A for fleet size, it would be more efficient to use case VV-A, Amphibious AGV as the main handling equipment for Inter Terminal Transfer (ITT). In order to transfer a few containers in priority, case VV-A/AAGV is the best option as it takes the least amount of time with the least amount of container re-handling points.

4.5.3 Case SV: Yard To Quay

Yard to Quay Case is synonymous with Storage to Vessel scenario. Here, a set of containers have to be transported from the Storage yard of Hutchinson Ports ECT Euromax to Vessels at each of the other Four Terminals. This transport requirement can be fulfilled by either using Truck, Barge or Amphibious AGV as the primary equipment of ITT. To compare and understand the results, this case is first explained with respect to the mode of Inter Terminal Transport and then followed by a discussion on the results.

Case SV-T

When using a Truck as the main equipment for Inter Terminal Transport for Case SV, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 2 simulation chains namely A and B(as shown in figure 4.31). Chain A consists of the process where the agent Truck interacts with the Storage Yard of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Storage Yard of either of the 4 Terminals based on the order allocation. Chain B consists of the agent AGV interacting with the Storage Yard of one of the 4 terminals where it picks up containers and drops it at the Deep Sea Quay within the same terminal.

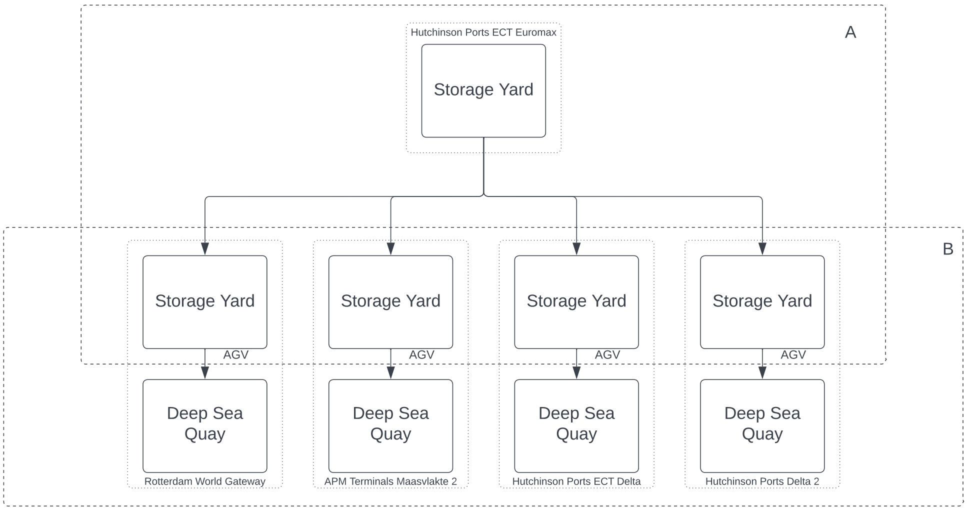


Figure 4.31: Container Flow between agents, Case SV-T

Case SV-B

When using a Barge as the main equipment for Inter Terminal Transport for Case SV, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 3 simulation chains namely A, B and C(as shown in figure 4.32). Chain A consists of the process where agent AGV interacts with the yard agent of Hutchinson Ports ECT Euromax and transports containers to the Barge Quay of the same terminal. Chain B consists of the process where the agent Barge interacts with the Barge Quay of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Barge Quay of either of the 4 Terminals based on the order allocation. Chain C consists of the agent AGV interacting with the Barge Quay of one of the 4 terminals where it picks up containers and drops it at the Deep Sea Quay within the same terminal.

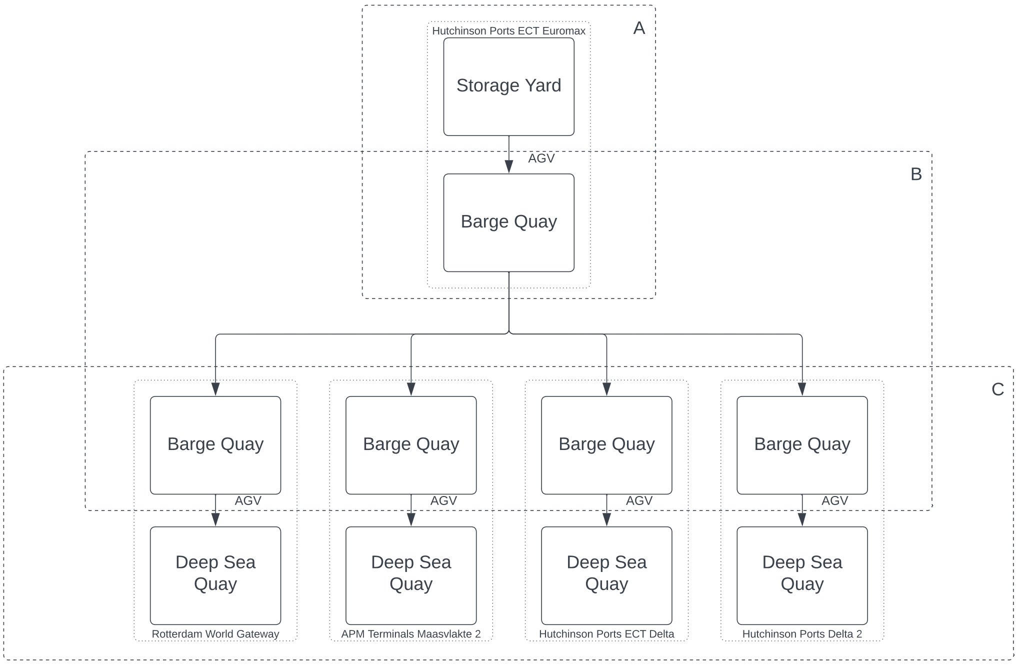


Figure 4.32: Container Flow between agents, Case SV-B

Case SV-A

When using a Amphibious AGV as the main equipment for Inter Terminal Transport for Case SV, the container flow is as shown in figure 4.33. The AAGV agent interacts with the Yard Agent of Hutchinson Ports ECT Euromax where it picks up containers from there, travels on land and enters the sea through the AAGV Ramp. Then it travels on water till it reaches the AAGV Ramp, enters land again and drops the container off at the Deep Sea Quay of one of the for terminals based on order allocation.

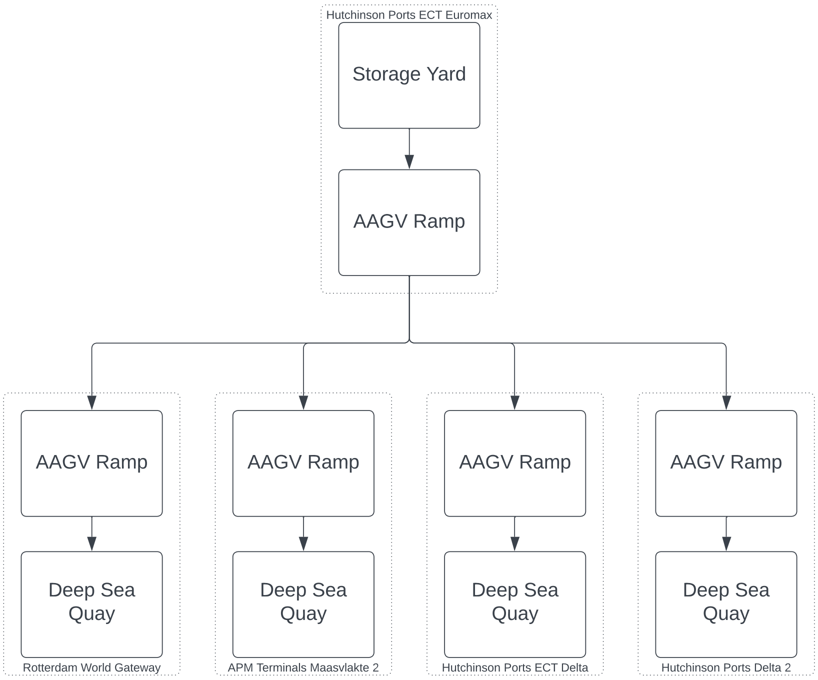


Figure 4.33: Container Flow between agents, Case SV-A

Results and Discussion

The Simulation results are divided based on the sub cases of case SV. Figure 4.34 compares the time taken to transport a container, throughput, total fleet size and fulfillment rate of cases SV-T, SV-B and SV-A. The least time to transport a container from a storage yard to a vessel berthed in another terminal is seen in case SV-T. By transporting containers using Truck the time saving is almost 40% compared to that of using AAGVs as seen in Case SV-A. In case SV-B, it takes 473.46 minutes to transport 100 containers (200 teu). This time difference between case SV-T or SV-A and case SV-B is due to the difference in container handling capacities, mooring requirement of barges and the need of supplementary logistic chains with AGVs to complete the process in case SV-B. The time difference between case SV-T and SV-A is because of multiple factors like speed limitation of AAGV in water, speed limitation of AAGV in land (within terminal) and development of container exchange route (CER) for Trucks with greater speed limits. The throughput of case SV-T and SV-A are very comparable with each other, case SV-A having the edge over Case SV-T by 18 teu/hr. The Throughput of case SV-B is almost 30% lower than that of case SV-A. Throughput helps in understanding the container handling capacity of the logistic chain. Throughput helps in understanding the trend of the Fulfillment rate. As shown in Figure 4.34, Fulfillment rates of cases SV-T, SV-A and SV-B are 89.55%, 95.29% and 64.37% respectively. From fulfillment rate and throughput it can be understood that the logistic chains are more efficient in case SV-A compared to case SV-T and SV-B by 5% and 25% respectively. Fleet Size in case SV-A are considerably high than compared to that of case SS-T or SS-B. The fleet size of case SV-T, case SV-A and SV-B are 146 (trucks+AGVs), 224(AAGVs) and 121 (barges+AGVs) respectively. The Cases SV-T, SV-A and SV-B have 3, 2 and 4 container re-handling points respectively. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size, greater fulfillment rate and least amount of container re-handling points. Upon comparing SV-T, SV-A and SV-B on this basis it can be found that the performance of logistic chain between case SS-T and SS-A is close, case SV-A having a edge over SV-T on KPIs like fulfillment rate and throughput while case SV-T has an edge over SV-A with respect to fleet size. In order to understand this scenario closely, a route breakdown is done to analyze how these results differ for individual routes. This analysis is beneficial to see if the effect of average/approximation plays a vital role in the results shown in Figure 4.34.

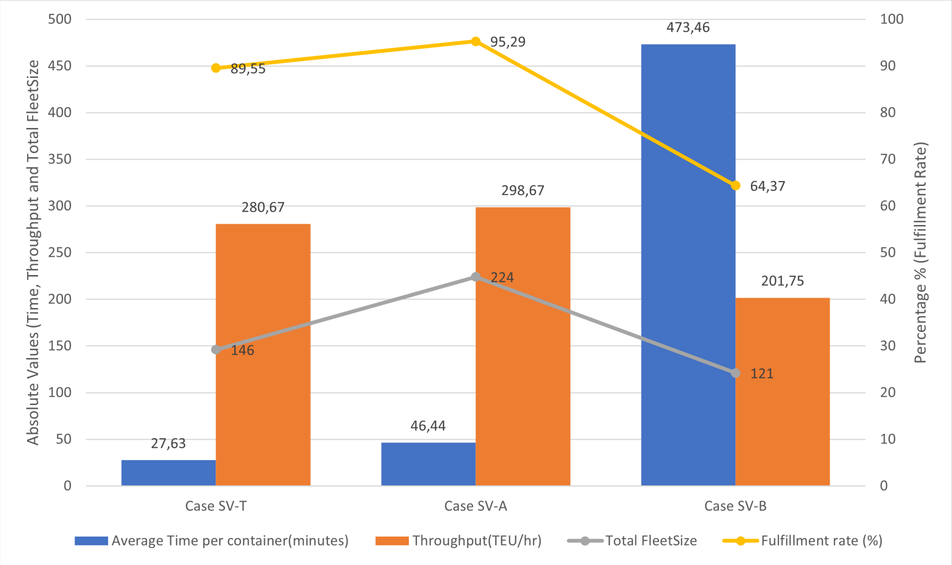


Figure 4.34: KPIs: Time, Throughput, Fleet Size and Fulfillment Rate

The container flow is as shown in Figures 4.31, 4.32 and 4.33, but is made linear or broken down separately. These results are depicted in Figure 4.35. It is observed that the trend of case SV-A having better performance of logistic chain over case SV-T is similar for all routes. A slight discrepancy is seen in the route Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2. For this route, it is observed that the difference in KPIs are lower between cases SV-A and SV-T. The KPIs like throughput, fulfillment rate and fleet size are lower by 2.5 teu/hr, 3% and 6 handling equipment respectively. As it is observed that there was a slightly different output than that of 4.24, this result is affected by the averaging/approximation effect.

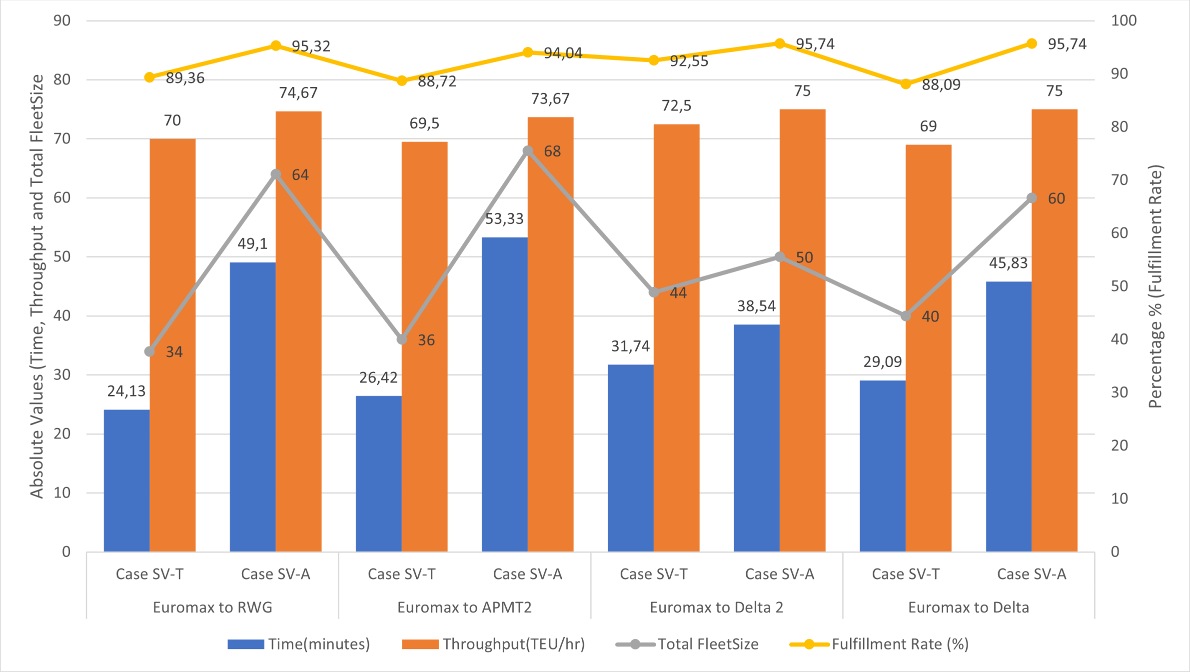


Figure 4.35: Route wise Analysis

This slight anomaly can be understood by referring Figures 4.19, 4.20 and 4.11, it can be seen that the distance between the storage yard location of Hutchinson Ports ECT Euromax and the deep sea quay location of Hutchinson Ports Delta 2 is somewhat greater by using the road than the AAGV route. The difference is also due to the need of supplementary logistic chain that are required to complete case SV-T in Hutchinson Ports Delta 2 with AGVs. Another difference is the speed limits each of these handling equipments have to abide by, an average 60 kmph for the truck and 12 kmph for the AAGV. The difference in their routes can been seen in the appendix. From these results it can be seen that Case SV-A would be the most suitable due to it's high efficiency with respect to throughput and fulfillment rate. Even though case SV-T has an edge over case SV-A for fleet size, it would be more efficient to use case SV-A, Amphibious AGV as the main handling equipment for Inter Terminal Transfer (ITT). In order to transfer a few containers in priority, case SV-A/AAGV is the best option as it takes the least amount of time with the least amount of container re-handling points.

4.5.4 Case VS: Quay To Yard

Quay to Yard Case is synonymous with Vessel to Storage scenario. Here, a set of containers have to be transported from a Deep Sea Vessel at Hutchinson Ports ECT Euromax to the Storage Yard of other Four Terminals. This transport requirement can be fulfilled by either using Truck, Barge or Amphibious AGV as the primary equipment of ITT. To compare and understand the results, this case is first explained with respect to the mode of Inter Terminal Transport and then followed by a discussion on the results.

Case VS-T

When using a Truck as the main equipment for Inter Terminal Transport for Case VS, there is a need for a supplementary logistic chain, which is assisted by AGVs. This Case is split into 2 simulation chains namely A and B(as shown in figure 4.36). Chain A consists of the process where agent AGV interacts with the Deep Sea Quay of Hutchinson Ports ECT Euromax and transports containers to the Storage Yard of the same terminal. Chain B consists of the process where the agent Truck interacts with the Storage Yard of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Storage Yard of either of the 4 Terminals based on the order allocation.

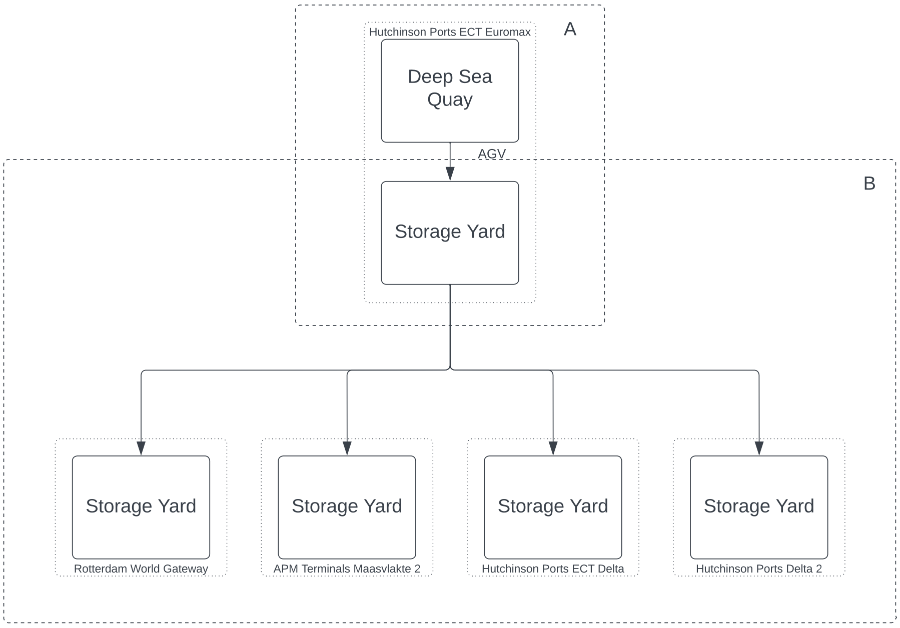


Figure 4.36: Container Flow between agents, Case VS-T

Case VS-B

When using a Barge as the main equipment for Inter Terminal Transport for Case VS, there is a need for supplementary logistic chains, which are assisted by AGVs. This Case is split into 3 simulation chains namely A, B and C(as shown in figure 4.37). Chain A consists of the process where agent AGV interacts with the Deep Sea Quay of Hutchinson Ports ECT Euromax and transports containers to the Barge Quay of the same terminal. Chain B consists of the process where the agent Barge interacts with the Barge Quay of Hutchinson Ports ECT Euromax where it picks up containers and drops it at the Barge Quay of either of the 4 Terminals based on the order allocation. Chain C consists of the agent AGV interacting with the Barge Quay of one of the 4 terminals where it picks up containers and drops it at the Storage yard within the same terminal.

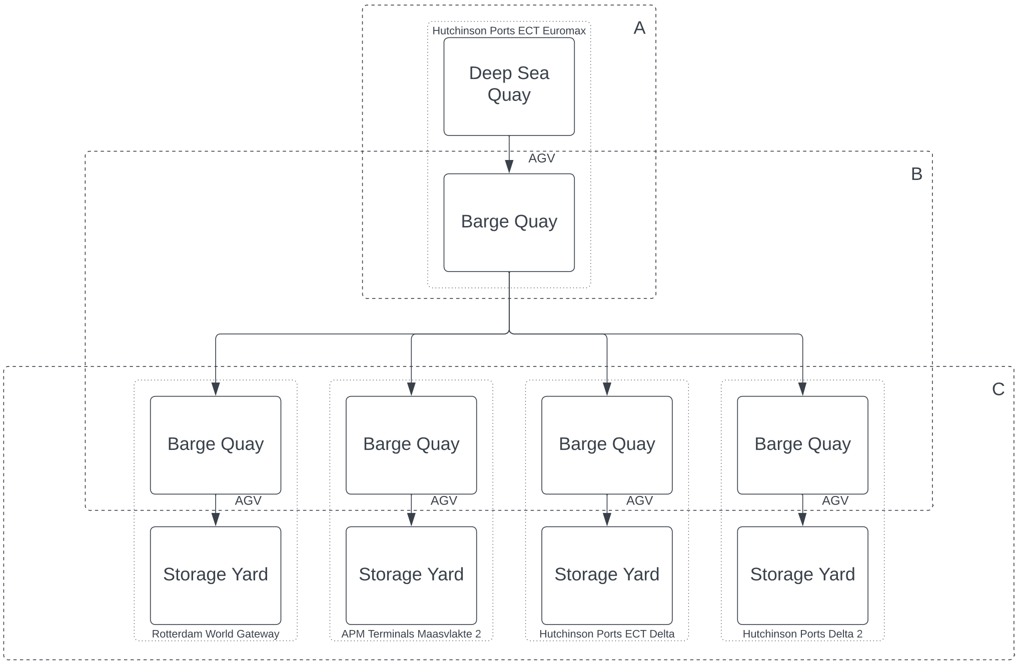


Figure 4.37: Container Flow between agents, Case VS-B

Case VS-A

When using a Amphibious AGV as the main equipment for Inter Terminal Transport for Case VS, the container flow is as shown in figure 4.38. The AAGV agent interacts with the Deep Sea Quay Agent of Hutchinson Ports ECT Euromax where it picks up containers from there, travels on land and enters the sea through the AAGV Ramp. Then it travels on water till it reaches the AAGV Ramp, enters land again and drops the container off at the Storage Yard of one of the for terminals based on order allocation.

Results and Discussion

The Simulation results are divided based on the sub cases of case VS. Figure 4.39 compares the time taken to transport a container, throughput, total fleet size and fulfillment rate of cases VS-T, VS-B and VS-A. The least time to transport a container from a vessel to the storage yard of another terminal is seen in case VS-T. By transporting containers using Truck the time saving is almost 33% compared to that of using AAGVs as seen in Case VS-A. In case VS-B, it takes 473.46 minutes to transport 100 containers (200 teu). This time difference between case VS-T or VS-A and case VS-B is due to the difference in container handling capacities, mooring requirement of barges and the need of supplementary logistic chains with AGVs to complete the process in case VS-B. The time difference between case VS-T and VS-A is because of multiple factors like speed limitation of AAGV in water, speed limitation of AAGV on land (within terminal) and development of container exchange route (CER) for Trucks with greater speed limits. The throughput of case VS-T and VS-A are very comparable with each other, case VS-A having the edge over Case VS-T by 2 teu/hr. The Throughput of case VS-B is almost 30% lower than that of case VS-T or VS-A. Throughput helps in understanding the container handling capacity of the logistic chain. Throughput helps in understanding the trend of the Fulfillment rate. As shown in Figure 4.39, Fulfillment rates of cases VS-T, VS-A and VS-B are 94.55%, 95.29% and 64.37% respectively. From fulfillment rate and throughput it can be understood that the logistic chains are more efficient in case VS-T and VS-A compared to VS-B by 30%. Fleet Size in case VS-A are considerably high than compared to that of case VS-T or VS-B. Case VS-T, case VS-A and case VS-B have a fleet size of 152 (trucks+AGVs), 224 (AAGVs) and 99 (barges+AGVs) respectively. The Cases VS-T, VS-A and VS-B have 3, 2 and 4 container re-handling points respectively. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size, greater fulfillment rate and least amount of container re-handling points. Upon comparing VS-T, VS-A and VS-B on this basis it can be found that the performance of logistic chain between case VS-T and VS-A is close, where case VS-T has the edge over fleet size while all the other KPIs are better for Case VS-A by a small margin. In order to understand this scenario closely, a route breakdown is done to analyze how these results differ for individual routes. This analysis is beneficial to see if the effect of average/approximation plays a vital role in the results shown in Figure 4.39.

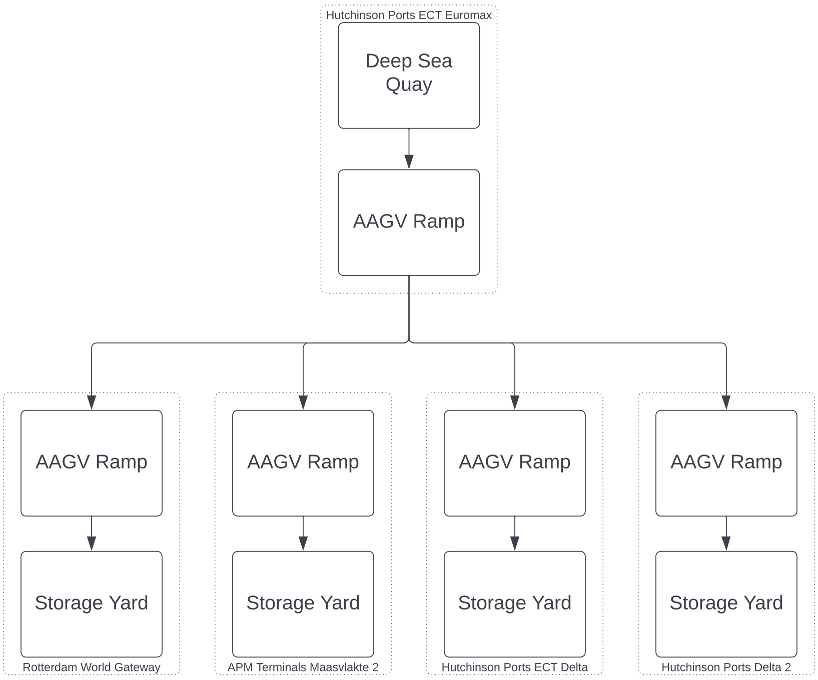


Figure 4.38: Container Flow between agents, Case VS-A

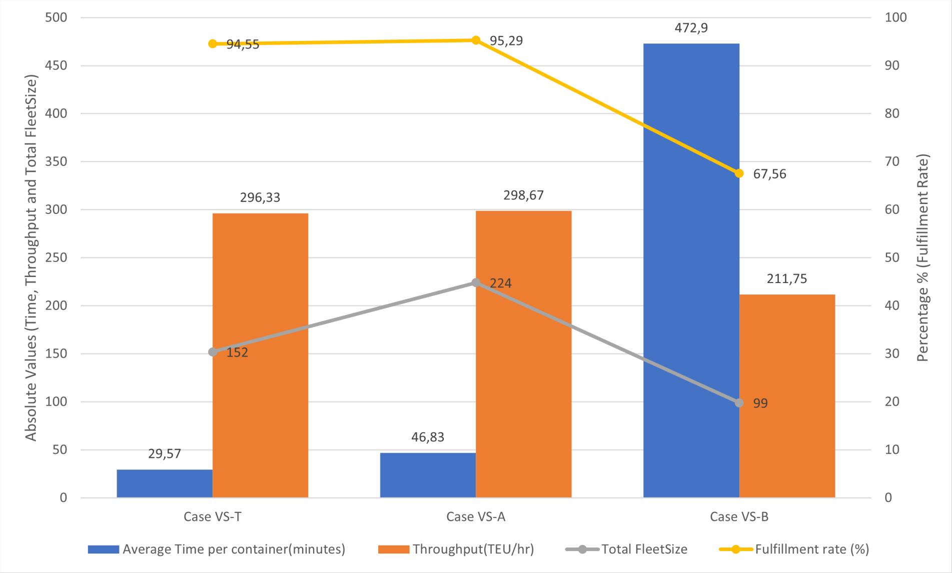


Figure 4.39: KPIs: Time, Throughput, Fleet Size and Fulfillment Rate

The container flow is as shown in Figures 4.36, 4.37 and 4.38, but is made linear or broken down separately. These results are depicted in Figure 4.40. It is observed that the trend of case VS-A having better performance of logistic chain over case VS-T is similar for all routes. The trend of case VS-T having an edge over case VS-A in terms of the KPI throughput and fulfillment rate is similar except for the route Hutchinson Ports ECT Euromax to Rotterdam World gateway. For this route, it is observed that the case VS-T has an edge over case VS-A with a greater throughput by 1.6 teu/hr and fulfillment rate by a little over 2%. The trend of case VS-T having an edge over case VS-A in terms of the KPI fleet size is also similar for all routes other than the route Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2. For this route, it is observed that case

VS-A has greater fleet size than case VS-T but just by 8 handling equipment. This is a reduction in a considerable amount of handling equipment. The throughput and fulfillment rate are also greater than by almost 3 teu/hr and 3.5% which is a lot less than the results in Figure 4.29. As the output is just slightly different than that of 4.29, this result is not affected greatly by the averaging/approximation effect.

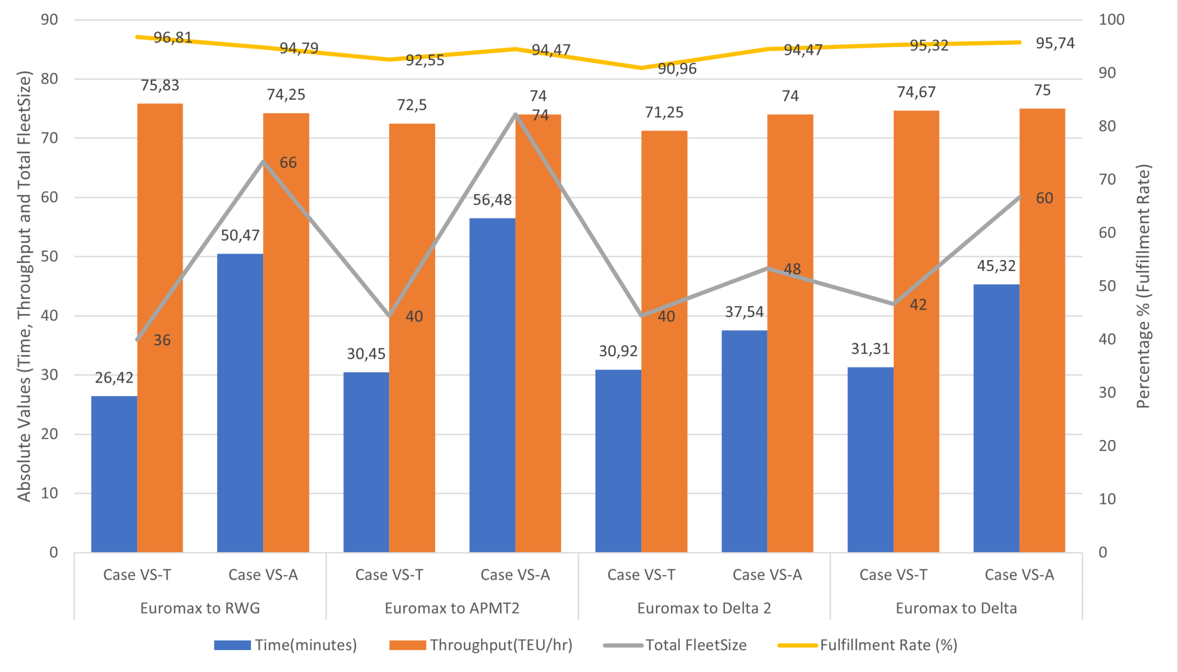


Figure 4.40: Route wise Analysis

These anomalies can be understood by referring Figures 4.19, 4.20 and 4.8, it can be seen that the distance between the deep sea quay location of Hutchinson Ports ECT Euromax and the storage yard location of Hutchinson Ports Delta 2 or Rotterdam World Gateway is greater by using the road than the AAGV route. The difference is also due to the need of supplementary logistic chain that are required to complete case VS-T at Hutchinson Ports ECT Euromax for both routes. The distances between the deep sea quay to the AAGV ramp and the AAGV ramp to the yard area of the terminals are to be fulfilled by AGVs. The difference in their routes can been seen in the appendix. From these results it can be seen that Case VS-T would be the most suitable due to the already available truck fleet, available infrastructure (CER) and lower fleet size. Even though case VS-A has an edge over case VS-T for 3 routes with respect to fulfillment rate and throughput, it would be more efficient to use case VS-T, Truck as the main handling equipment for Inter Terminal Transfer (ITT). In order to transfer a few containers in priority, case VS-A/AAGV is the best option as it takes the least amount of time with the least amount of container re-handling points.

4.5.5 Discussion

The outcomes of all the cases are presented in subsections 4.5.1, 4.5.2, 4.5.3 and 4.5.4. Additional data regarding the simulation can be found in the appendix, which collectively provide the performance of Amphibious AGVs in various Logistic chains. The results evidently indicate that Amphibious AGVs have surpassed the requirements of efficient inter terminal container transport in terms throughput, fulfillment rate and utilization for certain cases. This notable concept can be used to improve efficiency of logistic chain and also act as a redundant handling equipment which could be used as a solution towards solving the ever growing problem of container backlog.

As discussed in [9], there is a growing problems with respect to container handling. There is extensive research being carried in the field of mitigating container marshalling problems. Container Marshalling is the process of receiving cargo from one mode of transport and loading it in the terminal for export or further transit [70]. This problem of container marshalling is divided into two: Container Pre-Marshalling problem (CPMP) and Container Re-Marshalling Problem (CRMP). There have been 22 publications on CRMP and 8 publications on CPMP between 2006 and 2016 [9], this shows the gravity of the issue. Solving the problem of encountering delays with respect to container re-handling points can be avoided by employing AAGVs for container ITT. Figure 4.41 represents the number of re-handling points for all the cases and sub cases. For container transport over a short distance like within the Maasvlakte, it is ideal to have a uni-modal container transport and preferable to have lesser number of container re-handling points. Sub case A is ideal for all cases while sub case T is suitable for Case SS alone.

This gives the option to choose between case SS-T and case SS-A for case SS and it is cases VV-A, SV-A and VS-A for cases VV, SV and VS respectively.

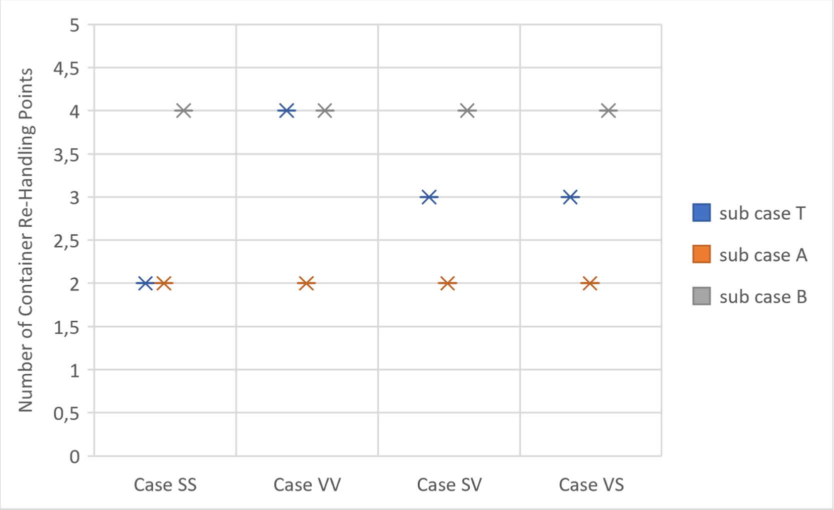


Figure 4.41: Case wise Re-Handling Points KPI Comparison

Figures 4.42, 4.43, 4.44 and 4.45 represent the fleet size and it's split. These results help us understand the need for AAGV for intra terminal operations as they can perform the tasks of AGVs. For case SS, the chosen efficient sub case is SS-T. Therefore a fleet of 112 trucks are required, this service is provided by various trucking companies that operate in the port of Rotterdam. For case VV, the chosen efficient sub case is VV-A. Therefore a fleet of 231 AAGVs are required, this service can be provided by the terminal operators themselves to reduce their dependencies on stakeholders. It is a similar situation for case SV where case SV-A is efficient with an AAGV fleet size of 224. For case VS, the chosen efficient sub case is VS-T. Therefore a fleet of 112 trucks and 40 AGVs are required, this truck service is provided by various trucking companies that operate in the port of Rotterdam and in order to standardise equipment AAGVs can be used to supplement the function of AGVs. Figures 4.46, 4.47 and 4.48 represent in depth the opportunity for AGV operations to be taken over by AAGVs. For case SS, the selected fleet consists completely of trucks. For case VV and case SV, the selected fleet consists of all AGVs. But for case VS, the fleet consists of a mix between AGVs and trucks. This exact split is as seen in Figure 4.48. Employing these Amphibious AGVs can also help in increasing the storage space of ports by the reduction of material Handling equipment that are used for certain transshipment. Rethinking and redesigning existing port areas can help making ports more green and ready to handle more number of containers. For a port like Rotterdam as shown in Figure 4.1, an Amphibious Automated Guided Vehicles could be beneficial due to presence of multiple Havens. The Shortest distance or shortest time need not be achieved just by using land or water based transport equipment's for inter-terminal transport.

4.6 Sensitivity Analysis

Sensitivity analysis is integral in analytical reports, offering crucial insights into the validity of findings. It entails systematically adjusting critical model elements to gauge their effect on outcomes. This section clarifies the methods used, variables examined, and the consequences of these adjustments, bolstering the study's credibility and relevance. For this research the chosen parameter that is adjusted is the Demand/Container Input per day. This parameter is adjusted based on the findings and reporting of [26] which is used in [96] and [58]. A tolerance limit of -10% to 10% is taken with a step of 5%. The Projected demand for Scenario 1(High Demand Scenario) and Scenario 2(Reduced Demand Scenario) are also used to compute sensitivity. This data can be seen in table 4.10.

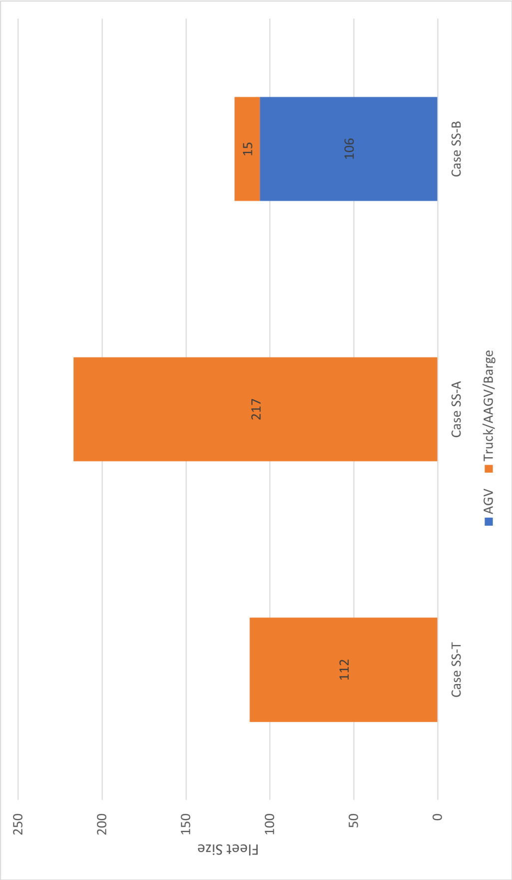


Figure 4.42: Case SS: Fleet Size Comparison with Split

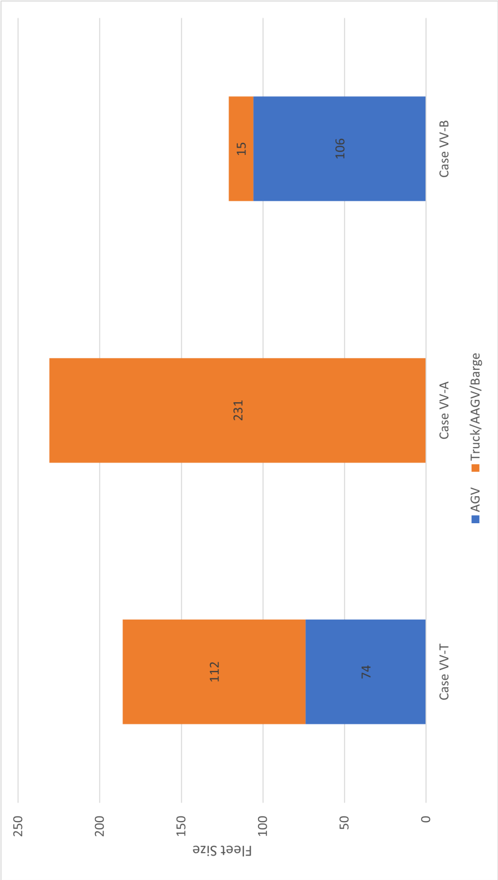


Figure 4.43: Case VV: Fleet Size Comparison with Split

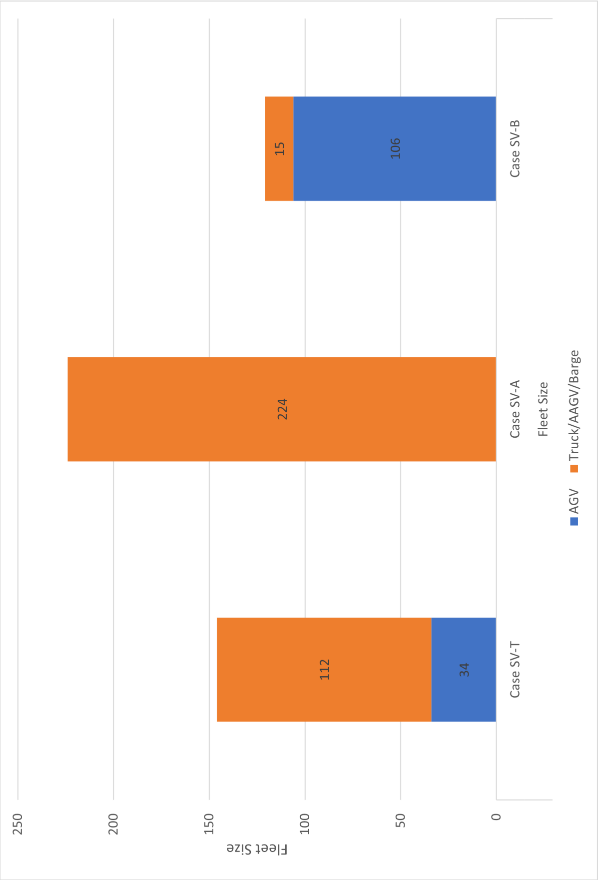


Figure 4.44: Case SV: Fleet Size Comparison with Split

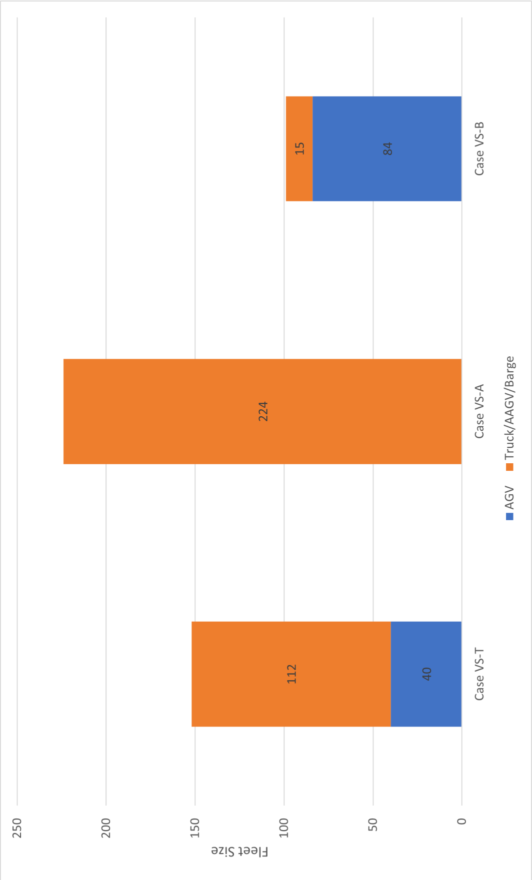


Figure 4.45: Case VS: Fleet Size Comparison with Split

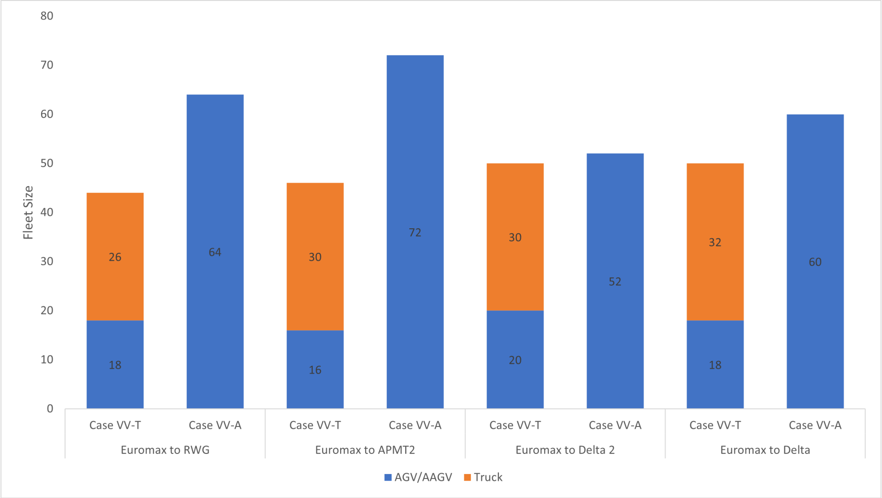


Figure 4.46: Case VV: Route wise Fleet Size Comparison with Split

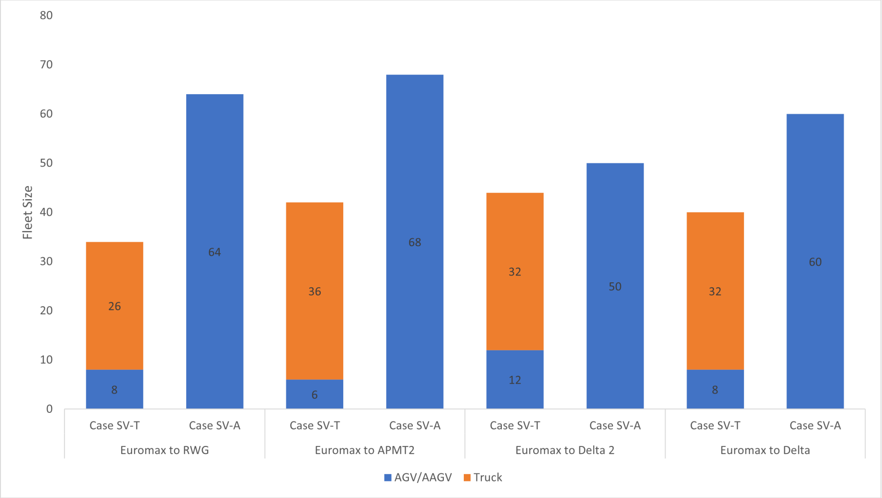


Figure 4.47: Case SV: Route wise Fleet Size Comparison with Split

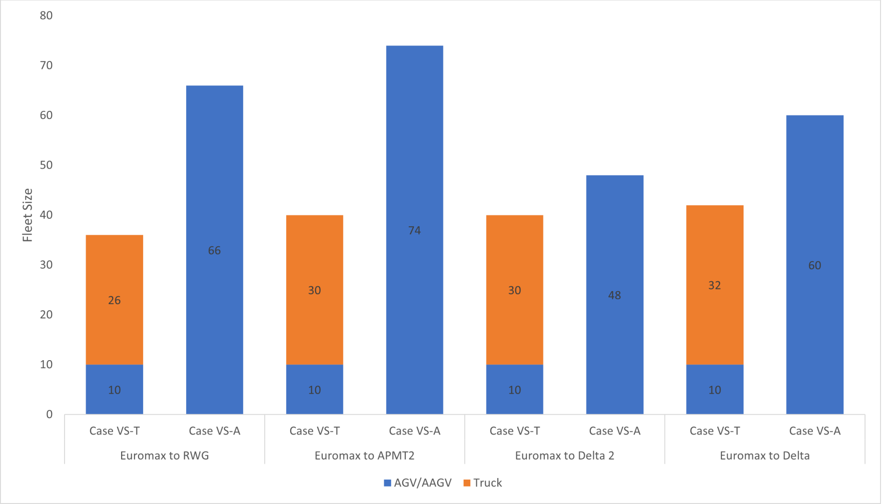


Figure 4.48: Case VS: Route wise Fleet Size Comparison with Split

Table 4.10: Demand Variability, [26][96][58]

Demand 2030	
Projected Average Demand -10%	3385
Projected Average Demand -5%	3573
Projected Average Demand	3761
Projected Average Demand +5%	3949
Projected Average Demand +10%	4137
Projected Reduced Demand Scenario	2945
Projected High Demand Scenario	4576

Sensitivity analysis is only performed for Case VV and Case SV as only for these 2 cases employing Amphibious AGVs is beneficial over Trucks or Barges. AAGVs have an edge over other modes wrt KPIs like Throughput, Re-Handling points, Fleet Size and Fulfillment Rate.

4.6.1 Case VV: Quay To Quay

It is found in subsection 4.5.2, that Amphibious AGVs could be employed to increase the efficiency of the logistic chain in Case 2. A sensitivity analysis is performed to understand how KPIs like Time, Throughput, Fleet Size and Fulfillment rate are effected. Graph 4.49 depicts how these KPIs are effected based on the change in Projected demand as per table 4.10. It is seen that the time taken to transport a container and the Fulfillment rate remain almost constant. This is an indicator that the efficiency of the system is constantly maintained. The Throughput and Fleet Size show an increase at a constant rate to maintain this efficiency. The slope of Throughput is greater than that of the Fleet Size. This depicts that AAGV would be suitable to handle greater container demand.

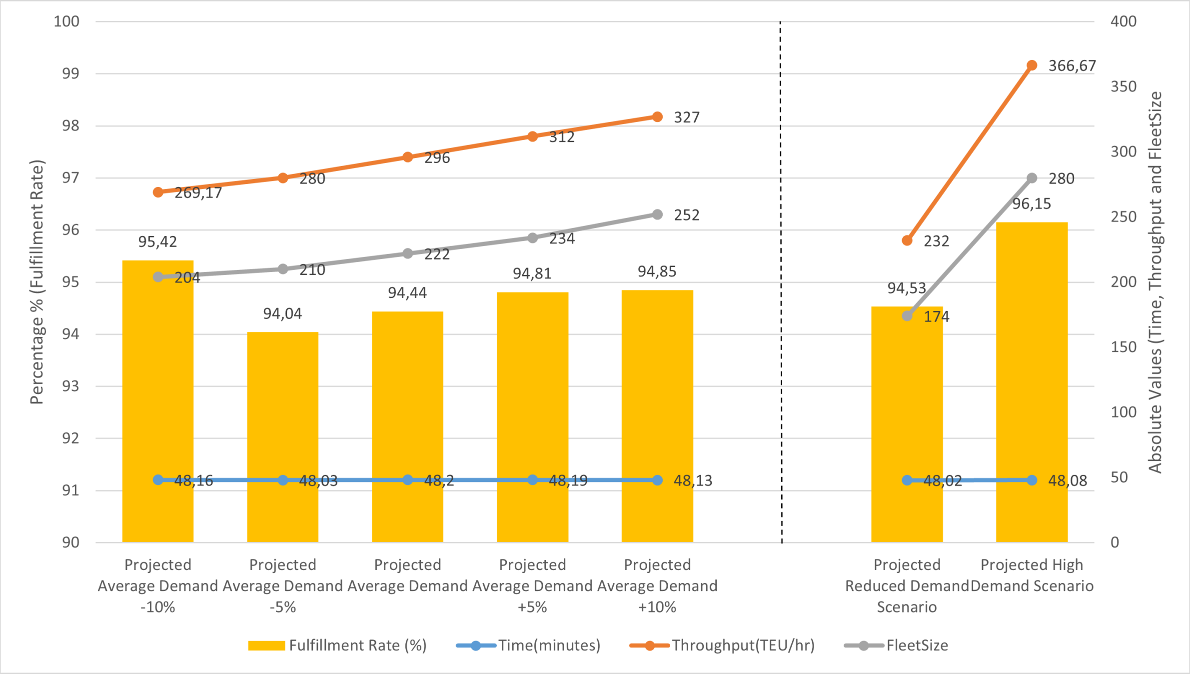


Figure 4.49: KPIs: Time, Throughput Fleet Size and Fulfillment rate

4.6.2 Case SV: Yard To Quay

It is found in subsection 4.5.3, that Amphibious AGVs could be employed to increase the efficiency of the logistic chain in Case 3 but at the cost of having a greater fleet size than trucks. A sensitivity analysis is performed to understand how KPIs like Time, Throughput, Fleet Size and Fulfillment rate are effected. Graph 4.50 depicts how these KPIs are effected based on the change in Projected demand as per table 4.10. It is seen that the time taken to transport a container and the Fulfillment rate remain almost constant. This is an indicator that the efficiency of the system is constantly maintained. The Throughput and

Fleet Size show an increase at a constant rate to maintain this efficiency. The slope of Throughput is greater than that of the Fleet Size. This depicts that AAGV would be suitable to handle greater container demand.

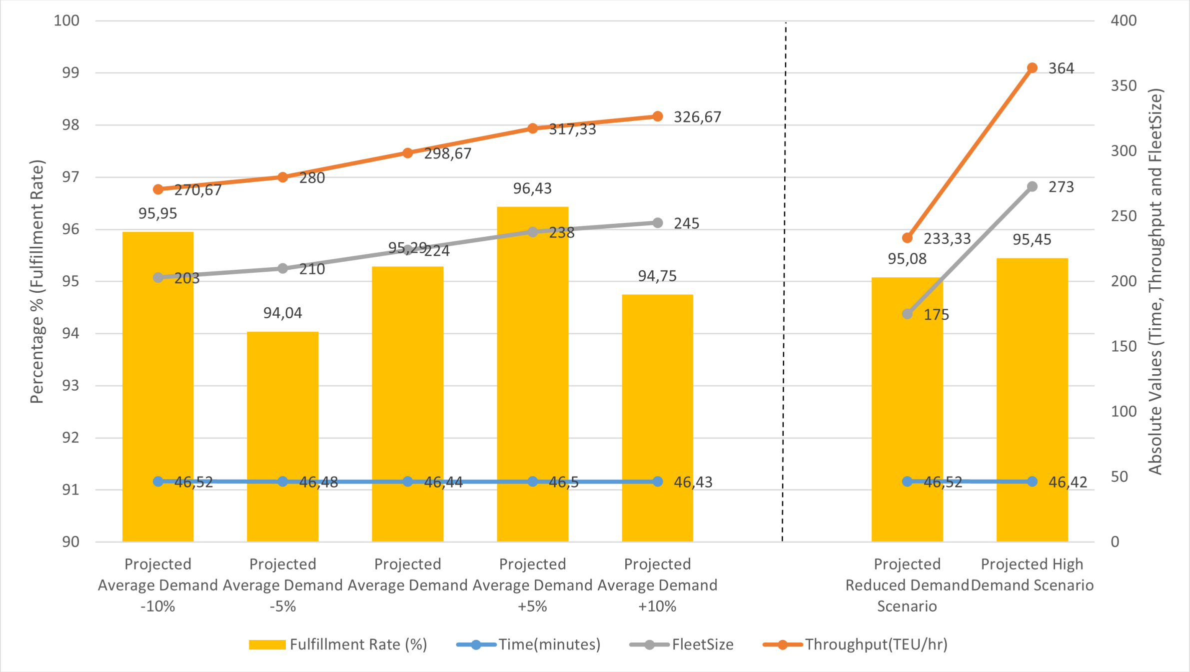


Figure 4.50: KPIs: Time, Throughput Fleet Size and Fulfillment rate

Similar results are observed for the sensitivity analysis of Case 2 and Case 3. This implies that this is the general behaviour of Amphibious AGVs in Container ITT. Sensitivity analysis is not performed for Case 1 and Case 2 because the use of Trucks as the Inter Terminal handling equipment is more beneficial than Amphibious AGVs.

4.7 Space Utilization

This section sheds light on why there is a need for space in container terminals, how space can be created and how this created space can be utilized by the Terminal Operators.

Container terminals, pivotal nodes in the global supply chain, are finding themselves at the center of a rapidly changing industry. With a surge in global trade, these terminals are facing unprecedented demands for their services. The main driving force behind the need for additional space within container terminals is the escalating volume of containers and ships passing through their facilities. This increase in container traffic reflects the expanding scope of global commerce, compelling terminals to enhance their capacity and capabilities to meet the rising flow of goods and merchandise. The maritime sector has undergone a significant shift with the introduction of larger container vessels. This change has profound implications for container terminals. To accommodate these massive ships, terminals must now offer deeper berths, larger stacking areas, and employ cutting-edge handling equipment. These infrastructure adaptations are crucial in ensuring that terminals remain in sync with the evolving requirements of the shipping industry, further emphasizing the necessity for extra space within these vital facilities. Automation and technological integration are another critical factor driving the need for additional space in container terminals. The incorporation of advanced technologies, such as automated stacking cranes and systems, requires not only physical room but also a strategic reorganization of terminal layouts. By embracing automation, container terminals improve their operational efficiency and throughput capacity, ultimately leading to more efficient and competitive operations. Upgrading infrastructure is a crucial endeavor for container terminals aiming to stay ahead in the industry. To meet evolving industry standards and adapt to the needs of larger vessels and increased traffic, terminals must invest in new facilities and equipment. This essential undertaking mandates the allocation of extra space within the terminal's footprint. These upgrades are not only vital for the terminal's operational efficiency but also for ensuring compliance with industry best practices. Expanding yard capacity and stacking areas emerge as a critical consideration in optimizing container handling. As the demand for container storage grows, terminals must expand their stacking areas and strategically optimize yard space. This is imperative in ensuring the smooth flow of containers through the terminal, ultimately enhancing overall operational efficiency. The integration of intermodal transportation is a key aspect of modern container terminals. To facilitate seamless connections between different modes of transportation, terminals must allocate space for truck and rail facilities, as well as specialized areas for container transfer. This integration not only streamlines the movement of goods but also enhances the terminal's connectivity with broader transportation networks. In the pursuit of environmental sustainability and regulatory compliance, container terminals set aside space for eco-friendly initiatives and compliance measures. This commitment reflects the industry's dedication to reducing its environmental impact. By designating areas for sustainable practices and compliance measures, terminals contribute to a more environmentally balanced and sustainable future[27].

		Truck		AAGV		Barge	
	Weight	Rating	Value	Rating	Value	Rating	Value
Quay Cranes	1	0	0	0	0	0	0
Automatic Stacking Cranes	4	2	8	0	0	0	0
Barge Quay Cranes	2	0	0	0	0	2	4
Ramp	5	0	0	2	10	0	0
Total			8		10		4

Rating scale: 1 = High amount of area taken, 2 = Somewhat high amount of area taken, 3 = Ideal amount of area taken, 4 = Low amount of area taken, 5 = Least amount of area taken

Figure 4.51: Weighted Decision Matrix

Figure 4.51 depicts the weighted decision making matrix which is used for the equipment trade-off Analysis. We can see the Amphibious AGV has the highest total value, which means that it has most ideal area usage compared to using barge or truck. This decision criteria is common for all Cases, as the initial and Final handling equipment are neglected in the weighted decision matrix. The weighted rankings are 1 for Quay Cranes, 4 Automated Stacking Cranes, 2 for Barge Quay Cranes and 5 for Ramp. This is because equipment like Quay Cranes, Automatic Stacking Cranes and Barge Quay Cranes use up area of the terminal greater than that of a ramp. A ramp is set to be constructed in an non-utilized part of the terminal as shown in section 4.2. Quay Crane occupies the highest amount of space, then followed by the Barge Quay Crane as it has significantly shorter outreach, backreach and rail guage [6]. The Autonomous Stacker Crane has a smaller rail guage than the Quay Crane or Barge Quay Crane in general but the area in between these rails are used for container storage, thereby taking lesser area. So based on this information, a decision has to be made that using AAGV can benefit by freeing up the usage of Barge Berths and the operating schedule of redundant handling equipment.

4.8 Conclusion

This sections sums up all the inferences made from various results for the case study across all experiments in this chapter. This chapter first delves into understanding the geography of the port of Rotterdam and then converting them into inputs as required by the developed simulation model. Case wise results are discussed in this chapter. In order to summarize these results, a case wise comparison is performed for all KPIs. When AAGVs are employed as the main inter terminal handling equipment the fleet size is maximum, this is because of the uni-modality of the handling process. This uni-modality also affects the time take for transferring a single container handling equipment to get from origin to destination, AAGVs having a greater time compared to trucks across all cases. Barges take the greatest time as they have a greater capacity than trucks and AAGVs. Upon employing AAGVs supplements the logistic process with greater throughput and fulfillment rate. When trucks are employed as the inter terminal handling equipment, the throughput and fulfillment rate are are little lower than that of using AAGVs across majority cases. The throughput and fulfillment rate when barges are employed are very low compared to using trucks or AAGVs, this occurs due to the additional process requirements while employing barges. Making AAGVs and trucks more efficient to use for container inter terminal transport within the Maasvlakte than barges. These results can be seen from the graphs in figure 4.52, 4.53, 4.54 and 4.55. These results are a culmination of the performance of logistic process over multiple routes. Hence, these results could be effected by averaging. As the KPIs for AAGVs and trucks are very close, analysing this effect of averaging is crucial.

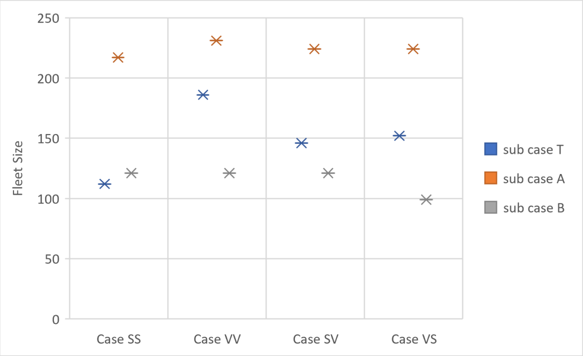


Figure 4.52: Case wise FleetSize KPI Comparison

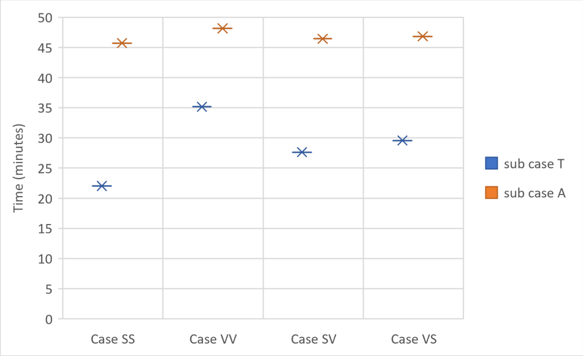


Figure 4.53: Case wise Time KPI Comparison

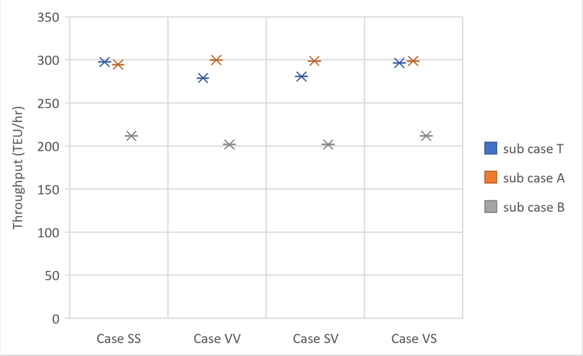


Figure 4.54: Case wise Throughput KPI Comparison

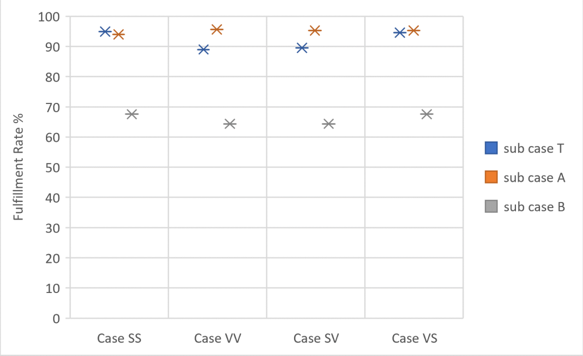


Figure 4.55: Case wise Fulfillment Rate KPI Comparison

To understand the performance edge of AAGVs and trucks over each other, a route analysis is performed. From this it can be seen that performance is affected not just route wise, but also case wise. The result inferences of employing AAGVs as the inter terminal handling equipment route wise are as shown in Table 4.11. Upon correlating these inferences with the distance matrix as shown in Table 4.12, the profile of routes where AAGVs could be employed can be identified. AAGVs can be employed as the inter terminal handling equipment where the distance difference to truck is atleast 50% lesser than that of employing trucks.

Table 4.11: Inferences from Route Analysis where AAGV has an edge over Trucks

1	**Hutchinson Ports ECT Euromax to Rotterdam World Gateway**		
	Case VV	Throughput	9%
		Fulfillment Rate	6%
2	**Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2**		
	Case VV	Throughput	9%
		Fulfillment Rate	8%
3	**Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2**		
	Case VV	Throughput	28%
		Fulfillment Rate	21%
	Case SV	Throughput	4%
		Fulfillment Rate	3%
	Case VS	Throughput	4%
		Fulfillment Rate	4%
4	**Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta**		
	Case VV	Throughput	9%
		Fulfillment Rate	8%
	Case SV	Throughput	9%
		Fulfillment Rate	8%

Table 4.12: Distance Matrix

Routes	**Truck**	**AAGV**
Hutchinson Ports ECT Euromax to Rotterdam World Gateway	15.5 km	8.5 km
Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2	20 km	9.5km
Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2	20 km	6 km
Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta	20 km	7 km

Additionally, a sensitivity analysis is performed to see how change in demand affects these KPIs. Fleet Size increase with a constant slope while time taken for a handling equipment to move from origin to destination remains constant. Throughput increases with a constant slope and fulfillment rate remains constant. The slope of throughput is greater than that of the fleet size. Hence, employing Amphibious AGVs is suitable when demand is greater for short range inter terminal transport. Employing AAGVs also contribute towards freeing barge berths and the work schedule of multiple re-handing equipment within a terminal. The research is concluded in chapter 5 where all the research questions are answered.

Chapter 5

Conclusion

The objective of this thesis was to see if amphibious vehicles can contribute towards ITT problems such as delays and space availability. A conceptual model was developed using Agent Based Modelling(ABM) and Genetic Algorithm(GA). This chapter focuses on answering the research questions and drawing conclusions from the output of the model. Additionally, this chapter has recommendations for future research in this topic.

5.1 Concluding Remarks

This section answers the research questions as defined in section 1.3. A detailed answer to each of these sub-research questions will help answer the main research question.

1) What is a suitable strategy to quantify and compare different modes of ITT?

In chapter 2, an in depth literature review is conducted to explore various simulation and optimization techniques that could be used to quantify the required logistic chains. As this thesis delves into the introduction of a novel concept of Amphibious AGVs, it is important to understand the behavior of this new material handling equipment. Agent Based Simulation was chosen to be the Simulation type as it is a powerful modeling technique used to study and optimize the movement of goods and information within complex supply networks. This approach employs agents, to represent various components like suppliers, manufacturers and material handling equipment. Each agent operates based on predefined rules and interacts with other agents, allowing for a dynamic representation of real-world logistics processes. It reacts to stimuli like container demand fluctuation with the help of iterative runs of the simulation for diverse scenarios and their respective outcomes are assessed.

There is a requirement for an optimization experiment in order to maximize the utilization of the fleet of material handling equipment used in the logistic chain. The chosen optimization technique is genetic algorithm (GA) because it is a powerful optimization technique inspired by the process of natural selection. It's particularly effective for solving complex problems where traditional methods might struggle. When applied to optimizing resource utilization, genetic algorithms excel in finding near-optimal solutions in a wide range of scenarios. The "genes" represent the potential solutions, each with a set of parameters influencing utilization of the allocated resource. The algorithm iteratively refines these solutions over generations to improve their fitness, ultimately converging towards an optimal or near-optimal configuration.

There are multiple platforms with the functionality of integrating Genetic Algorithm and Agent Based Simulation. The two predominant platforms are Arena and AnyLogic. Due to the availability of GIS map feature in AnyLogic, it is chosen as the platform on which this research is to be conducted. The GIS map helps in getting real time routes and distance which is helpful to mimic real time situations.

2) What is the impact of implementing Amphibious AGVs on port equipment interaction?

In chapter 3 a study is done to compare logistic chains where different material handling equipment are used to perform the same task in a given case. These Logistic chains are quantified with the help of a case study on the Port of Rotterdam in chapter 4. The most prominent impact of implementing AAGVs is the reduction container re-handling points. Re-Handling points have significant implications on the efficiency of container terminals as they are prone to operational delays. These delays cannot be quantified as they depend on multiple factors and situations and could span anywhere from a few minutes to a couple days. Some of the common reasons for delays at re-handling points for inter terminal transport are congestion, processing delays, poor inter modal connectivity and shortage of equipment. There is a need for addressing these issues as these are the bottlenecks of the supply chain. Multiple research articles have been published trying to address these issues by using greedy, heuristics, exact and robust approaches (as seen in [9]). This thesis dives into a design approach to mitigate this problem with the concept of uni-modal transport for short distances.

The number of re-handling points are reduced drastically by employing AAGV as compared to employing traditional methods. Figure 4.41 depicts the difference in re-handling points across various cases. Due to this reduction re-handling points, employing AAGVs can free up the operating schedule of multiple handing equipment which could be used for other purposes to meet the ever growing demand.

3) To what extent can the integration of Amphibious AGVs improve port efficiency with respect to the current logistics chain?

Integrating Amphibious AGVs into container ITT operations is both a boon and a bane, depending on the case. For a case of transportation between storage yard and storage yard in the port of Rotterdam at Maasvlakte, it is beneficial to use a truck as the handling equipment rather than a barge or AAGV. This is due to the availability of infrastructural support, the container exchange route But in the case of Vessel to Vessel, it is beneficial to use AAGV as it reduces hassle with the gate elements and re-handling points. Due to this reduced hassle, these logistics chains have greater throughput and fulfillment rate compared to that of traditional equipment. For the case of storage yard and vessel, the logistic chains with AAGVs have an edge over truck and as well as barges with respect to throughput and fulfillment rate but at the cost of fleet size. In the case of vessel to storage yard, truck has the edge over AAGVs and barges. Even though trucks have greater re-handling points and also have an additional supplementary logistic chain employing AGVs, they still can provide better overall performance of logistic chain. The above four cases are named as Case SS, Case VV, Case SV and Case VS respectively and a comparison on their results can be seen in Figures 4.24, 4.29, 4.34 and 4.39 respectively.

In general, Amphibious AGVs are suitable to tackle the problems with delays that arise at container re-handling points. They have an edge over traditional transport in cases where traditional transport require additional supplementary logistic chains to fulfill the process. The efficiency of trucks and AAGVs are almost comparable in all cases, but the delays involved in re-handling points are not accounted for. AAGVs generally require greater fleet sizes than traditional equipment to operate, this is due to their uni-modal transportation nature. This nature also affects the time take to transport a container from origin to destination. A sensitivity analysis is conducted for cases where amphibious AGVs are deemed better than traditional equipment. From this sensitivity analysis it can inferred that AAGVs are suitable to handle higher demands over short distances. This conclusion is made based on the trend of fleet-size with respect to throughput and fulfillment rate.

Overall, Amphibious AGVs are beneficial for container ITT with respect to throughput and fulfillment rate but at the investment cost of greater fleet-size for to transport containers over short distances.

4) What profile of Routes and Scenarios are beneficial to be handled by Amphibious AGVs?

The routes that are suitable for Amphibious AGVs are highly dependent. The routes that are beneficial are dependent based on the difference in distances and re-handling points between the various ITT handling equipment. In the case of storage yard to storage yard for the port of Rotterdam, Amphibious AGV is beneficial across the route of Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2. While in the case of vessel to vessel, AAGVs are beneficial across all routes and in the route of Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2 the fleet size of case VV-A is similar to that of case VV-T. Same observations are seen for the case of storage yard to vessel. For the case of vessel to storage yard, AAGV has better throughput and fulfillment rate for the routes Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2, Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2 and Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta. These routes come at the cost of very high fleet-size other than that of Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2 where the difference in fleet-size is low. The above cases are Case SS, Case VV, Case SV and Case VS respectively and their results on route analysis are depicted in Figures 4.25, 4.30, 4.35 and 4.40 respectively.

In general, Amphibious AGVs can be employed in routes where the distance to speed ratio of the AAGV route is lesser than that of other traditional equipment. The scenarios that are beneficial are predominantly those with involve interaction with quay side container handling equipment. In the case of Rotterdam, Case VV and Case SV over all routes and Case VS over a single route.

5) What is the potential amount of space that can be generated through trade-offs in port equipment and what are the possible ways to utilize this additional space?

By answering the above research questions, it can be understood that Amphibious AGVs are not suitable for all cases. Hence, the potential amount of space that can be created is with respect to the operation schedules of various material handling equipment. A weighted decision matrix is made based on this to understand the dependency on material handling equipment as seen in Figure 4.51. This matrix is case neutral and does not consider the material handling equipment requirement based on origin and destination. By using AAGVs in case VV, the operating schedule of equipment such as two ASCs or two barge

QCs can be cleared based on the comparison truck or barge. Similarly for case SV or case VS it is one ASC or one ASC and one barge QC can be cleared based on the comparison truck or barge. Freeing up barge QCs operating schedule contributes towards free up barge berths, this is crucial as a lot of ports have high barge waiting times. In 2018, the barge wait time was between 12 and 24 hours for the port of Antwerp and between 6 to 48 hours in the port of Rotterdam depending on the terminal [15]. These waiting times cause unnecessary substantial delays.

Overall, it can be concluded that AAGV can free up barge berths and yard stacking crane schedule which can be utilise to serve other barges in the queue or other trucks that need to embark to a destination that is better to be served by the container exchange route. This freeing up of barge berths also addresses the issues with respect to high waiting times for barges at almost all major container ports around the world.

And finally the main research question,

How does the use of Amphibious AGVs in the context of container port operations improve the productivity of Inter Terminal Transport(ITT)?

Amphibious AGVs play a vital role in improving the productivity of the port my transforming the efficiency of container ITT logistic chains. This efficiency differs based on the geography of the port, scenario of use, the availability of infrastructure and need of the port to handle greater capacities. AAGVs provide greater throughput and fulfillment rate compared to other traditional handling equipment for most cases. This high outcome comes at the cost of a slightly greater fleet size. For selected scenarios and routes the fleet size of AAGVs is very comparable to that of trucks. The fleet size is inversely proportional to the re-handling points of other handling equipment. This greater fleet size could lead to congestion if more number of small handling equipment are allowed to operate in the barge and vessel route. Hence, the capability of these AAGVs to form a grid and operate based on a hive minded system addresses this problem of congestion and visual pollution. Further information about the hive minded system can be found in the appendix. Amphibious AGVs show great potential towards improving the efficiency of port logistics even though the delays at re handling points were modelled with an optimistic approach. Additionally from the sensitivity analysis, it can be found that AAGVs are maore suitable to handle greater container transport demand. This future proofs the use of AAGVs for container ITT. AAGVs could also be a potential solution for terminal operators to form a group based on requirement and manage their requirement by themselves without relying on barge operators and trucking solutions for ITT. This thesis represents an initial exploration of the implementation of Amphibious AGVs for port operations aimed at improving the efficiency of container ports.

5.2 Recommendations

This section discusses the results and methodology employed in the thesis. Firstly, it is examined whether the chosen methodology adequately addresses the main research question. Based on the preceding information, it can be concluded that introducing an agent based model was useful to understand the behaviour of Amphibious AGVs. The primary focus of the thesis was to identify if Amphibious AGVs support towards making port operations more efficient. To quantify the methodology, there was a need to select a geography. For this research Port of Rotterdam was chosen. The results could have been different if a another port was chosen.

Several assumptions were made in this thesis, which could impact the obtained results. Assumptions such as constant speed of material handling equipment, projected demand for 2030, equipment goes back empty to origin, no congestion or delays accounted for and Amphibious AGVs use barge routes in water and AGV routes on land. These factors could affect KPIs like time, throughput, fleet size and fulfillment rate. Additionally, the current model was developed entirely using AnyLogic software. However, using different software might yield similar or different results, and this aspect needs to be verified. The current model uses the concept of optimal fleet utilization at maximum capacity, this assumption may not always hold true in real time. The position of the agents (yard, quay, barge quay) are all approximated to the central location, this could affect the outcome of the experiments. In the case of handling times, due to the availability real time data for QCs and ASCs a triangular distribution is used with the help of the average handling time. But in the case of AAGV ramp, it is still a concept and not data is available. Hence, a uniform distribution is assumed. This correlation between real time data and theoretical data could also hinder the accuracy of study. From the context of the software used, AnyLogic uses open street map data for data with respect to routes and distances. This data could differ with respect to the provider of the OSM service. The optimization results could also differ based on the performance capability of the laptop used.

This research does not only focus on the operational efficiency of logistic chains but also the impact on sustainability by implementing Electric amphibious AGVs to replace truck and barges that predominantly operate on traditional combustion engines. AS the implementation of electric trucks can be expected in 2030, the AAGVs are developed in such a way that they could use similar/common infrastructure for the process of battery swapping.

Building upon the findings and insights gained from the current study, the following recommendations aim to address the identified further research avenues for enhancing the understanding and effectiveness of Amphibious AGVs in port operations. The research conducted thus far has shed light on the development steps involved in making an inter terminal transport logistic chain more efficient, as well as the identification of the nature and behaviour of AAGVs when operated as fleets.

One important area for further research is verifying if the developed model acts as a digital twin when employed by using the professional or the university researcher version of AnyLogic for container ITT of AAGVs. This would help get rid of the assumption of demand input in the form of rate and analyse the flow of containers through multiple modalities. Another important area is to broaden and test the applicability of Amphibious AGVs for various ports around the globe where there is a need to mitigate congestion and delays. It can also be explored if Amphibious AGVs can be reconfigured for other port operations other than that of container terminals. This model can be modelled and applied over other route networks within the Port of Rotterdam or within the Maasvlakte to understand the extent of impact Amphibious AGVs could contribute towards. Long range transport scenarios should also be included in this network. Further research needs to be done in terms of policy, this should help policy makers to make a set of rules to govern the usage of Amphibious AGVs in the context of port operations. A cost benefit analysis has to be further performed to find the efficacy of employing Amphibious AGVs. This could additionally support this research by defining another key performance indicator - cost.

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Appendix A

Scientific Paper

Research Paper starts from the next page

Efficient Inter Terminal Container Transport using Amphibious Vehicles - A Simulation Approach

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***Abstract*—In the 21^{st} century, maritime landscape is confronted with issues such as congestion and delays due to the ever increasing maritime trade volumes. This paper explores the possibility of utilising the concept of amphibious vehicles as a potential solution to address the issue of congestion and enabling the autonomous container terminal operations. For this research, an agent based model is developed to study the impact of amphibious vehicles on space optimization and reduction of material handling equipment within a given port region. The study analyses the performance of the proposed concept over several key performance indicators such as time taken by a handling equipment from origin to destination, container throughput, handling equipment fleet size and container demand fulfilment rate. The developed simulation model is then applied to the chosen case study of the port of Rotterdam. Additionally, the study also performs a sensitivity analysis to simulate how container demand variations affects the efficiency of logistic chains with these amphibious vehicles. This paper highlights the effect of these amphibious vehicles on tackling problems faced by container terminals due to increased global trade. Through an extensive analysis of existing literature and developed model, this paper provides valuable insights into the future of container terminal operations.**

***Index Terms*—Amphibious Vehicles, Amphibious Autonomous Guided Vehicles, Container Re-handling Points, Agent Based Modelling, Genetic Algorithm**

I. INTRODUCTION

The integration of national economies into a global economic system, commonly known as globalization, has led to a substantial surge in international trade over the past century. This growth, exemplified by a 400-fold increase in exports from 1913 to 2014, has significantly reshaped global economic dynamics. As the world experiences sustained economic expansion, the demand for efficient maritime trade operations has never been more crucial. This phenomenon has driven the need for innovations in container handling equipment and transshipment strategies within container terminals.

In this context, a novel concept of Amphibious Automated Guided Vehicles (AAGVs) emerges as a potential game-changer. Amphibious AGVs, capable of seamlessly transitioning between land and water, present an innovative solution to streamline container transshipment processes. By integrating these versatile vehicles into container terminal operations, we aim to reduce re-handling points, alleviate congestion, and ultimately enhance overall port efficiency.

This research paper investigates the potential impact of implementing Amphibious AGVs in container terminal operations, with a specific focus on the Port of Rotterdam. By employing simulation-based analyses, we aim to quantitatively compare the efficiency gains achieved through this innovative approach. Through this study, we seek to provide valuable insights into the transformative potential of Amphibious AGVs in optimizing container terminal logistics.

II. LITERATURE REVIEW

In this chapter, a comprehensive exploration of modeling methodologies relevant to logistic process simulation, vehicle routing, fleet sizing, and fleet utilization has been conducted through a thorough literature review. Various scholarly sources in these domains have been analyzed to identify prevalent methods, their applications, and their effectiveness in addressing similar research questions. The choice of modeling methodology for this research will be informed by the insights gleaned from existing literature, ensuring a well-informed decision aligned with the established practices and proven effectiveness in similar studies.

A. Simulation

Prior to implementing a process in the real world, assessing its performance is crucial. Simulation, deemed cost-effective, serves as a valuable mechanism to evaluate process design [25]. Agent-Based Models, especially useful for mimicking real-time processes such as Inter Terminal Transport (ITT), simulate autonomous agents and their interactions to observe network-wide effects, offering insights distinct from traditional models [19]. Model Based Systems Engineering (MBSE), seen in a study on Manufacturing System Planning (MSP) using Systems Modelling Language (SysML), provides a shared understanding and facilitates analysis through graphical representation, but challenges exist in adoption, expertise, and model scope limitations [39][22].

For instantaneous state changes as seen in ITT systems, discrete event simulation proves valuable. This method provides a comprehensive understanding of process operations, identifies queue formations, and assesses the potential impact of enhancements on overall system performance [19]. Widely used across logistics, production, and ports, discrete event simulation enables the analysis of operations in diverse systems [6][36][34].

Using OSM for vehicle routing involves data preparation to refine geographic details and create a graph representing intersections and roads. Routing algorithms like Dijkstra's or A* identify the most efficient paths between locations, considering constraints like one-way streets and time windows, laying the groundwork for advanced optimization [13][37].

Simulation emerges as a powerful tool for cost reduction, throughput enhancement, and risk mitigation in port and container terminal operations. It aids in internal logistics analysis, decision support, and disruption response [24]. Agent-based modeling, highlighted for its strengths in accounting for dynamic interactions, spatial components, and bounded rationality, stands out among simulation approaches. It does not rely on constant equilibrium, reflecting real-world complexity, but may face limitations regarding the number of effectively simulated agents [33].

B. Optimization

Problem-solving algorithms are categorized into two types: exact and approximation algorithms. While exact algorithms guarantee identifying an optimal solution or proving its nonexistence, the efficiency of computation often leads to the use of approximate algorithms when finding optimal solutions becomes impractical within time constraints [41].

Exact Algorithms encompass Design of Experiment (DOE) and Mathematical Iterative Search. DOE efficiently uncovers factor effects and interactions, aiding data-driven decision-making in engineering and research. Mathematical Iterative Search explores solution spaces iteratively to optimize objective functions, particularly effective in scenarios with challenging solutions or noisy objective functions [27][43].

Approximation Algorithms such as Meta-Heuristics and Problem Specific Search are generally faster than exact algorithms. Meta-Heuristics include Genetic Algorithm, Simulated Annealing, and Tabu Search, while Problem Specific Search involves techniques like Greedy Algorithm and Randomized Rounding algorithm [44][30][20][28][11].

Determining the number of Material Handling Equipment in a system involves routing strategies, Pick & Deliver locations, and various factors like transport load demands, AGV capacity, and routing. Fleet sizing aims to optimize based on time constraints, traffic management, and assignment [42].

Optimizing utilization in resource-constrained environments directly impacts efficiency and productivity across domains. Genetic Algorithms (GAs), inspired by natural selection, navigate complex solution spaces. Their applications span various domains, excelling in global search and adaptability [16][3][14].

GAs offer competitive advantages in resource allocation, production process optimization, and transportation and logistics, leveraging evolutionary principles to achieve maximum efficiency and productivity [7]. These algorithms play a crucial role in modern optimization methodologies across diverse fields.

C. Platform

Selecting the optimal simulation software to model and evaluate logistic processes is a critical decision in research. The comparison between two prominent platforms, AnyLogic and Arena, becomes imperative, given their varied features. Both platforms offer a blend of Agent-Based Modeling and Genetic Algorithm-based optimization [1][2]. However, for scenarios demanding real-time route simulation essential in the context of Inter-Terminal Transport (ITT), the absence of a Geographic Information System (GIS) map feature in Arena becomes a notable drawback. In contrast, AnyLogic, leveraging Open Street Maps (OSM), incorporates this crucial GIS feature, aligning seamlessly with the need for real-time route emulation.

A comprehensive comparative analysis depicts the distinctive attributes of AnyLogic and Arena. The decision-making process leans favorably towards AnyLogic for its GIS interface through OSM, crucial for accurately mimicking real-time routes within ITT simulations. Its Agent-Based Modeling capability proves pivotal in understanding the interactions among multiple handling equipment, essential for establishing logistic processes. Moreover, the integration of Genetic Algorithm optimization within AnyLogic streamlines process optimization efficiently, adding to its suitability for this research's objectives.

The chosen platform, AnyLogic, acts as the cornerstone in constructing a digital twin for futuristic ITT processes. By amalgamating Agent-Based Modeling, Genetic Algorithm optimization, and OSM-based GIS mapping, the aim is to develop a robust digital representation mirroring the complexities and dynamics of real-world ITT scenarios. This approach seeks to provide a comprehensive understanding of logistic processes, particularly ITT, and pave the way for innovative solutions in this domain.

The meticulous selection of AnyLogic over Arena stems from the critical need to replicate real-time routes and locations essential in modeling ITT processes. This decision aligns with the research's objective to construct an accurate digital twin for logistical evaluation. Ultimately, the integration of Agent-Based Modeling, Genetic Algorithm optimization, and GIS mapping through AnyLogic serves as the foundation for this comprehensive exploration into future ITT logistics.

III. METHODOLOGY

This section examines logistics chains for container ITT, beginning with an analysis of the benchmark scenario reflecting current practices. To deepen comprehension, four distinct cases are constructed based on situational factors and requirements. These cases are compared against the benchmark and novel logistic chains employing Amphibious AGVs. Agent Based Modelling (ABM) is utilized for quantifiable comparison, conducted on AnyLogic: Personal Learning Edition 8.8.3. This approach enables a comprehensive evaluation of efficiency and efficacy in different logistical setups.

A. Benchmark: Current Logistic Chain

In the current logistics operations, upon a vessel's arrival at the quay side, it docks and is serviced by quay crane(s). These cranes facilitate the transfer of containers to the yard using Automated Guided Vehicles (AGVs). Once in the yard, stacking cranes organize the containers. If a container is designated for transport via truck, an Automated Stacking Crane (ASC) places it onto the truck. For containers destined for barges or trains, the AGV, aided by the ASC, moves the container to the respective loading points—a barge quay or a Rail GC (Rail Guided Crane). At the barge quay, a quay crane loads containers onto barges, while at the Rail GC, containers are loaded onto trains. To gain comprehensive insights into container handling processes between terminals, the logistics chain design is segmented into four distinct cases:

1) Container Transport from Storage to Storage (SS)
2) Container Transport from one Vessel to another Vessel (VV)
3) Container Transport from Storage to a Vessel (SV)
4) Container Transport from a Vessel to Storage (VS)

These cases aim to elucidate the number of container rehandling points involved in fulfilling specific processes. Subsequent subsections elaborate on each case, delineating their subcases based on the mode of inter-terminal handling equipment.

B. Container Transport by AAGV

This sub section illustrates the potential alterations in the logistics chain when employing Amphibious AGVs within the scenarios discussed earlier.

Amphibious AGVs, or Amphibious Automated Guided Vehicles, represent a revolutionary development in Container Terminal Operations. They possess the unique ability to operate on both land and water, potentially replacing conventional AGVs and barges. This innovation stems from the adaptability of existing Amphibious vehicle technology.

The design of the AAGV closely mirrors conventional AGVs in terms of size, power, and battery features. Notably, it seamlessly transitions between land and water autonomously, utilizing conceptual transfer systems. This enables it to navigate calm port waters efficiently. The design emphasizes compatibility with existing port machinery, minimizing additional investments. Figure 1 depicts how the AAGV would look in land and water mode.

The AAGV's versatility allows it to interact with all sides of the port, potentially replacing AGVs, Multi Trailer Systems, Trucks, and Barges. This adaptability has the potential to significantly reduce the number of Material Handling Equipment required for container transshipment.

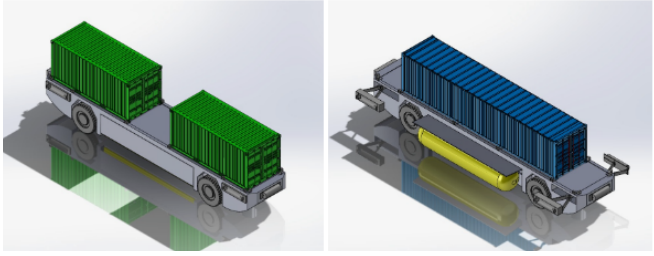

Fig. 1. Amphibious AGV in Land Mode(left) and Water Mode(right) [5]

C. Simulation Model

From the literature review, AnyLogic emerged as the optimal modeling tool. Its simulation capabilities offer verifiable statistics and visual representations, making it suitable for capturing the dynamics of business processes, including internal logistics within ports and terminals [31]. AnyLogic provides a platform for Agent Based Modelling, integrating GIS (Geographic Information System) maps. Agent Based Modelling is chosen for its ability to simulate real-time chains and understand agent behavior and interactions. The GIS Map feature leverages Open Street Map (OSM) for route planning. Additionally, AnyLogic offers the use of Genetic Algorithm for optimization experiments. The modeling of the logistic chain is executed using the process modeling library within AnyLogic.

1) Stakeholder Agents: The logistics process involves diverse agents, each serving specific functions:

- Storage Yard, Deep Sea Quay, Barge Quay, AAGV Ramp: Static agents defining specific locations for container handling.
- Truck, Barge, AGV, AAGV: Dynamic agents mirroring real-world vehicles, interacting with various locations and populations based on scenario constraints.
- Order: Represents demand generation and assignment of orders for container movement.

These agents, from static yard locations to dynamic vehicle simulations, collectively contribute to simulating and analyzing the complex logistics process.

2) State Chart Model: The State Chart Model in AnyLogic initiates the logistics process, starting in a 'Normal Work' state where terminals operate without the need for Inter Terminal Transport. At a defined rate, the state transitions to 'Wanting Details' based on the Container Demand and Material Handling Equipment Capacity ratio. This rate is defined by:

$$\text{Transition Rate} = \frac{\text{Container Demand}}{\text{Capacity of Material Handling Equipment}} \tag{1}$$

In the 'Wanting Details' state, Inter Terminal Transport is required, triggering the creation of a new order object. This order is dispatched from the originating Terminal in the process model. Upon delivery confirmation at the destination, a message is relayed to the State Chart Model, prompting a transition back to 'Normal Work'. The model is as seen in figure 2.

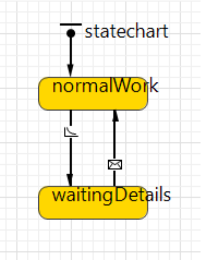

Fig. 2. State Chart Model

3) Process Model: The logistic chain model in AnyLogic utilizes process blocks to simulate entity movement within a system. Figure 3 visually represents how these blocks are applied specifically to simulate truck delivery of containers from a port to Customer port(s).

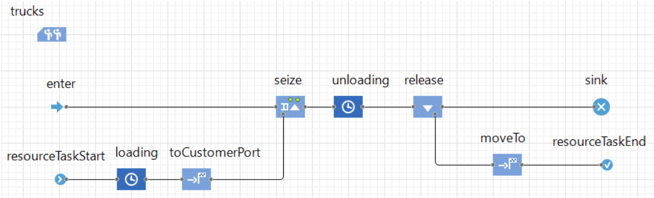

Fig. 3. Process Model of a Truck delivery

These blocks form the framework for modeling various stages and steps within the logistic chain as summarized below.

The model begins with the Enter block, receiving demand requirement orders from the State Chart Model. Seize blocks then capture this demand, while parallel processes commence using Resource Task Start to manage a pool of truck resources.

The simulation encompasses critical stages like container loading, simulated using Delay blocks. Triangular distribution is applied for equipment such as Quay Cranes and Stacking Cranes, utilizing available data on handling times.

$$DelayTime = triangular(min, max, mode) \tag{2}$$

Where,

- Min - The minimum amount time taken for a particular process
- Max - The maximum amount time taken for a particular process
- Mode - The most likely amount of time taken for the process

Conversely, Amphibious AGV Ramp processes employ uniform distribution due to theoretical data assumptions.

$$DelayTime = uniform(min, max) \tag{3}$$

Where, min is the minimum amount of time taken and max is the maximum amount time taken for a particular process.

Move To blocks facilitate the vehicle's movement to the destination, where orders are assigned to loaded vehicles. Post-unloading and delivery confirmation, vehicles are released from orders and terminated at Sink blocks.

Output measures include container input/output and average transport time, quantified using Time Measure Start and Time Measure End blocks.

This concise depiction encapsulates the diverse process blocks and their functions within the logistic chain model, providing a clear overview of the simulated processes and outputs.

4) Optimization Experiment: Efficient resource utilization is crucial within the logistic chain model. Utilization rate, defined as the ratio of resource units being used to the total number of units multiplied by 100, is a key metric. It is expressed as:

$$\text{Utilization Rate} = \frac{\text{Demand(D)}}{\text{Fleet Size(V)}} \times 100[\%] \tag{4}$$

To optimize resource utilization, a Genetic Algorithm is employed, aiming to set the agent utilization at a maximum of 85%. This upper limit ensures resource redundancy to address unforeseen circumstances, maintaining operational efficiency within the logistic chain model.

TABLE I
INDICES, SETS, PARAMETERS AND DECISION VARIABLE

Indices and Sets	
i	Index of cases (i) $\forall i \in I$ = {SS-T, SS-B, SS-A, VV-T, VV-B, VV-A, SV-T, SV-B, SV-A, VS-T, VS-B, VS-A}
Parameters	
D_i	Number of resource units used in case i $\forall i \in I$
V_i	Total number of resource units in case i $\forall i \in I$
Decision Variable	
U_i	Utilization rate of resource unit in case i $\forall i \in I$ and $U_i = \frac{D_i}{V_i}$

Objective Function:
The objective function is to maximize the utilization of the total number of resource units in the system.

$$\text{Maximize} \quad U_i \quad \forall i \in I \tag{5}$$

Main Constraint:
This constraint ensures that the utilization rate is maintained lesser than or equal to the chosen optimality of 85%.

$$U_i \leq 85\% \quad \forall i \in I \tag{6}$$

Additional Constraint 1:
This constraint ensures that the demand parameter is lesser than the fleet size parameter. This is because the number of resource units used has to be lesser than the total number of resource units.

$$D_i \leq V_i \quad \forall i \in I \tag{7}$$

Additional Constraint 2:
This constraint ensures that the decision variable lies between 0 and 100%.

$$U_i \in [0, 100][\%] \quad \forall i \in I \tag{8}$$

Additional Constraint 3:
This constraint ensures that the demand parameter is always a natural number.

$$D_i \in N \quad \forall i \in I \tag{9}$$

Additional Constraint 4:
This constraint ensures that the fleet size parameter is always a natural number.

$$V_i \in N \quad \forall i \in I \tag{10}$$

Where,

- N is the set of natural numbers; N$\rightarrow [1, \infty)$
- Percentage is a positive real number

The primary objective is to maximize truck utilization within the logistic chain model while capping it at a maximum threshold of 85%. This optimized value serves as the input for determining the number of units within the resource pool for the given process. The computed output of this optimization serves as the 'Fleet Size' parameter, ensuring an optimized balance between maximizing truck usage and maintaining operational redundancy within the logistic chain model.

5) Data Analysis: The outputs of the simulation, undergo post-processing to derive key performance indicators (KPIs) such as throughput and fulfillment rate. These computations are delineated as follows.

Throughput: Throughput, defined as the container movement rate per unit time, is calculated using the formula:

$$\text{Throughput} = \frac{\text{Number of Containers at Sink}}{\text{Total Time of the System}} \times 2, \text{[TEU/hour]} \tag{11}$$

Fulfillment Rate: Fulfillment rate measures the ratio of containers processed through the system against the expected volume:

$$\text{Fulfillment Rate} = \frac{\text{Number of Containers at Sink}}{\text{Container Demand}} \times 100, [\%] \tag{12}$$

The performance of a logistic chain is used to compare the efficiency of various logistic chains. An ideal case is when it takes lesser amount of time to transport containers, greater throughput, lesser fleet size and greater fulfillment rate. The order of Importance of this KPI is as follows

$$\text{Fulfillment Rate} \geq \text{Throughput} > \text{Fleet Size} >> \text{Time} \tag{13}$$

IV. CASE STUDY - THE PORT OF ROTTERDAM

This section presents the application of the methodology outlined in the previous section, focusing on the Port of Rotterdam — one of the world's largest and most vital ports. The choice of Rotterdam is driven by its strategic significance due to its geographical advantage, burgeoning transport needs, and pivotal role in global maritime trade.

To address the escalating transport quantities, the Port of Rotterdam initiated the Maasvlakte 2 expansion project, reclaiming 2,000 hectares of land in the North Sea. This expansion increased container storage capacity by 20 million TEUs and introduced a new deep-sea quay, catering to the largest container vessels globally. Additionally, the implementation of container smart scanning technology enhances operational efficiency by seamlessly logging container information using barcodes, enabling better tracking and management of containers [9][23][10].

The post-COVID era witnessed unprecedented growth in port activities, with projected container handling expected to surpass 20 million TEUs by 2025. Rotterdam's unique geography, depicted in Figures 4 and 5, positions it as a major transshipment hub in Europe.

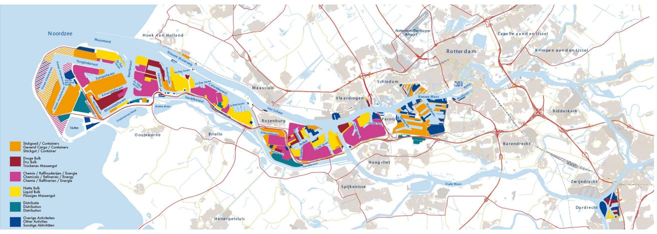

Fig. 4. Map of the Port of Rotterdam, [26]

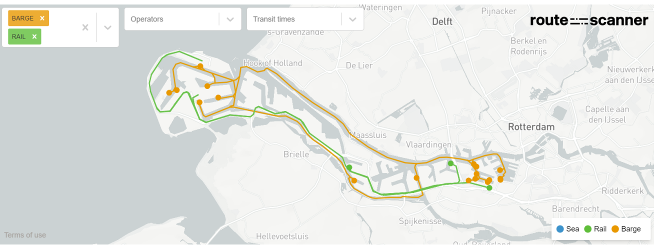

Fig. 5. Container Transport in the Port of Rotterdam, [17]

Beyond container traffic, Rotterdam handles bulk cargo, chemicals, and petroleum products. Specialized terminals cater to efficient handling and storage of various commodities, distinguishing Rotterdam as a key hub for Europe's oil imports and chemical handling. Moreover, inland terminals and dry ports utilize multiple modes of inter-terminal transport (ITT), including road, rail, and barge, facilitating diverse cargo distribution and storage [17].

The Maasvlakte 2 expansion project, featuring APM Terminals Rotterdam and Rotterdam World Gateway terminal, significantly enhances Rotterdam's container handling capabilities. State-of-the-art infrastructure and expanded navigation channels allow access for the largest vessels, essential for accommodating growing container ship sizes [29].

Figure 6 illustrates barge and rail connectivity within Maasvlakte, highlighting the strategic importance of inter-terminal transfers (ITT) between deep-sea terminals. In 2014, 1803 containers were transferred between these terminals, and by 2030, projections indicate a daily average handling of 3761 containers, emphasizing the growing demand for efficient ITT solutions [38][12][36][21].

This research aims to evaluate the comparative advantages of Amphibious AGVs over conventional modes like Truck and Barge for container ITT within ports such as Rotterdam.

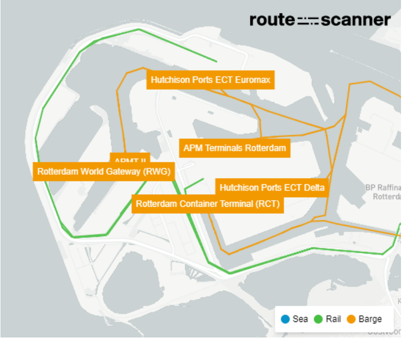

Fig. 6. Transport Routes in Maasvlakte, [17]

Anticipating the operational availability of Amphibious AGVs by 2030, this study assesses their potential benefits, considering their conceptual stage and the evolving landscape of port logistics.

A. Simulation Approach

This table outlines the crucial parameters and their respective values necessary for the simulation model. The inputs serve as foundational data to generate desired outputs and analyze the efficiency of various inter-terminal transport logistics within the port setting.

TABLE II
LIST OF INPUTS FOR THE SIMULATION

Parameter		Value
Speed	Truck	60 Kmph
	Barge	13 Kmph[35]
	AGV	11 Kmph[32]
	AAGV	12 Kmph
Handling Time per Container	Quay Crane	1-3 minutes[4]
	ASC	1-3 minutes[18][4]
Time on Ramp for each AAGV		1.5-2.5 minutes
Time Taken for Mooring a Barge		20-90 minutes[40]
Quantity	Truck	2 TEU
	Barge	200 TEU[8]
	AGV	2 TEU
	AAGV	2 TEU
Container Input per day		3761 Containers
Number of Quay Cranes Serving	Deep Sea Vessel (Post Panamax and above)	6 Cranes[15]
	Barge	1 Crane[15]

The location of agents in the major terminals of Maasvlakte is an important input for the simulation. The main agents are Storage Yard, Deep Sea Quay, Barge Quay and Ramp. These agents are marked with blue, yellow, green and red GIS pins respectively in figure 7. The central location of the Storage Yard is used as the GIS point location of the Storage Yard agent. The central location of the the Deep Sea Berths is used as the GIS point location of the Deep Sea Quay agent and the central location of the Barge Berths is used as the GIS point location of the Barge Quay agent.

Fig. 7. Location of Agents

Fig. 8. Terminal Locations

Figure 8 provides a satellite view of the terminal locations in Maasvlakte. Marked in black is Hutchinson Ports ECT Euromax, in red is Rotterdam World gateway, in blue is APM Terminals Maasvlakte 2, in purple is Hutchinson Ports Delta 2 and in green is Huthinson Ports ECT Delta. Correlating Figures 7 and 8 provides an insight on the location of the agents terminal wise.

Every process is simulated for a run time of 24hours. The data obtained are all based on a single day scenario. In order to establish Multi Modal Transport network keeping in mind the capacity of the student version of AnyLogic, split simulation method is adapted where every mode is simulated separately. But the linear chain is computed exactly for 24 hours. For the ease of computing results it is assumed that the container demand is equal in all container terminals. In order to model this system the Container Demand is divided by the number of receiving terminals.

$$\text{New Container Demand} = \frac{\text{Container Demand}}{4} = \frac{3761}{4} \approx 940 \tag{14}$$

All the containers originate at Hutchinson ports ECT Euromax and are distributed equally between Rotterdam World Gateway, APM Terminals Maasvlakte 2, Hutchinson Ports Delta 2 and Hutchinson Ports ECT Delta. These logistic chains are designed case and sub case wise. Case SS, VV, SV and VS with sub cases T, B and A(Truck, Barge and Amphibious AGV). The benchmark logistics chain is compared with the new logistics chain in each case. All the simulations in this thesis were performed using a 12th Gen Intel(R) Core(TM) i7-1260P 2.10 GHz with a 16 GB RAM (64-bit operating system, x64-based processor) laptop.

B. Results and Discussion

This sections sums up all the inferences made from various results for the case study across all experiments in this chapter. This chapter first delves into understanding the geography of the port of Rotterdam and then converting them into inputs as required by the developed simulation model. Case wise results are discussed in this chapter. In order to summarize these results, a case wise comparison is performed for all KPIs. When AAGVs are employed as the main inter terminal handling equipment the fleet size is maximum, this is because of the uni-modality of the handling process. This uni-modality also affects the time take for transferring a single container handling equipment to get from origin to destination, AAGVs having a greater time compared to trucks across all cases. Barges take the greatest time as they have a greater capacity than trucks and AAGVs. Upon employing AAGVs supplements the logistic process with greater throughput and fulfillment rate. When trucks are employed as the inter terminal handling equipment, the throughput and fulfillment rate are are little lower than that of using AAGVs across majority cases. The throughput and fulfillment rate when barges are employed are very low compared to using trucks or AAGVs, this occurs due to the additional process requirements while employing barges. Making AAGVs and trucks more efficient to use for container inter terminal transport within the Maasvlakte than barges. These results can be seen from the graphs in figure 9, 10, 11 and 12. These results are a culmination of the performance of logistic process over multiple routes. Hence, these results could be effected by averaging. As the KPIs for AAGVs and trucks are very close, analysing this effect of averaging is crucial.

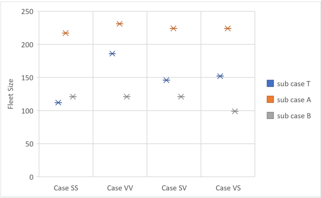

Fig. 9. Case wise FleetSize KPI Comparison

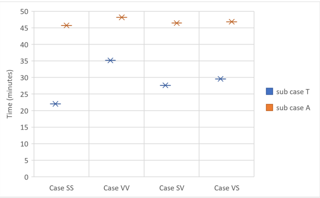

Fig. 10. Case wise Time KPI Comparison

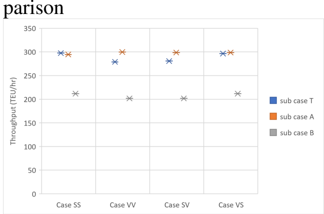

Fig. 11. Case wise Throughput KPI Comparison

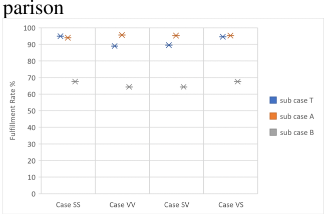

Fig. 12. Case wise Fulfillment Rate KPI Comparison

Figure 13 represents the number of re-handling points for all the cases and sub cases. For container transport over a short distance like within the Maasvlakte, it is ideal to have a uni-modal container transport and preferable to have lesser number of container re-handling points. Sub case A is ideal for all cases while sub case T is suitable for Case SS alone. This gives the option to choose between case SS-T and case SS-A for case SS and it is cases VV-A, SV-A and VS-A for cases VV, SV and VS respectively.

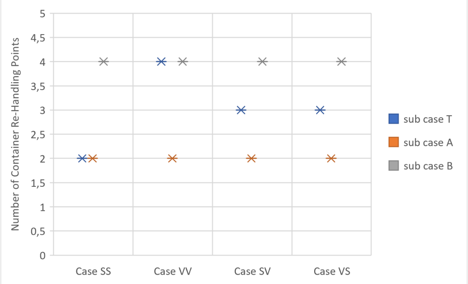

Fig. 13. Case wise Re-Handling Points KPI Comparison

To understand the performance edge of AAGVs and trucks over each other, a route analysis is performed. From this it can be seen that performance is affected not just route wise, but also case wise. The result inferences of employing AAGVs as the inter terminal handling equipment route wise are as shown in Table III. Upon correlating these inferences with the distance matrix as shown in Table IV, the profile of routes where AAGVs could be employed can be identified. AAGVs can be employed as the inter terminal handling equipment where the distance difference to truck is atleast 50% lesser than that of employing trucks.

TABLE III
INFERENCES FROM ROUTE ANALYSIS WHERE AAGV HAS AN EDGE OVER TRUCKS

1	**Hutchinson Ports ECT Euromax to Rotterdam World Gateway**		
	Case VV	Throughput	9%
		Fulfillment Rate	6%
2	**Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2**		
	Case VV	Throughput	9%
		Fulfillment Rate	8%
3	**Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2**		
	Case VV	Throughput	28%
		Fulfillment Rate	21%
	Case SV	Throughput	4%
		Fulfillment Rate	3%
	Case VS	Throughput	4%
		Fulfillment Rate	4%
4	**Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta**		
	Case VV	Throughput	9%
		Fulfillment Rate	8%
	Case SV	Throughput	9%
		Fulfillment Rate	8%

TABLE IV
DISTANCE MATRIX

Routes	**Truck**	**AAGV**
Hutchinson Ports ECT Euromax to Rotterdam World Gateway	15.5 km	8.5 km
Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2	20 km	9.5km
Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2	20 km	6 km
Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta	20 km	7 km

Additionally, a sensitivity analysis is performed to see how change in demand affects these KPIs. Fleet Size increase with a constant slope while time taken for a handling equipment to move from origin to destination remains constant. Throughput increases with a constant slope and fulfillment rate remains constant. This can be seen in figure 14. The slope of throughput is greater than that of the fleet size. Hence, employing Amphibious AGVs is suitable when demand is greater for short range inter terminal transport. Employing AAGVs also contribute towards freeing barge berths and the work schedule of multiple re-handing equipment within a terminal.

V. CONCLUSION

A. *Quantifying and Comparing ITT Modes*

The study delves into assessing various simulation and optimization methods to gauge logistic chains, exploring the introduction of Amphibious AGVs. Agent-Based Simulation is chosen for its efficacy in modeling complex supply networks, representing components and interactions to optimize logistics.

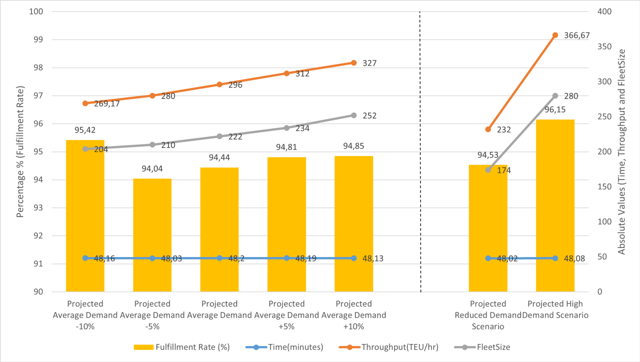

Fig. 14. Sensitivity of KPIs with respect to demand

The optimization experiment employs genetic algorithms due to their effectiveness in resource utilization, leading to near-optimal solutions. Choosing AnyLogic, with its GIS map feature, aids in real-time route simulation, offering a comprehensive view for research.

B. *Impact of Amphibious AGVs on Port Equipment Interaction*

The integration of Amphibious AGVs notably reduces container re-handling points, a critical factor impacting terminal efficiency. This reduction addresses operational delays stemming from congestion, processing, or equipment shortages, improving supply chain bottlenecks.

C. *Improving Port Efficiency with Amphibious AGVs*

Amphibious AGVs enhance throughput and fulfillment rates but often require larger fleets for short-distance transport, influencing operation timelines. Sensitivity analysis highlights their suitability for high-demand, short-distance transport scenarios, emphasizing their potential efficiency gains.

D. *Beneficial Routes and Scenarios for Amphibious AGVs*

The feasibility of Amphibious AGVs relies on route specifics and re-handling points compared to traditional equipment. The advantageous scenarios predominantly involve quay-side container handling, especially in scenarios like vessel-to-vessel transport in Rotterdam.

E. *Generating Space through Equipment Trade-offs*

By optimizing equipment schedules, AAGVs create additional space, particularly freeing up barge berths and the operation schedule of handling equipment at re handling points, thus reducing high waiting times and mitigating unnecessary delays at major ports.

F. *Enhancing ITT Productivity with Amphibious AGVs*

Amphibious AGVs improve ITT efficiency, albeit with varied outcomes influenced by geographical context, infrastructure, and operational demands. These vehicles offer higher throughput and fulfillment rates, potentially aiding in addressing future container transport needs and reducing reliance on external operators.

VI. RECOMMENDATIONS

The recommendations stemming from the current study aim to expand the understanding and effectiveness of Amphibious AGVs in port operations. While the research highlighted steps to enhance inter-terminal transport chains and characterized AAGV behavior in fleets, several crucial avenues for further exploration were identified.

Firstly, verifying the developed model as a digital twin using professional or university researcher versions of AnyLogic for Amphibious AGV container transport could eliminate demand rate assumptions, allowing a comprehensive analysis of container flow through various modalities. This step ensures the model's accuracy and applicability in diverse scenarios.

Expanding the applicability of Amphibious AGVs to global ports experiencing congestion and delays presents an essential research direction. Evaluating potential reconfigurations for operations beyond container terminals could uncover novel uses and efficiencies for AAGVs in different port contexts.

Further exploration within the Port of Rotterdam or Maasvlakte, applying the model to different route networks, can reveal the broader impact of Amphibious AGVs. Integrating long-range transport scenarios into this network assessment would provide comprehensive insights into AAGVs' potential across various transport distances.

Additionally, investigating policy implications would be crucial, guiding policymakers in formulating rules governing Amphibious AGV usage within port operations. Such policies could optimize AAGV deployment and operational efficiency while ensuring regulatory compliance.

Finally, conducting a comprehensive cost-benefit analysis would add depth to the research by introducing cost as another key performance indicator. Assessing the efficacy of employing Amphibious AGVs in terms of cost implications can provide valuable insights into their economic viability.

These research avenues would significantly contribute to the understanding and optimization of Amphibious AGV utilization in port operations, expanding their scope and impact while addressing critical operational and policy considerations.

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