Transshipment for the 21st Century

A Novel Approach to Deep Sea-Hinterland Transportation

By

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TU Delft

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Abstract

Transshipment is a key component of modern-day shipping logistics. Container supply chains rely on transhipment hubs to access remote locations. With globalisation driving growth in container trade, maritime congestion is rising at container terminals in ports worldwide. This is expected to worsen as demand continues to grow. The ill effects of this congestion are particularly being felt along transportation networks between deep-sea container terminals and Hinterland terminals. Therefore, this research aims to suggest solutions that address current problems and meet current targets, while also delivering future-proof and scalable transshipment options across a range of ports and hinterlands worldwide. This work in particular will evaluate the impact of novel maritime concepts such as amphibious AGVs, floating terminals, and super barges and how they can contribute to developing efficient container transportation networks that could address the congestion problem of incoming container barges at deep-sea container terminals. The key performance indicators (KPIs) emphasize reduced maritime congestion, while also aiming to achieve similar daily throughput, transport time, and reduced transporter fleet sizes. To implement this, an agent-based simulation methodology quantifies the existing problems along the deep-sea-hinterland network and validates the feasibility of the proposed transportation networks. The proposed innovative concepts and the current container transshipment scenario are implemented in the simulation environment of the Port of Rotterdam. The global applicability and scalability potential of the proposed transshipment solutions is further demonstrated on a much larger scale by testing them in the Hong Kong-Pearl River Delta, which covers an area similar to the size of the Netherlands. From an innovation point of view, concepts like Amphibious AGVs and floating terminals depict versatility in mobility and flexibility in execution respectively. This work, therefore, opens up an intriguing future scope for maritime transshipment that is both sustainable and adaptable, while also discussing limitations and concerns that need to be carefully considered.

Keywords-Transshipment, Agent Based Modelling,Globalisation,Deep Sea-Inland Waterway Network, hinterland, Amphibious AGV, Floating Terminals

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Abhishek Rajaram
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Summary

Transhipment is the holy grail of maritime shipping today since its success defines world trade. What transhipment has given us over the last many years is accessibility. Hub ports connect smaller surrounding ports and have networks of trade security and economy running through them. A major hassle within this network today is hinterland transport and how it links up with transhipment and this forms the crux of the research

This research focuses on finding novel transhipment solutions along deep sea-inland waterway networks for efficient hinterland transport. The research recognized the problems faced by the actors specifically deep sea terminals of home ports, international terminals, hinterland terminals and a network of transporters. The major problem is growth. Deep sea terminals envision a growth of 200% [5], governments want to increase barging to support local businesses and reduce reliance on trucks. All this while, global trade and demand is also growing at a steady pace with world shipping trade accounting for 14 Trillion Dollars in 2019. Therefore an aim of this research was to find a combined solution for growth satisfying all major actors. The research looked to first find out the challenges in existing inter-terminal barge networks today and a variety of problems appeared ranging from coordination and communication issues to regulation to congestion. A major point tackled during this research is barge congestion and its effect on transhipment along the deep sea-hinterland network. The research started of with identifying and validating this problem of congestion. In order to do this agent-based modelling frameworks were constructed to study and simulate the network of the earlier-mentioned actors(Terminals, containers and transporters). Taking the port of Rotterdam as a test canvas, the models validated the ongoing congestion problem in terminals and this revealed more problems such as berth congestion, quay crane congestion and long queues involved in the container loading and unloading process for barges. While transport times looked competitive, it became clear that this was not sustainable in the long run because berths are limited and with added constraints of terminal space, growth can not be desired with the current setup. Transshipment solutions were then explored keeping in mind the various constraints. These were explored in two ways, one was to find new transporters that could help solve this crisis and another was to find ways to incorporate new transhipment hubs within the same port canvas. In this process, novel concepts like floating terminals, and barge hubs were identified as these can be constructed or reconfigured within existing constraints as resources. Designs of floating terminals were made for small-scale and large-scale applications (3.5 and 3.6). However, two recurring problems were congestion and double handling. To address congestion, the concept of a super barge was introduced. These are essentially high-call size-high-density barges that can move containers in high volumes from Maasvlakte to Hinterlands. These can reduce the number of regular small barges that cause congestion at deep-sea terminals in Maasvlakte. Similarly to prevent the double handling of containers by trucks + barges, the concept of an amphibious AGV was introduced. This transshipment vehicle can travel on land and water thereby reducing distances massively. All these transhipment concepts were now explored in the form of logistical adaptations that can be incorporated in Port of Rotterdam. Based on their feasibility studies from industry and literature; short, medium-term and long-term solutions that employed the aforementioned concepts were thought of. Short-term solutions focused on the use of existing infrastructure and technologies(like barge hubs and super barge). The medium-term and long-term solutions saw the introduction of new concepts like Amphibious AGVs and floating terminals.

The different network solutions were tested for KPIs such as congestion and frequency of barges, container throughput rate, transport time and fleet sizing. The amalgam of the above KPIs provided an informed decision on the windows within which all the solutions work. It was found that the final chain solution gave the most optimum results. The final chain solution recorded a 12 per cent improvement in time savings, and 14 per cent greater container throughput but the biggest gain was made in congestion of barges which saw a 90% reduction. The idea of this research was to develop solutions that will be relevant in 2050 figuring in the growth. Keeping this in mind various experiments related *to modal split, hinterland split and berth: demand was performed. This was to understand how the proposed solutions work within the KPIs factoring in future demand.In order to test the global applicability of this idea, the final chain solution was compared against a benchmark in the Hong Kong-China Pearl River delta. The results showed an improvement of 21 per cent in both time and throughput along with the same 90 per cent reduction in barge congestion(from 120 regular barges to 12 Super Barges). The pearl river delta case study. The bottom line of this work is that the maritime and port industries should explore these transhipment concepts, especially the floating terminal and Amphibious AGV. This research recognizes that such concepts can even be applied to inter-terminal transport in regions like the Maasvlakte and Hong Kong Kwai Tsing. Amphibious AGV can also open the door for supporting numerous small-scale industries by enabling them to own and transport goods to major ports via these AAGVs. This research was not only done to alleviate one problem, but in order to open up a new perspective for future transshipment and hinterland transport which the author believes has been sufficiently done so in this work.*

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Nomenclature

Abbreviations

Abbreviation	Definition
DST	Deep Sea Terminal
IWT	Inland Waterway Transport
AAGV	Amphibious Autonomous Guided Vehicles
AGV	Automated Guided Vehicles
TEU	Twenty foot equivalent unit
FT	Floating Terminals
BH	Barge Hub
RMG	Rail Mounted Gantry Cranes
ABM	Agent-Based Modelling
GIS	Geographic Information System
ULCV/ULCS	Ultra Large Container Vessel/Ship
APMT	A.P.Moller Maersk
HIT	Hutchinson International Terminals
RST	Rotterdam Shortsea Terminals
BCW	Barge Center Waalhaven
CTT	Combi Terminal Twente-Rotterdam

1

Introduction

1.1. Background

Globalisation in markets today has led to an astronomical rise in trade between nations. Opening up of markets have prompted unification in transport chains worldwide while also diversifying transportation options for greater accessibility within nations. With these transportation chains being better defined, world trade has been growing at an annual growth rate of 2.7% [63]. This is where container shipping comes into the picture; the 2.7% CAGR translates to an encouraging container shipping trade growth of 2.5% [36]. This increase in demand has also been encouragingly complemented by the increase in container ship capacities which have reached to 24000TEUs today when compared to sub-10000TEU capacities 20 years back. The container handling has also seen a 230% increase since the year 2000[50]. Simultaneously or rather consequently hinterland transportation has also seen this astronomical rise in last many years, When we look at intermodal hinterland transportation, demands have grown so drastically that fleets of transporters (trucks,AGV,Barges) have also increased along with the demand[15]. But the most affected here is the maritime hinterland transportation. One would also wonder why this is very important and the reason here is efficiency is transportation can also eventually influence the price we pay for our goods and commodities[37]. A more efficient transshipment system, would lead to faster delivery of goods/containers and this can bring down total prices. A lot of regions around the world rely on inland waterway transport to move large amounts of containers efficiently. While trucks and trains do exist, inland waterway transport is also cheaper and sustainable in terms of emissions/TEU incurred[94]. With global maritime platforms looking to achieve net zero carbon emissions by 2030, ports are pushing for greater Inland Waterway transport growth to both comply with the Paris Agreement while also tackling growth simultaneously[44][90]. The below graphs both depict growth of 200% and above while also showing how Inland waterway transport which once saw a decline is now back on the rise to meet demand and sustainability goals. The growth of inland waterway transport is also a positive because Barges are usually family owned businesses and provide a livelihood not only for the operators but also for small businesses that need to transport their goods cheaply[78].

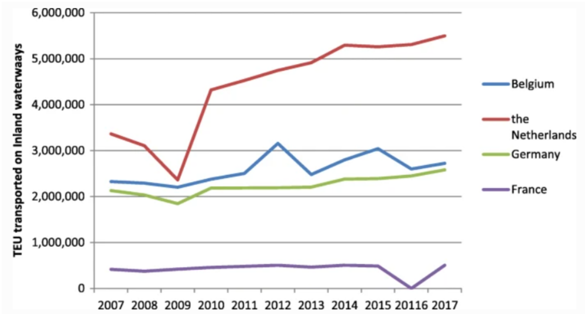


Figure 1.1: Inland Shipping Growth- Europe[83]

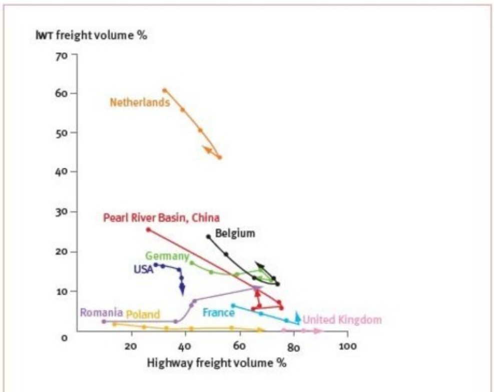


Figure 1.2: Inland Waterway Prevalence& Growth-World[92]

For hinterland transport, containers are usually transported from deep-sea terminals and it follows a process as delineated below.

Figure 1.3: Chain of Hinterland Transport[33]

While expansion plans are underway for inland waterway networks/barge transportation, it must be noted that barge congestion is already a major issue in ports like Rotterdam,Antwerp[33] and even in major transshipment ports like Hong-Kong[85] where deep-sea container terminals face congestion of 20-22 Barges/Day and 120 Barges/Day respectively. Deep-sea container terminals are also en route to their expansion goals. Terminals such as APM Terminals in Port of Rotterdam are currently upgrading their deep sea terminal from a current handling capacity of 2 million TEU to 4.7 million TEU by 2026[5]. While one may ask why would this actually pose a problem, it is because most deep-sea terminals do not have any plans to upgrade their barge berth facilities despite growth in deep-sea to hinterland transportation. One must also keep in mind that it is financially infeasible and environmentally unsustainable to keep expanding terminals and land endlessly[102]. Barge operators therefore need to find new ways to tackle the congestion at deep sea terminals. As a small history to this, Barge operators do not have contractual relationships with deep sea terminals, so neither is the deep sea terminal obliged to give them priority nor are the barge operators required to pay berth fees[83]. To worsen problems, in Port of Rotterdam, where inland waterways are prevalent, only 41% of the barges arrived/departed within the standard 2 hour window of arrivals[33]. This has caused chaos in barge berth allocation and in worse cases, deep sea terminals have also been forced to allocate deep sea berths to load or unload barges, delaying deep sea ships in the process. Adding on to the problems,barges arriving/departing from deep-sea terminals transport meagre call sizes to the hinterland during each trip(6-33 TEU)[33],this prompts more barge trips and more congestion at both deep-sea terminals and the inland waterway network in general. The problems seen here, therefore indicate opportunities to use improved transporters that are more reliable and adaptable to changing demand,New Terminal Solutions that are sustainable ,and finally new transshipment network ideas that can enable efficient deep sea to hinterland transportation.

This study was therefore initiated to investigate the problem of congestion along the deep-sea terminal-Hinterland network and explore solutions that satisfy both deep-sea terminals and barge operators. One of the major goals of this work was future-proofing the entire transportation process. Therefore, a strong emphasis was placed on using innovative concepts and methods that are universally applicable to all ports and networks for both the present and the coming years. In this process, groundbreaking concepts, such as floating container terminals, Amphibious AGVs, and methods like Agent-Based Modeling, were explored to create novel transshipment network ideas. This work is dedicated to that purpose.

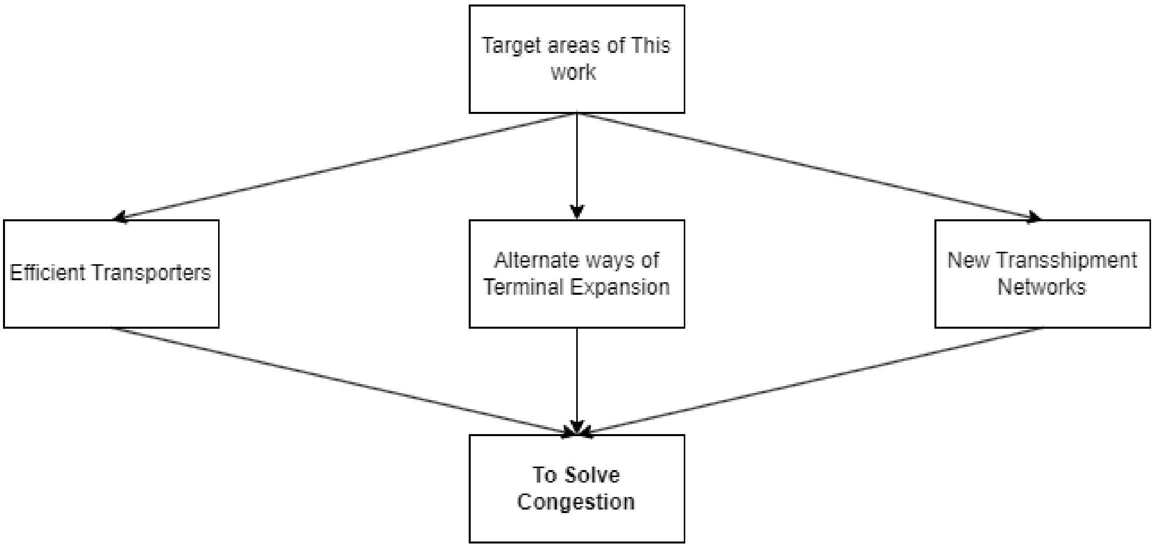


Figure 1.4: Opprotunities and Target Areas

This work focused only on the transport process between the shipping line and the Inland operator and not beyond that(refer1.3).

1.2. Problem Motivation

With globalisation, both deep sea container trade and hinterland container trade are expanding. Transhipment ports today face an uphill task in solving contrasting issues. On one hand, major Ports like Rotterdam, Hong Kong and Shanghai aim to increase barging and reduce truck traffic to control emissions[44][94], while on the other hand, deep-sea operators are reluctant to accommodate frequent barge calls due to the potential negative impact on deep-sea terminals such as massive congestion,delays for deep-sea vessels and reduced productivity[33]. Many Deep Sea Terminals at transhipment ports have ambitious growth plans of doubling their capacity as early as 2026[5], and simultaneously inland waterway networks are undergoing expansion. There is a need for future-proof solutions that address congestion and future demand for both deep sea operators and inland waterway barge while keeping all constraints of expansion in mind.

1.3. Research Questions

Given the motivation and implication of this congestion on world trade, this research wishes to delve into the following:

How can an **efficient transshipment solution** be developed to address **barge congestion** and enhance Hinterland transport within the **Deep Sea-Inland waterway Network**, ensuring competitive throughput rates, transport times, and reduced fleet sizes amid the simultaneous goals of barge significance and deep-sea terminal growth? The sub questions for this is as follows:

Current Challenges:

- What challenges currently impact inter-terminal barge networks in their operations between inland and deep-sea terminals?
- How do these challenges influence the overall performance of Barge/Deep Sea Operators in the existing transshipment setup along the Deep Sea Terminal-Inland Waterway network?

Logistical Adaptations:

- Considering land/space constraints in most ports, what logistical adaptations and transshipment changes can be explored along these networks?
- What short-term, medium-term, and long-term goals can be established for implementing revamped transshipment setups that satisfy all stakeholders?

Impacts and Trade-offs:

- What potential time-to-throughput impacts can be anticipated with changes in port conditions, aiming to reduce barge congestion and frequency at Deep Sea Terminals?
- What are the logistical,business and policy implications/trade-offs on future growth due to these novel transshipment networks and concepts?

Global Applicability:

- To what extent can these transshipment changes be globally applicable across ports and hinterlands worldwide?

1.4. Contribution of Research and Scope

This research significantly addresses the rapidly growing global container trade, particularly its profound impact on hinterland transport. The exponential growth of container trade has resulted in severe congestion within ports and waterways. To address this dual challenge of increasing barge transportation while alleviating congestion, there is a pressing need to explore innovative strategies for more effective solutions.

This study's primary objective is to identify and overcome the bottlenecks hindering expansion in container shipping. It aims to shed light on how groundbreaking transhipment concepts and network strategies can shape the future of container shipping and its interaction with the hinterland.The contributions of this research can be categorized into three main areas:

1. **Innovative Transshipment Concepts**: The first contribution revolves around the introduction and implementation of new transhipment concepts such as floating terminals, Amphibious AGVs, Barge Hubs within the current infrastructure. The adaptability and scalability of these ideas will determine their effectiveness in handling future container traffic
2. **Transportation Network Enhancement**: The second significant contribution lies in how these concepts function within the broader transportation network of the container supply chain, optimizing efficiency and reducing congestion. This will be done by formulating and experimenting with multiple transshipment network strategies ranging from deep sea to hinterland that make use of the concepts mentioned in the first contribution.
3. **Workability of Existing Infrastructure**- This research will place an emphasis on understanding how existing infrastructure can be better utilized within the current scheme of things. Accordingly, this work will divide all solutions into short-term, mid-term and long-term suggestions based on how their feasibility to be implemented in a said time.
4. **Scientific Methodology for Modeling**: Lastly, this research offers a structured and scientific methodology for modelling and implementing the aforementioned ideas, providing a systematic approach to addressing the challenges posed by the growing container trade.

This research delves into the complexities of global container trade, aiming to alleviate congestion and enhance the container supply chain through innovative transhipment concepts, network strategies, and rigorous scientific modelling. This will be done keeping the Hinterlands major point of focus.

1.5. Structure of Thesis and Research

The report starts with a brief introduction of the problem at hand with a short discussion on the overall impacts of barge congestion and the subsequent repercussions on growing trade/handling capability. This leads us to the focus areas of research and research questions pertaining to this work. The following chapter is a presentation of the literature survey which discusses both gaps and state-of-the-artwork (2). Chapter 3 sheds light on the overall methodology, choices, and elements that are considered in this work (3.2.1).A set baseline methodology will then dictate the simulation strategy and model in the next chapter (4). This will feature information on the model used, software and type of approach. The combination of the methodology and simulation strategy forms the environment to test both current operation (5.7) and proposed solutions (5). This is followed by chapters on experiments (**??**) conducted and subsequent results (8.5.3). The research concludes with a final chapter on the findings and future recommendations (9).

1.6. Research Methodology

The research methodology of this entire thesis will involve multiple steps as delineated in figure 1.5. The research started with a two-part literature study which is interlinked. The first part of the research focuses on exploring the various problems in the container shipping industry. Several issues were looked at from an angle of transhipment, hinterland transport as well as inter-terminal transport. Major ports were also studied during this process. Gaps and problems in literature and industry were noted. Subsequently, the second part of the literature focused on two areas. The first area was on new transhipment concepts such as Amphibious AGVs, Barge Hubs and Floating Terminals. The second area explored was the methods to simulate a full-fledged port environment such as agent-based modelling, discrete event simulation, optimization methods,etc. Once a baseline was set, the research methodology headed to the interview phase where crucial insight was taken from industry experts on the container traffic situation at ports(in this case Port of Rotterdam). The insight of the literature and the interview was used to simulate and understand the current problems associated with barging and deep-sea shipping. Subsequently, new solutions were proposed and tested using the same environment as before. The experiments involved the testing of the best solution found and the benchmark (current case) after which results and findings were obtained.

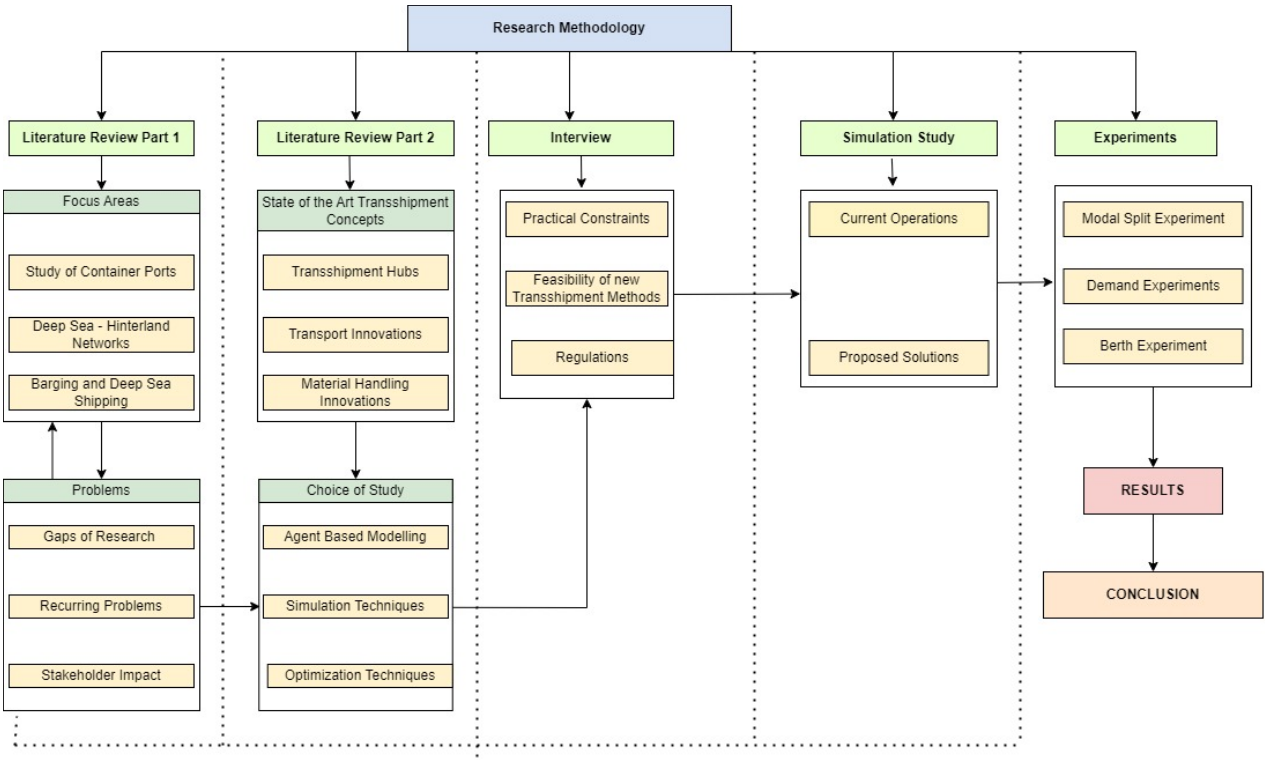


Figure 1.5: Research Methodology

2

Literature Review

2.1. Classification of Literature

With the pertinent problem of barge congestion at deep sea terminals being established, this work predominantly places the emphasis on two streams of literature which are as follows

- **Innovative Concepts**- This involved exploration of concepts crucial for efficient transshipment- Study on transshipment hubs and efficient transporters were carried out
- **Methods**- Exploring methods that can replicate the situation perfectly. This is both in terms of a simulation/optimization approach and a network strategy approach.

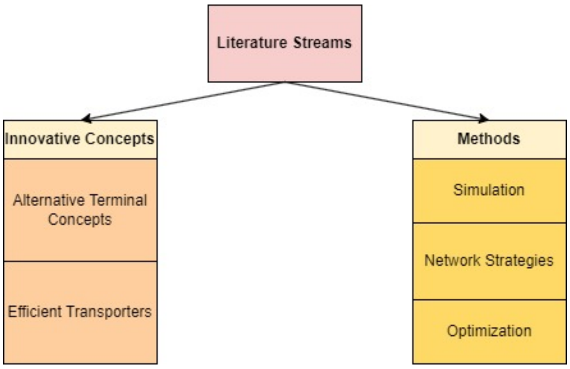


Figure 2.1: Literature Streams

2.2. Innovative Concepts

2.2.1. Novel Terminal/Transshipment Hub Concepts

A reasons to investigate this area was to determine possible ways of tackling future demand without unecessarily expanding the port in both new land reclamation and area. This will ensure more optimization of space while enabling new avenues for transshipment.

One of the promising innovative terminal concepts explored so far is that of a floating terminal. Essentially a floating terminal is a floating offshore platform that mimics the functionality of a regular container terminal. A floating terminal can also be made modular in design such that it is adaptable to different kinds of port and demand, In terms of what has been achieved in literature, several design concepts have been proposed. Dirk Rother and Baird's work in 2013[7] proposed a design that used run-down panamax vessels and barges to create the floating terminal dock with rail-mounted gantry cranes placed over it. Three similar concepts were made and it was concluded in the end that floating terminals could cost potentially just 1/3rd of the actual amount that would be needed to realise a full-fledged land terminal. The work also showed that in terms of return on investment, floating terminals could give a return on investment in just over a year. A limitation is that quay lengths of 1km as seen in current terminals cannot be replicated with this ship-reusable concept. Several concepts with expanded capabilities have been investigated in the past.Another promising work which focused on productivity was that of Dr Jovana Jovanova and Ir.W.Van Den Bos [39]. The work discussed container crane concepts such as the carrier crane which can be used for a dual-sided transfer(over the head transfer) of containers across the dock, eliminating the need for stacker cranes and yard vehicles on the whole. This prevented extra handling equipment on terminal. On average, anywhere between 40-50 AGVs/straddle carriers can be prevented by using concepts like carrier crane for direct transhipments. A similar over the head crane transfer idea was also investigated in a 2020 work[56]. The dual sided portainer crane spans the ULCV,feeder and barge. This modular storage concept means that almost 50-80% in initial investment was reduced. From a sheer network strategy, the Space@Sea work[80] proved the time(72% handling time savings) and throughput(10% higher) benefits of implementing a floating terminal concept. Floating Terminals will be key in connecting hinterland traffic with deep sea terminals. Their scalability also opens up options to handle or split deep sea terminal traffic eventually such as feeder traffic.

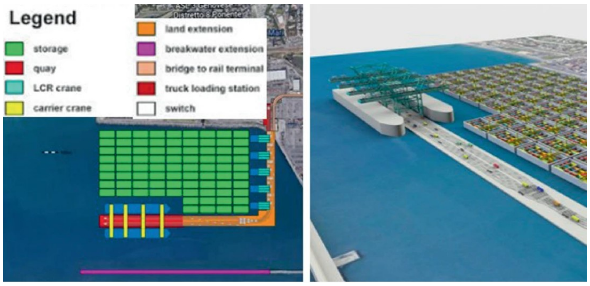


Figure 2.2: Direct Transshipment-Yard+Multiple Vessels[56]

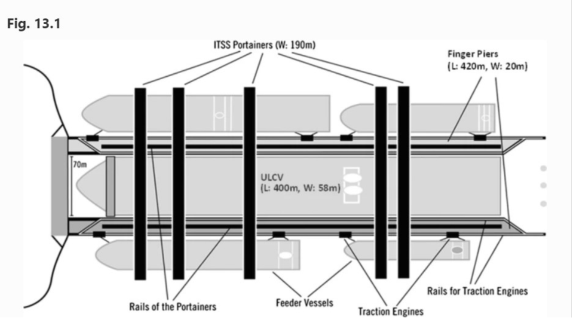


Figure 2.3: Direct Transshipment-Over the Quay[39]

The concept of a barge hub was first seen in a series of literature papers by Rob Konings [67] with regard to new transhipment concepts aimed at efficient handling of barge traffic in Port of Rotterdam. Essentially in the literature's own words, a barge hub would be an intermediate terminal that would provide extended hinterland services by moving the centre of traffic and congestion from deep sea terminals to a terminal that is more accessible by Hinterland actors.The Work discusses multiple barge hub concepts of which the fourth concept is chosen. This type of barge hub is where container consignments from hinterland are fully discharged at the barge hub before being distributed to other hinterland actors. A key advantage with this concept is that,even an existing terminal can be converted into a barge hub.An advantage with barge hubs are,that large call sizes can be readily brought into one terminal before being distributed to other hinterland terminals. The advantages of this however could be limited if hinterland terminals are closer to the barge as in that case a direct shipping to concerned terminals could be faster and that has also been proved literature[42]. A common point that should be discussed under both modular/floating terminals and barge hubs is that such transshipment concepts have been proven feasible only for small cargo volumes[61]. While this is not directly related to a transshipment hub system, port feeder barges have also been ardently looked at. This is essentially a barge-cum-crane handling system[46] which is of low-investment. Essentially this is an efficient crane on barge mechanism that loads,unloads and transports container by itself[19][54]. However pointed out in Hassel's work[61], this might not sit well with deep sea and hinterland operators who will be urged to use a third-party provider.

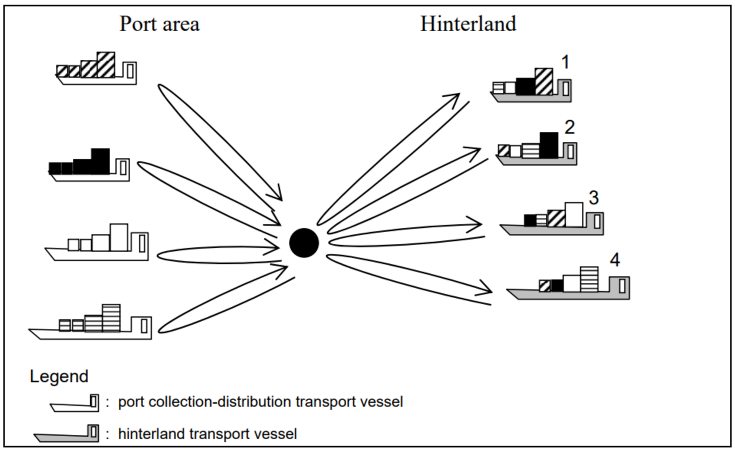


Figure 2.4: Barge Hub Concept[67]

Inferences for Transshipment hubs

It can be understood that concepts such as floating terminal and barge hub are convincing enough to positively influence a transshipment network for both deep-sea shipping and Hinterland shipping. Modular terminals are promising but, works suggest that having a fixed permanent location adds to the value of the terminal operator as well. Therefore floating terminals and barge hubs will be a part of different solutions.

2.2.2. Efficient transporter

Problems with Current Transporters

A few problems noted with current transporters are as follows

- At the moment many transporters cause double handling/rehandling of containers. As indicated in the author's earlier work [70], there is need for a common transporter and system that is capable of interacting with yard,quay and landside while avoiding double handling (avoid multiple truck+barge handling).
- An alternative to the established problem of small barge call sizes has to be found out

Transporter to Address Efficiency/Container Rehandling

Efficiency has often been a strong word container shipping since improving it goes beyond optimization algorithms that history can suggest. This is where new concepts are necessary. One such concept is that of an Amphibious AGV. The previous generation of regular AGVs contributed to the whole rehandling conundrum with every procedure requiring a land travel and water travel. This adds to the total transport time and limits possibilities. An amphibious AGV would be a one-stop solution which will travel on both land and water along short distances for swift transport. Only two such concepts exist in literature,an initial thesis by TU Delft's Timo Kleefstra[41] and a future improved work by another set of TU Delft students [23].The literature showed that potentially for short distances like inter-terminal transport, an AAGV could reduce transfer times by 21% compared to trucks. Essentially a 25 km inter-terminal transport in Port of Rotterdam[11] could be reduced to just 3km if AAGVs are used. The versatility of AAGVs ensures that they can achieve a major goal of this project, that is to divert hinterland congestion from deep sea terminals. Another innovation in efficient short range transport is the waterborne AGV which was first conceptualised in 2014 by H Zheng and Dr.Rudy Negenborn[101].This showed a lot of promise in its application and subsequently a lot of work has been done in the area of control and coordination for waterborne AGVs.Especially in and around the Maasvlakte in Rotterdam[11], which also forms a major part of this thesis work. However a major drawback compared to AAGV is that they would still need an extra handling point between water and land, therefore giving the overall versatility advantage to AAGV.

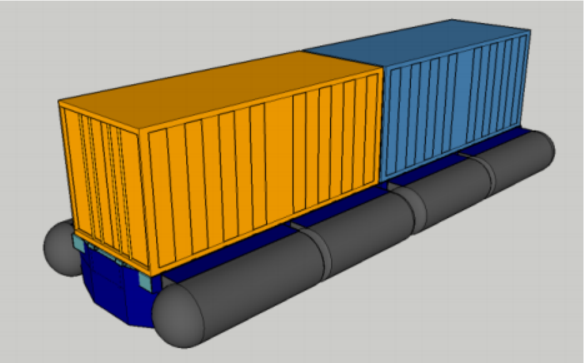


Figure 2.5: AAGV-Timo Kleefstra's Design[41]

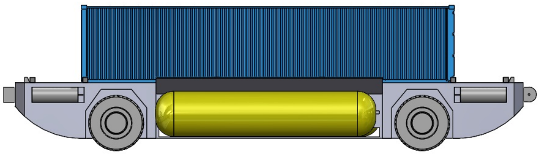


Figure 2.6: AAGV-Integrated Project Team Design[23]

Transporter to Address Call Size Problems

One of the major gaps realised initially were the low call sizes[28] prompting multiple trips to the hinterland. This is a universal problem and requires to be addressed. An immediate solution, will be to use much bigger call sizes while being transported to the hinterland. This would also provide interesting opportunities for the barge hub[42] and floating terminal concepts[56] as they themselves work on using large call sizes. While there is no separate concept that gives a name to these high-call size barges, this will be referred to as ”Super Barge” henceforth and this would essentially be a high density barge that transports 400 TEU-700 TEU. As an idea, the concept of a high density Cosco electric container ship exists in the inland waterways of shanghai[55]. Call size will be varied between 400-700 TEU. Super barge has the ability to take on containers scheduled for different hinterland terminals as one consignment to a container hub before distributing the same to the hinterland.

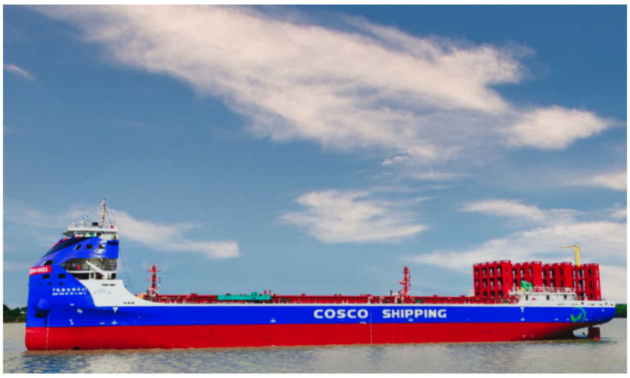


Figure 2.7: Cosco 700 TEU container ship-Super Barge [55]

2.3. Methods

The literature also has a dedicated section on methods which will help meaningfully link all concepts. Any deep sea- hinterland model's main engine would be a mix of simulation,optimization and a network strategy

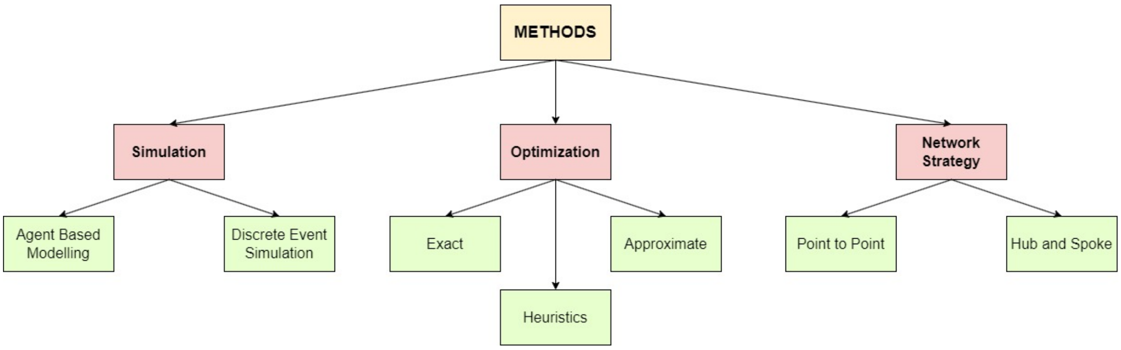


Figure 2.8: Methods

2.3.1. Simulation in Maritime Transport

To best replicate a maritime transshipment process, along with its behaviour, simulation is used. When we are simulating a transportation process from deep sea terminals to hinterland, it is required to know which process creates the bottle neck and also if solutions are found, a range of solutions is desired to make an informed business decision. This is essentially possible only through simulation.When KPIs such as time, throughput and congestion are considered, then it is simulations that gives us a picture of best solution and worst outcome within same model. This is not possible in optimization. There are two main methods that have been predominantly used and they are agent-based modelling and discrete event simulation.

Discrete Event Simulation

A discrete event simulation refers to any system who process is the main focus of modelling [53]. In fact the whole system is considered as a process[3], for example lets consider a ship which is arriving at a port. In discrete event simulation, this ship would first arrive, then be moored, subsequently berthing after which it starts unloading containers by initiating a Quay crane. Once unloading is done, it begins to take on new sets of containers and once loading is accomplished, it departs. If we notice this closely, this followed a very sequential process where each task depended on the completion of the previous task. Essentially at each time step,a new process takes place hence the name discrete event. This sequential process allows for a very organised process but is not flexible when multiple processes need to take place simultaneously[24].

Agent Based Modellling

Agent-based model approach is a computational model that simulates actions and interactions of autonomous agents[97]. The main subjects of the study are classified as agents and the corresponding computer simulations are used to study the interactions between various entities which are classified as agents[16]. Lets consider the same example of a ship arriving at a port. Here the first step is to consider who and what is involved, they are basically the ships themselves,the quay cranes,berths and trucks/AGVs. All these entities would be classified as agents and this defines the system[3]. Each agent would have its own tasks and activities while there will also be separate interactions between agents themselves. In this case, an agent ship would have a task of arriving , docking and leaving but when it interacts with the crane agent then loading/unloading would come in to the picture. This approach provides greater flexibility and also allows for parallel processing(activities take place simultaneously) compared to discrete event which is sequential in manner. Furthermore ABM defines a system first before diving into the interaction while DES is just sequential.

Autonomy of entities and possibility of simultaneous activities are a reason why Agent based Modelling is chosen over Discrete Event simulation[24].

2.3.2. Optimization

Optimization as a strategy is very important in order to find a definite answer. In this research, optimization is instrumental in determining the fleet size for different models Mathematical optimization is predominantly of three categories- 1)Exact 2) Approximate and 3) Heuristics.

Exact Algorithm Optimization

Exact algorithms are any algorithms that solve an optimization problem to optimality . This essentially means there will be no optimality gap recorded when the classic P=NP solution is computed. Evidently this would involve a high computational time. Algorithms like linear programming, dynamic programming fall under exact algorithm[87].

Approximation Algorithm Optimization

Approximation algorithms refer to those algorithms that find approximate solutions to optimization problems. Essentially, here the P=NP equation will not hold true. However approximate solutions are guaranteed to give an answer extremely close to the optimal one since their design and analysis involved mathematical proof that a solution would be returned in any case[98]. This also takes lower computation time. Greedy algorithm and local search are some examples of the approximation algorithm optimization[98]. This puts them at an advantage when compared to heuristics which can also return infeasible commands.

Heuristics

Heuristics is a technique for optimization that is more focused on giving a solution quickly rather than its quality. They are generally faster than exact/approxomate algorithms but the tradeoffs here are lower accuracy and lower precision[66]. Metaheuristics will not provide a globally optimal solution, but the final answer will be closer to optimality since optimization is iteratively also done on an entire set of feasible solutions[9].Despite their lower precision(compared to exact/approximation), for running large scale simulations like a deep sea -hinterland system where 10-20 agents could be involved in one simulation, heuristics are a good choice for optimizing the fleet size in the following simulation.A high quality algorithm commonly used in fleet sizing is genetic algorithm due to it inherent use of natural selection strategy. A population of solutions is first generated after which they are iterated based on their mutation and this process continues until a value close to the optimality/value equal to previous iteration is obtained[58]. This is compared with a fitness function that keeps the solution's optimalities in check. This genetic algorithm provides the best trade-off between speed, accuracy and precision for fleet sizing[13].

2.3.3. Network Strategy

There are predominantly two network strategies which are used in any logistics network to deliver goods. One is the hub and spoke strategy, the other is the point-to-point theory.

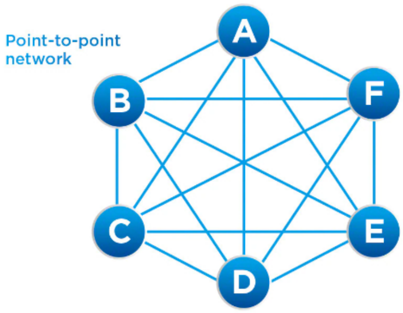


Figure 2.9: Point to Point Network[34]

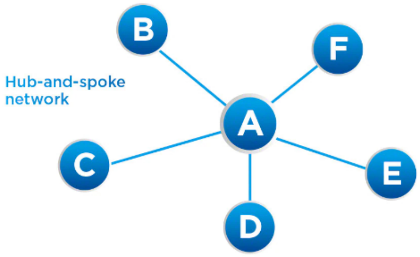


Figure 2.10: Hub and Spoke Network[34]

Point to Point

As per point-to-point theory, in order to connect all destinations in a network, you have individual transporters going from each point to adjacent or diagonal points. For example, lets assume an airline company wants to expand its network, if it applies a point to point theory then it connects everything from A to B to C to D to E to F and all points in between. This would require 15 unique aircraft to accomplish the network. When this translates to container shipping, the same nearly applies here as well. Especially when barges originate from the hinterland, then they would essentially visit all deep sea terminals in a point-to-point manner[83][65].

Hub and Spoke

When hub and spoke as a theory is looked at, one of the high density points in the network is made a hub from where transporters can originate. This hub would then be a common connection point for all the other destinations in the network. In the figure above, if A is made a hub then one would need only 5 transporters to connect all the points. Going back to the aircraft example, if someone has to travel from B to E, then A would be a transit point(or transshipment in maritime terms). Ideally this hub and spoke would be effective for long-distance travel of goods and this relevant in the case of container shipping which often involves long distance transfers. Assuming containers have to be transported from B to F then going via A is going to cost more fuel and time and more distance in the process[65].

Ideal Network strategy

When both hub and spoke, point to point are compared, it is clear that a maritime transshipment system would need a combination of both. Succesful shipping lines like Maersk[27] and aviation companies like Southwest[74] and Indigo[12] have used combination of both networks for transshipment and transit of goods respectively. As stated earlier, if a hub is close to the destination, then a direct -origin-to-destination(point-to-point) transfer would be logical. Similarly for long distance, hub and spoke works best. Therefore findings from literature recommend a combination of both networks for this work.

2.3.4. Literature Inferences and Choices

The final choices and inferences from literature are summarised in the figure below.

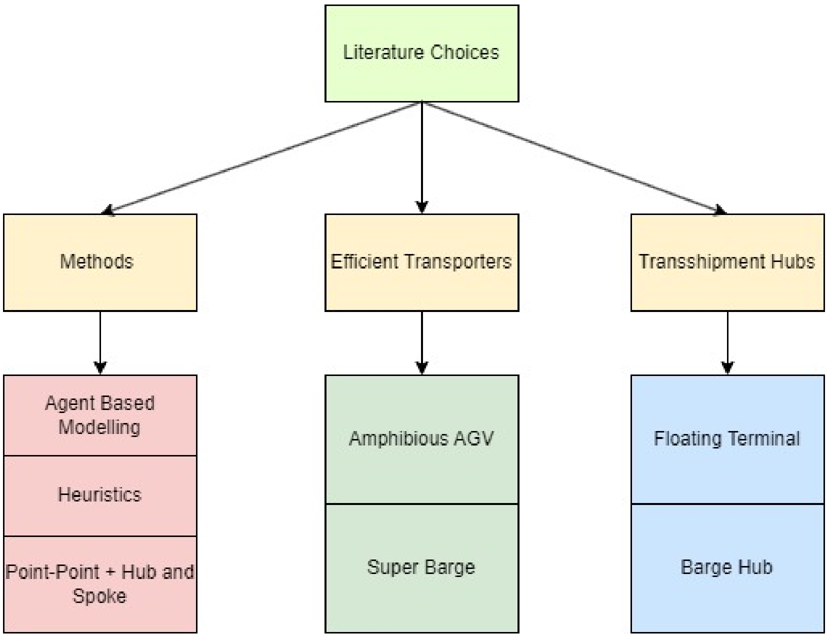


Figure 2.11: Methods

3

Methodology

3.1. Overview

The research followed a methodology(refer fig 3.1) that was used to answer all the research questions. The methodology starts off by identifying the elements of the environment that are to be investigated. In this case, the environment is the Seaport and Hinterland itself through which containers are transported to the hinterland. The first block precisely touches upon those two aspects, namely the actors which in this case refers to the ports& terminals, containers and transporters. The first block also touches upon the interaction between the above said elements as the ultimate goal is to replicate these entities and their operations in future steps.

The next block in the methodology places an emphasis on modelling and simulation. This is where the elements of the environment such as terminals and transporters are brought to life. Here a multi-agent system is used to define the elements in the environment. The simulation model and process logic link all these agents in a meaningful manner with respect to the parameters and constraints that are fed into the system. A software implementation validates the created model as well as analyses the generated data.

The final block in this methodology defines the overall performance evaluation of the created model. Here the Key performance indicators such as congestion, transport time, throughput and fleet trade-off are investigated from the analysed data. Based on this the effectiveness of each solution can be determined with regard to the running KPIs.

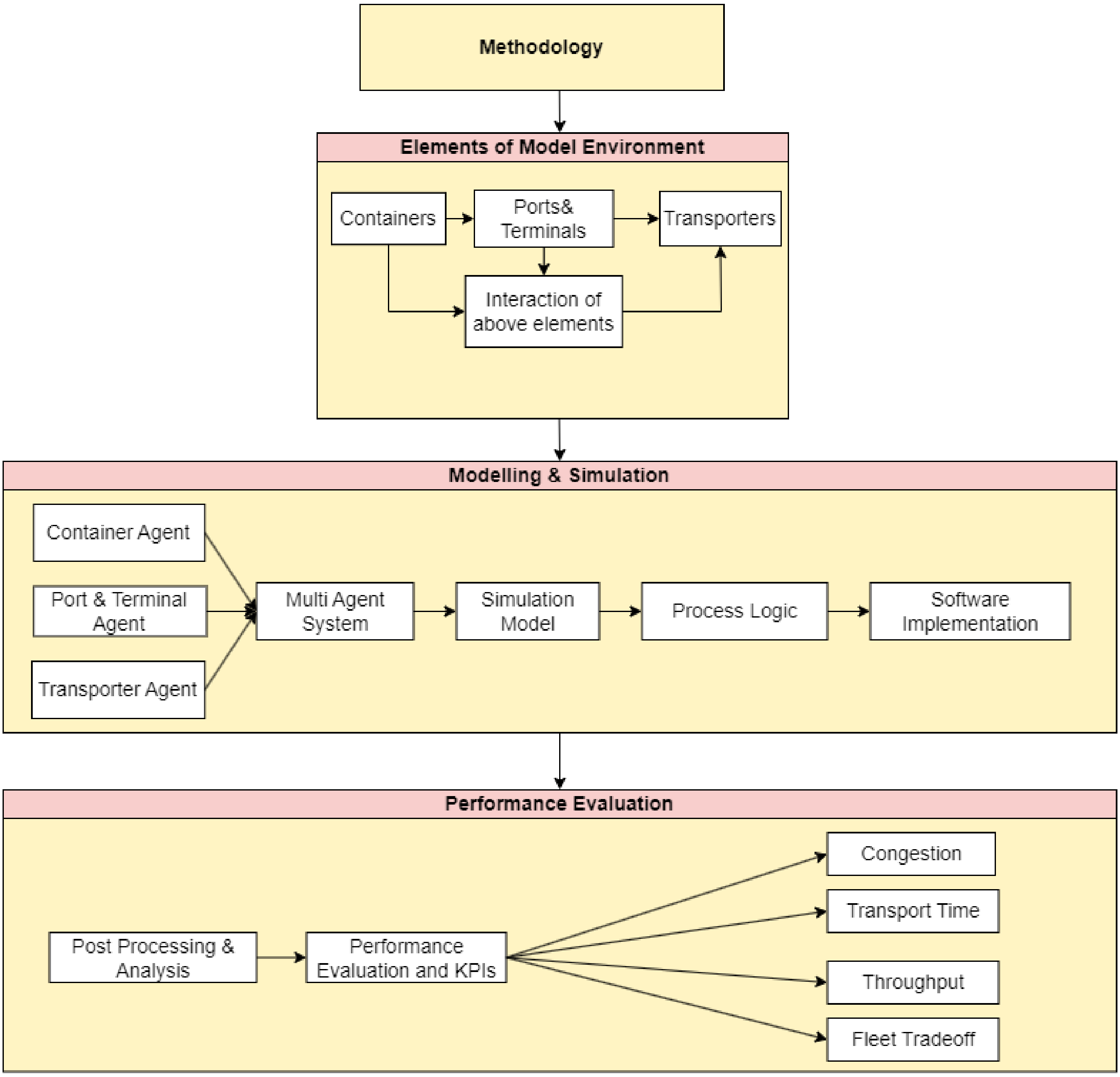


Figure 3.1: The Methodology at a glance

The following sections will expand on the aforementioned blocks and their respective components.

3.2. Containers

3.2.1. Description

Containers form the major subject of the shipping transportation chain ranging from any port to any terminal to its eventual Hinterland destination. Containers are unit load devices that carry goods ranging from bulks to perishables to certain liquid products. Twenty-foot containers are designed to hold 25 tons of cargo while 40-foot containers are certified to hold 30.5 tons of cargo. Shipping containers are mainly of two types, 20-foot and 40-foot containers. Therefore containers will be modelled as **orders** in the eventual model and simulation [75].

3.2.2. Configuration

. In essence transportation and delivery of containers are akin to how orders are handled in any supply chain. Therefore containers will be modelled as **orders** in the eventual model and simulation [75].Container orders are configured in such a way that they have a ”recipient” parameter to deliver containers(orders) to the final destination. Example- If hinterland is final recipient then they are referred to as the ”HinterlandRecipient” in the model.

3.3. Ports and Terminals

3.3.1. International Ports

This research considers ports as an agent or a collection of agents, for home ports such as Hamburg and Felixstowe,a single agent is considered. This is essentially a berth in a terminal. Since Rotterdam is the choice of port case study, it is a comprehensive collection of agents under different categories which are presented in subsequent sections. The collection of such agents are mentioned below

3.3.2. Deep Sea Container Terminals

A deep-sea terminal, also known as a deep-water port, is a specialized facility designed to accommodate large vessels, particularly those classified as Panamax and above. These terminals are crucial hubs in international trade, capable of handling a variety of vessels ranging from barges and feeders to massive deep-sea ships. Located in ports like Hong Kong and Rotterdam, these terminals experience significant daily traffic, with throughput ranging from 5000 TEU to 22000 TEU, highlighting their capacity to handle substantial cargo volumes efficiently.

Model Representation - Berths, Cranes, Loading/Unloading

The deep sea terminal is represented as a congregation of GIS (Geographic information system) points in the model. These points pertain predominantly to the berths for different kinds of ships. For instance, if there are 3 barge berths then this implies 3 GIS points under the agent assigned for barge berths. Similarly, if there is a berth reserved for a Deep Sea Ship and a feeder ship we will then have two GIS points respectively. This is delineated in table 3.1. It is also prudent to point out that the actions of quay cranes and barge cranes are controlled by parameters and time delay blocks which signify loading and unloading of containers in the process.

Table 3.1: Elements in Deep Sea Terminal

Components in Deep Sea Terminals	Model Representation
Deep Sea Berths (4000 TEU+ Ships)	Static Agent; GIS Points
Feeder Berths(1000-1500 TEU Ships)	Static Agent;GIS Points
Barge Berths	Static Agent; GIS Points
Deep Sea Ships	Moving Agent
Barges	Moving Agent
Feeder Ships	Moving Agent
Quay Cranes	Parameter + Time Delay Block
Barge Cranes	Parameter + Time Delay Block
Stacking/Yard area	Agent; GIS Points

General Processes Modelled in Deep Sea Terminal

While all processes pertaining to different solutions will be discussed in future sections, some general processes will be outlined here pertaining only to this research and only with respect to the Deep Sea Terminal.

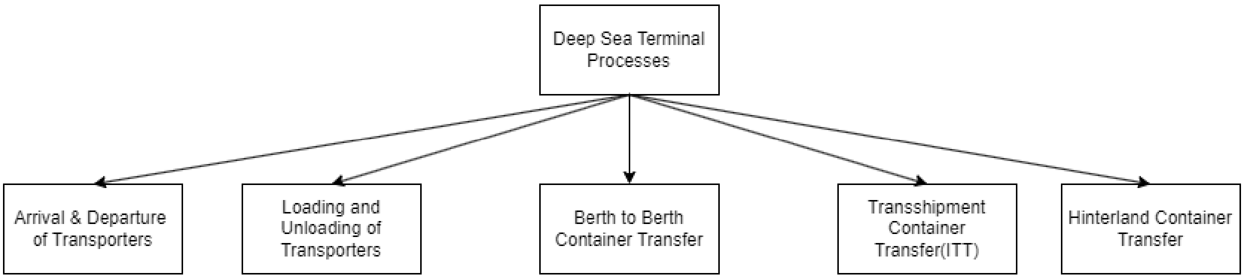


Figure 3.2: Processes Considered in Deep Sea Terminal[4]

- **Arrival and Departure of Transporters**- These refer to the arrival and departure of deep-sea ships, barges and feeders that occur on a daily basis.
- **Loading and Unloading of Transporters**

  The loading of unloading of all transporters follow a triangular distribution process ranging from a minimum number of crane moves(30 moves/hour) to a maximum of 50 moves/hour. This specific aspect is represented by a time delay block in the model that signifies loading and unloading. Based on the type of ship, the process is also complemented by dedicated parameters for the number of quay cranes(for barges, deep sea ships, etc)
- **Berth to Berth Container transfer within Terminal**- This transfer usually occurs when unloaded containers need to be moved from a deep sea/feeder berth to a barge berth. This is usually done for reasons of transhipment either between two deep sea terminals(Inter- Terminal Transfer) or Hinterland transfer of containers. This berth-to-berth transfer of containers usually happens through means of Trucks/AGVs along its dedicated route corridor.
- **Transshipment/landside Container Transfer** This refers to the transfer of all containers between deep-sea terminals or in essence inter-terminal transfer. This is accomplished via truck, barge and AGV. Transshipment also involves medium to long-term storage section which are yards/Stacks.
- **Hinterland Container Transfer** The last main operation and important subject of this research is the hinterland container transfer via barges from deep sea terminals to inland terminals.

3.3.3. Hinterland Terminals

Hinterland terminals refer to those container terminals that are located on inland waterways or simply Inland(dry ports). These are generally home to containers originating either from deep sea terminals/deep water ports for import purposes or from deeper hinterlands for export through Deep sea Terminals. Essentially the deep sea- Hinterland network practices an extreme hub and spoke network concept. Hinterland Terminals also exercise a lot of versatility by employing intermodal connections such as rail, barge and truck connections.

Table 3.2: Elements/Description of Hinterland Terminals

Hinterland Terminals	Model Representation
Barge Cranes	Parameter +Load/Unload Delay
Barge Berths &Super Barge Berths	Static Agents;GIS Points
Stacking/Yard Area	N/A,Direct Transfer to Landside assumed
AAGV Container Pickup Points	Static Agents;GIS Points
AAGV Ramp	Parameter + Time Delay

Components and Model Presentation

Table 3.2 presents an idea of the components in a hinterland terminal and the way they are represented at various stages of this research. As discussed in the earlier section, barge cranes are represented in the form of a loading and unloading block that runs on a triangular distribution. Certain parameters also support the information needed for time delay. These will be delineated in section 3.5.4. Crucial information such as barge/super barge berths will be designated as stationary agents identified by the

GIS points in the simulation model. Since this research focuses on the first-in-first-out transfer of containers at all stages, it is prudent to point out that stacking/yard area is not of any concern at Hinterland terminals. It has been assumed that all containers that arrive at the hinterlands will directly be shipped to customers or head to deeper hinterland networks. This is corroborated by the fact that hinterland terminals often have very compact yard areas. Owing to the deployment of innovative transhipment vehicles such as Amphibious AGVs, Hinterland Terminals will also be assumed to be equipped with AAGV ramps to enter and exit land as well as AAGV container pickup points. The representation of the aforementioned points can be understood from table 3.2.

Processes Modelled in Hinterland Terminals

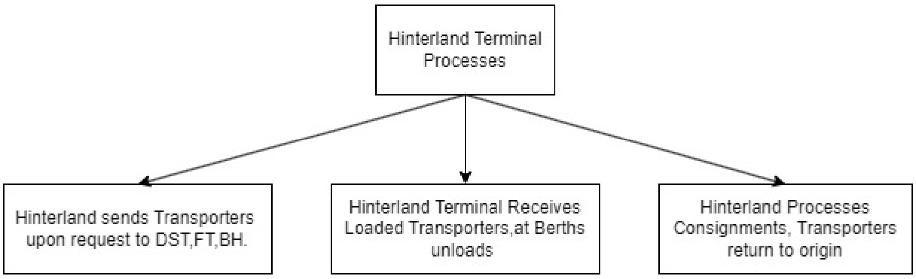


Figure 3.3: Process Modelled in Hinterland

Pertaining to this research, the processes modelled for hinterland are depicted in figure 3.3.

- **Hinterland Send Transporter Upon request**- Any hinterland transport begins with a request from another terminal to send transporters from the hinterland to collect container consignments from the concerned terminal. In this research, the potential terminals that will place the request to the Hinterland are the Deep Sea Terminals, Floating Terminals and the Barge Hub depending on the case investigated.
- **Hinterland Receives Loaded Transporters at Berths**- The transporter docking at the hinterland will subsequently unload containers at the berths available.
- **Hinterland Processes containers**- The transporter returns to its origin terminal once the process in complete .hinterland processes the containers and determines its final customer destination or next hinterland journey depending on the cargo type.

3.3.4. Barge Hub

Barge Hub Description

The barge hub in essence is still a hinterland terminal in design and specifications owing to the fact that the terminal would still handle the same kind of transporters. While a barge hub is similar in functionality, it is also meant to be bigger in scale to handle the incoming traffic through bigger vessels such as superbarges. As shown in table 3.3, the configuration and representation for all elements follow a similar tune to previous concepts. Owing to the introduction of Amphibious AGVs, the barge hub will have dedicated container pickup points/ramps for AAGVs located close to the berths. While barge hubs do have a sizeable yard area, similar to previous transhipment concepts barge hubs will also focus on direct first-in-first-out container transfer. It is prudent to point out that in all solutions explored with barge hub, the terminal used already exists and is merely a reconfigured version of the same terminal.

Table 3.3: Elements of Barge Hub& Model Description

Barge Hub Components	**Model Representation**
Barge Cranes	Parameter + Load/Unload Delay
Barge Berths & Super Barge Berths	Static Agents;GIS Points
Stacking/Yard Area	N/A, Direct Transfer Assumed
AAGV Container Pickup Points	Static Agents; GIS Points
AAGV Ramp	Parameter + Time Delay

Processes Modelled in Barge Hub

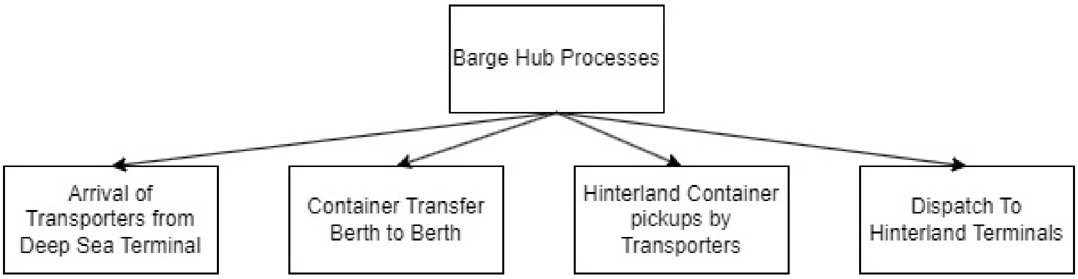


Figure 3.4: Processes Modelled in Barge Hub

- **Arrivals of Transporters from Deep Sea Terminal**- When a barge hub is deployed, it will receive high density transporters from deep sea terminals such as the Super barge which would carry anywhere between 400- 700 containers as a call size.
- **Container Transfer Berth to Berth**- Depending on the type of concept used containers may be transferred to other berths for transhipment/hinterland transport via this barge hub. This intra-terminal berth container transfer is accomplished via Trucks.
- **Hinterland Container pickups by Transporters**- The subsequent container pickups will be done by transporters such as AAGVs and barges depending on the type of concept used.
- **The container consignments are then dispatched to the hinterland via AAGVs/barges**.

3.3.5. Floating Terminal

The floating terminal is an offshore container exchange platform designed to mimic the activities of a deep sea and hinterland while providing the flexibility of space and cost. As discussed in earlier sections, the floating terminal is a powerful tool that can also be leveraged by ports to overcome the constraint of land since land reclamation is environmentally hazardous in the long run[86]. This research treats the Floating terminal concept very similar to how a barge hub is treated but here it will be considered as an intermediary/ distribution facility that can also handle containers for inter-terminal transport apart from hinterland transport. Therefore location of any floating terminal in this research regardless of country, will be located closer to deep sea terminals than the Hinterland. The floating terminal is also designed to handle AAGV, feeders and barges/super barges.

Conceptual design of a Floating Terminal

From the study of the above literature and the requirements pertaining to this work, it is clear that a potential floating terminal solution will need to have storage but be essentially free in terms of vehicles and yard cranes. Ideally, this floating terminal will also need to have an over-the-head crane transfer concept that would prevent additional handling equipment that would otherwise be needed in a conventional terminal. A conceptual design of a floating terminal is presented in figures 3.5 and 3.6. The two floating terminals predominantly differ in scale and are similar in functionality.

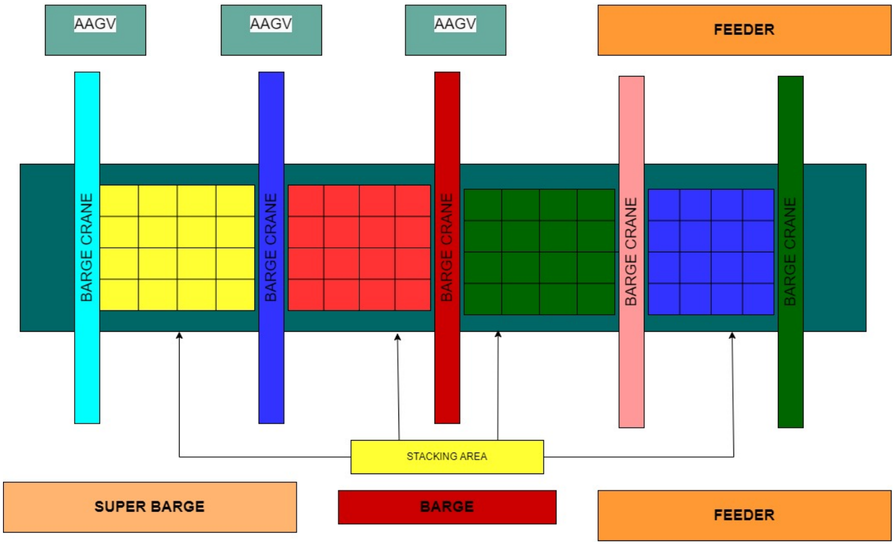


Figure 3.5: Floating Terminal Conceptual Design- Small Scale

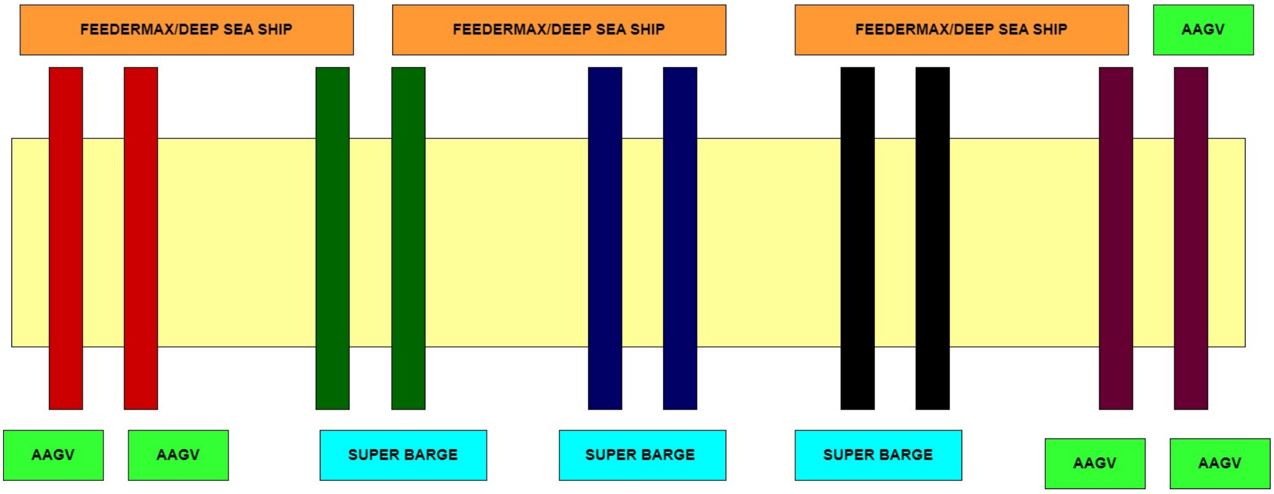


Figure 3.6: Floating Terminal Conceptual Design- Large Scale

The aforementioned diagrams represent the design of the respective small-scale and large-scale floating terminals. The floating terminal consists of a 500m and 1000m quay respectively and will house berths for different kinds of transporters. The possible combination of berths and cranes is presented in fig 3.5. Depending on the solution, the number of berths will vary for the respective combination of transporters that are employed. Both the floating terminal designs are flanked by rail-mounted gantry cranes that have the capability to transfer containers over the head with space under the crane being reserved for storage. The crane who's specifications have been considered for this is Liebherr's Rail Mounted gantry crane[49] that can span 70m or more based on requirement and can lift up to 65 tonnes of load. This also opens up the opportunity to lift two containers at once. Therefore the RMG Crane is also equipped with twin spreader technology that enables the double container lift technology. A spreader of this kind is presented in figure 3.8.

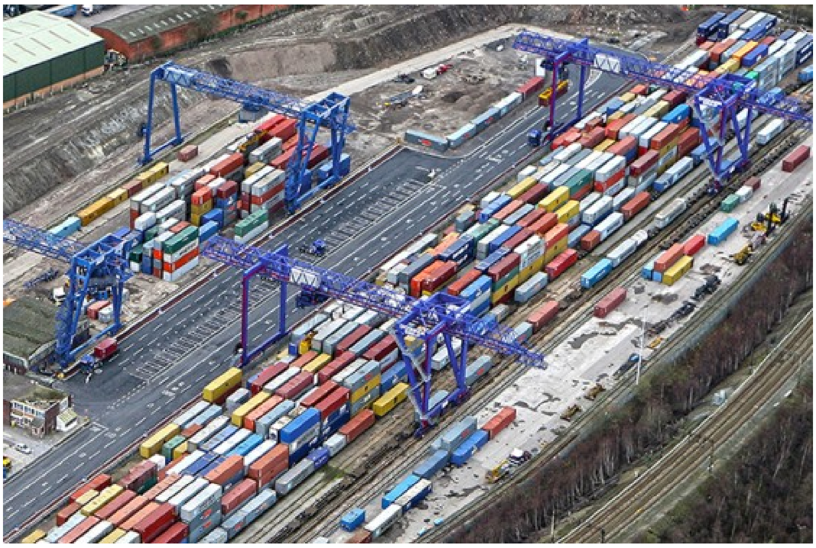


Figure 3.7: Liebherr Rail Mounted Cantry Crane(Dual Sided) [49]

Figure 3.8: Twin Spreader Technology [60]

The remaining design specifications of the floating terminal are listed in table 3.4. Some salient points to be discussed here are the resulting capacities of the floating terminal. The terminals are assumed to have 5 and 10 RMG cranes respectively and are capable of handling 300-500 TEU/hour for the smaller terminal and 600-1000TEU/hour for the bigger version. When an operational service of 350 days annually is assumed, the terminal cranes collectively will be able to handle 2.1 million and 4.2 million TEU on a yearly basis respectively. This is a conservative figure as terminals with similar resources are known to handle more footfall.The floating terminal as it is also has storage area as indicated in the images 3.5 and 3.6. The containers here are arranged in a similar manner for both terminals, therefore this results in a storage capacity of 6750 TEU for the smaller floating terminal and 13500 TEU for the bigger floating terminal design.

Table 3.4: Floating Terminal Design Specifications

Category	**Floating Terminal 1**	**Floating Terminal 2**
Crane Gantry Span	80m	80m
Quay Length	500m	1000m
Span Speed	60-70m/min	60-70m/min
Lifting Capacity	65 Tonnes	65 Tonnes
Type of Crane	Dual Sided RMG Crane	Dual-Sided RMG Crane
Number of Cranes	5	10
Container Moves/Hour	30-50 Moves/Hour	30-50 Moves/hour
Twin Spreader (2 Containers at Once)	Yes	Yes
Container Handling/Hour(with Twin Spreader)	300-500 TEU/Hour	600-1000 TEU/Hour
Operational Days/Year	350	350
Container Handling/Year	2.52 million- 4.2million TEU	5.04 million-8.4 million TEU
Stack Arrangement(ALL TEUs)	1. 25(Width Wise) 2. 6(Height Wise) 3.45(Length Wise)	1. 25(Width Wise) 2. 6(Height Wise) 3. 45(Length Wise)
Maximum Container Storage at Once	6750 TEU	13500 TEU

The respective floating terminals also have possible berth and crane configurations which have been delineated in table 3.5. While this is subject to change with different use cases, for example, a floating terminal with 5 RMG cranes(refer 3.5) will have 10 access points (2 per each crane). This potentially would allow for a combination of 1 feeder, 2 Super Barges(with 2 Cranes), 1 Super Barge(with 1 crane) and 3 AAGVs to be accommodated at the same time. Conversely, this could also be 2 Super Barges and 4 AAGVs at once in the Floating Terminal. The bigger floating terminal can also be configured similarly to the smaller version. As an example, the figure 3.6 represents a solution that will be investigated for the Hong Kong- Pearl River Delta Case study.

Table 3.5: Berth/Crane Configurations of Floating Terminal

Berths/Crane Configurations	**Floating Terminal 1 (Small Scale)**	**Floating Terminal 2 (Large Scale)**
AAGV	1. 3-4 Berths 2. 1 Crane/AAGV Berth	1. 5 Berths 2. 1 Crane/AAGV Berth
Super Barge	1. 2-3 Berths 2. 2 Cranes (or) 1 Crane/SB Berth	1. 3 Berth 2. 2 Cranes/Super Barge Berth
Regular Barge	1. 3 Berths 2. 1 Crane/Barge Berth	1. 3-5 Berths 2. 1 (or) 2 Cranes/Barge Berth
Feeder	1. 1 Berth 2. 2 Cranes/Feeder Berth	1. 3 Berths 2. 3 Cranes/Feeder Berth
Feeder Max	N/A	1. 3 Berths 2. 3 Cranes/Feeder Max Berth

Processes Modelled in Floating Terminal

Table 3.6: Elements/Description of Floating Terminal

Components in Floating Terminals	**Model Representation**
AAGV Berths	Static Agent; GIS Points
Feeder Berths(1000-1500 TEU Ships)	Static Agent;GIS Points
Barge & Super Barge Berths	Static Agent; GIS Points
Deep Sea Ships	Moving Agent;
Barges	Moving Agent
Super Barge	Moving Agent
Feeder Ships	Moving Agent
Rail Mounted Gantry Cranes	Parameter + Time Delay Block
RMG Transfer	Parameter + Time Delay Block
Stacking/Yard area	N/A, Direct Crane Transfer

The entire list of elements involved in the Floating terminal is presented in table 3.6. Notably, most of the blocks and elements are similar to the ones involved in Hinterland terminals and deep-sea terminals. It is also prudent to point out that the floating terminal will also employ direct crane transfer and therefore this research will not focus on the storage component of the floating terminal.

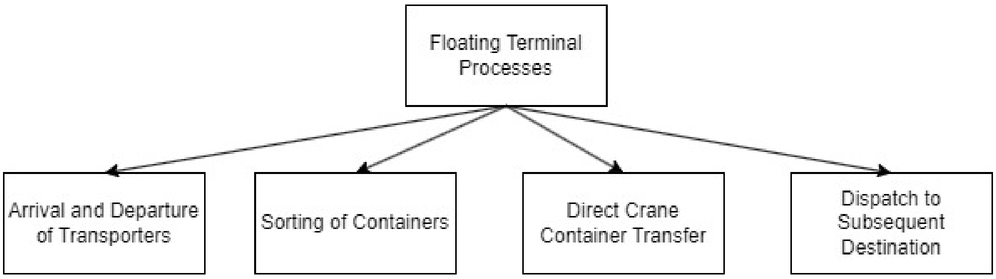


Figure 3.9: Processes Modelled in Floating Terminal

The processes involved in the operations of the floating terminal can be described as follows

- **Arrival and Departure of Transporters**- Due to its proximity to the deep sea terminal, the floating terminal receives containers either from the deep sea terminal scheduled for the hinterland or is in a position to send containers to the deep sea terminal itself. Additionally, the floating terminal can also receive feeders at its berths. This is apart from the fact that regular barges and super barges will use the floating terminal to transport them to the hinterland. As discussed earlier, the transporters can access the floating terminal according to figure 3.5.
- **Sorting of Containers**- Once the transporters arrive at the floating terminal, the containers need to be sorted as per their next destination and this is decided before the crane transfer. The reason for this is because then the concerned crane can swing into action to transfer the containers. Therefore it must also be noted that when transporters dock at the floating terminal, they dock only at those berths that are parallel to the transporter to which the container needs to be transferred. For instance in figure 3.5, towards the far left two AAGVs are situated opposite a super barge. This implies that both the AAGVs and super barge have a container transfer between them, similar to any other transporter that is parallel with each other.
- **Direct Crane Container Transfer**- Once the decision on berth choices as well as target transporter is decided, a direct crane transfer for containers takes place between the two parallel transporters. Once again there will not be involvement of the storage in this research as an instant container transfer is assumed.
- **Dispatch to subsequent destintation**- Once the containers are transferred to the transporters from the rail-mounted gantry crane then, the transporter is allowed to depart to its next destination which might either be the hinterland or the deep sea terminal.

3.3.6. Berths

Berths are another main component in this research. All berths are represented by GIS points and the number of destinations or origins also correlates to the number of berths that can be accessed by transporters. Berths/ destinations in general are represented in the form of arrays.

- Assume GIS points for deep sea berths They can be represented in an array *ArrayList < GISPoint > DeepSeaBerth = new ArrayList<GISPoint>();* where *DeepSeaBerth* houses all GIS points.
- Similarly for Barge berths, it would be *ArrayList < GISPoint > BargesBerth = new ArrayList<GISPoint>();* where *BargesBerth* houses all GIS points.

3.4. Transporters

Transporters represent any moving entity that carries a container from a designated origin to a destination. In this research, multiple transporters are involved with respective processes.

3.4.1. Deep Sea Ship

Deep sea container ship refers to ships that ply on international deep sea journeys transporting call-sizes of 3000 TEU[45] or greater. They are generally referred to as deep sea vessels owing to the deep draught they have. More specifically in this research, all deep-sea vessels considered will belong to the ultra-large container vessel class(ULCV). Some characteristics of this include a capacity of 14501 TEU or greater[17] and a length of 366m or more. Deep-sea ships also have a draught of 12m or greater.

Assumptions in This research about Deep Sea Ships

It can also be assumed that all deep-sea vessels in this research will have a minimum 3000 TEU call size[45]. Another major assumption in this research will be that each of these ULCVs will be served by 6 Quay cranes[59] at any given time. There will also be a mooring time of 1 hour to 1.5 hours [38] considered in the model.

Processes Modelled for Deep Sea Ships

To recall, containers in this process are modelled as orders and therefore a call size of say 3000 TEU would be considered as 1 order. In each deep sea vessel block, there also exists a **"client"** parameter that stores the information of the destination. Every journey to the client's destination would signify the completion of one order which in this example is 3000 TEU

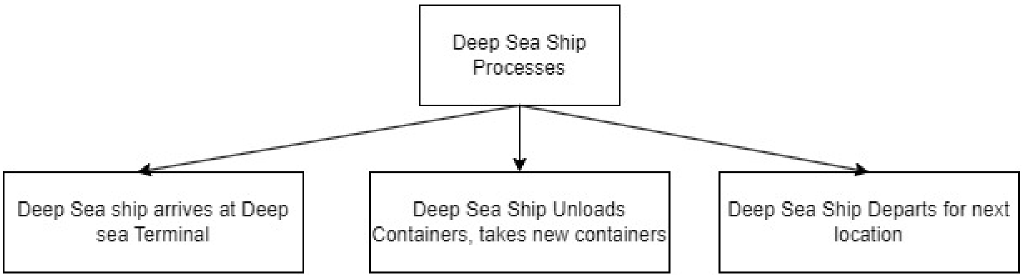


Figure 3.10: Deep Sea Ship Processes

- **Deep Sea Ship arrives at deep sea terminal**- The order would begin with the dispatch of the deep sea vessel from an international port. The ship then refers the client to understand the destination which will most certainly be another deep sea terminal. This is achieved by matching the "recipient" 3.2.2 parameter of container orders to the "client" parameter of the transporter. This way both containers and transporters are in agreement with each other with regard to the final destination stored in "recipient" .
- A snippet of the aforementioned point can be seen as
  If Containers and transporters are considered as a population of agents:
  then,
  ((Transporter)unit).client = agent.recipeint
  where every unit of the transporter retrieves its destination information from the "client" and confirms this with container order's final destination.

- **Deep Sea Ship Loads/Unloads**- The ship discharges and takes on board new containers before departing for its home location. This signifies the end of the order(fulfilment of a single 3000 TEU order).

3.4.2. Feeder

A feeder vessel refers to a container ship that connects inland spoke ports to major hub ports. These are generally the kind of ships that fall in between the category of barges and deep-sea vessels. A feeder vessel essentially would have a total capacity of anywhere between 1000-2000 TEU. Therefore a logical assumption for a feeder call size would be around 1000 TEU[40]. Feeders are generally 150m long and are serviced by 2 Quay Cranes/Barge cranes at their berths[8].

Processes Modelled in Feeder Ships

The feeder would follow a client and recipient process very similar to that of the deep sea vessel 3.4.1. The exception here is that the type of transporter, capacity and loading/unloading requirements vary.

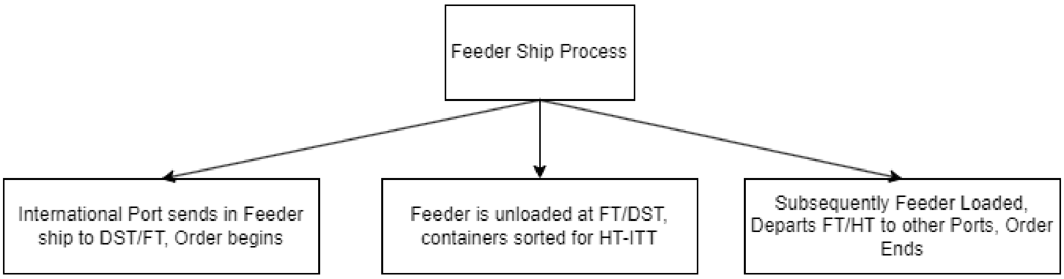


Figure 3.11: Feeder Processes Modelled

- International Ports- send in their feeder ships to deep sea terminals or floating terminals depending on the context. The journey signifies the start of the container delivery process or the order.
- Subsequently, a feeder ship is unloaded at the Deep sea terminal or floating terminal where they are sorted either for hinterland transport or inter-terminal transport. Depending on the port of application, a hinterland-inter terminal container split will be assumed.
- The feeder is then loaded and departs to its origin port. This signifies the end of the container delivery order between the international port and DST/FT.

3.4.3. Barges

Barges are one of the most commonly used transporters in inland waterways owing to their low cost of operation and mass container transport compared to trucks especially when transferring containers to the hinterland. In the model this is represented as a moving agent. The call size of barges are subjective and are subject to change [83]. They roughly range from 50-500 TEU [68].

Processes Modelled

The processes modelled with barges are summarised in the figure below.

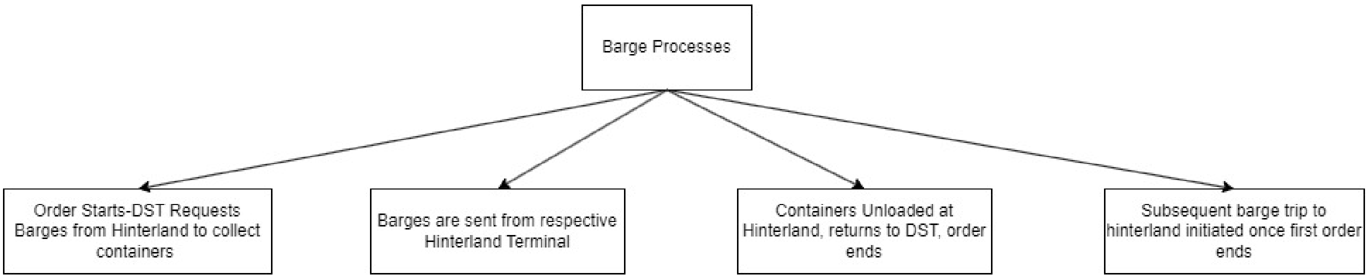


Figure 3.12: Barge Processes Modelled

- **Barge Request**- The deep sea terminals request barges from the Hinterland to collect their containers. This is the start of the Order.

- **Barges sent**- Barges are then sent from respective hinterland terminals
- **Barges at Deep Sea Terminal**- The barges reach the deep sea terminal, unload containers. The order ends
- **Barges Return**- Once the order ends,current barges return while triggering a new order.

3.4.4. Super Barge

As mentioned in the previous chapter, super barge is a high-density barge concept that lies between a barge and feeder in terms of capacity. The projected call size here is between 400 TEU and 700 TEU.

Processes Modelled

In essence the list of processes for a Super Barge resemble that of a regular barge. The only difference is in terms of destination of the Super Barge that can vary across the process.

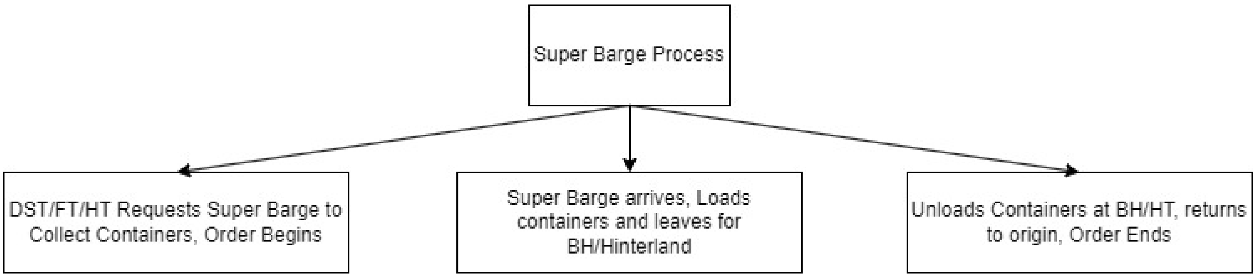


Figure 3.13: Processes Modelled in Super Barge

3.4.5. Amphibious AGV

The Amphibious AGV, despite being a very new entity has extremely similar processes. An additional notable step here is the entry/exit of the Amphibious AGVs through ramps at different kinds of terminals. Another variation occurs when amphibious AGVs interact with floating terminals with regards to crane transfer, that will discussed in future sections. The AAGV carries 2 TEU.The process is presented below.

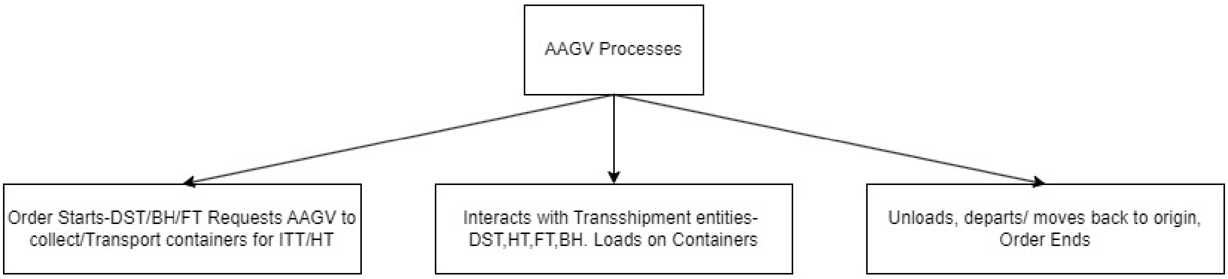


Figure 3.14: Processes Modelled in Amphibious AGV

3.4.6. Cranes

In this research, two kinds of cranes are prevalent. The first one is the Barge/Quay Cranes used at deep-sea and Hinterland Terminals. The other type of crane is a dual-sided rail-mounted gantry crane seen in floating terminals(Refer 3.6 and 3.5).

Quay Cranes

A regular Quay/Barge Crane has three direct processes. The crane initiates upon arrival of a transporter. Subsequently executes the laoding/unloading action and continues this loop until all containers are loaded/unloaded.

Transfer Process= Unloading Ship+ Loading to Truck

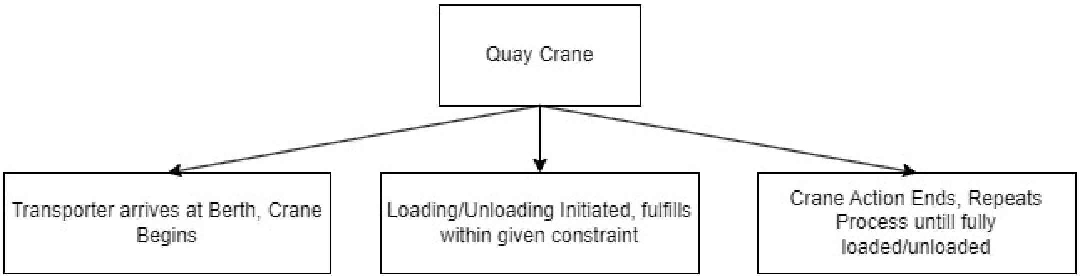


Figure 3.15: Processes Modelled in Quay Crane

Rail Mounted Gantry Crane- Floating Terminal

While most actions resemble the actions of a quay/barge crane, the main difference here lies in the cross-quay transfer of containers. As seen in the floating terminal designs 3.5, the RMG crane transfers containers across the quay and this involves a certain amount of time. This extra process differentiates RMG and quay cranes.

Transfer Process= Unloading Transporter+ Transfer Container along crane Span+ Unload to Stack/other Transporter

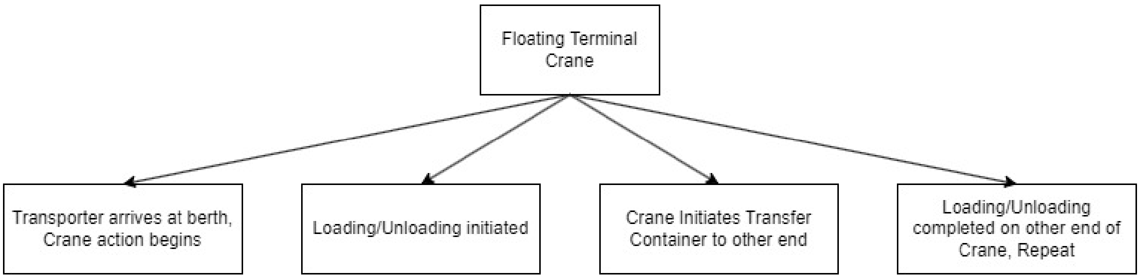


Figure 3.16: Processes Modelled in Floating Terminal Crane

3.5. Interaction of Entities in the Model

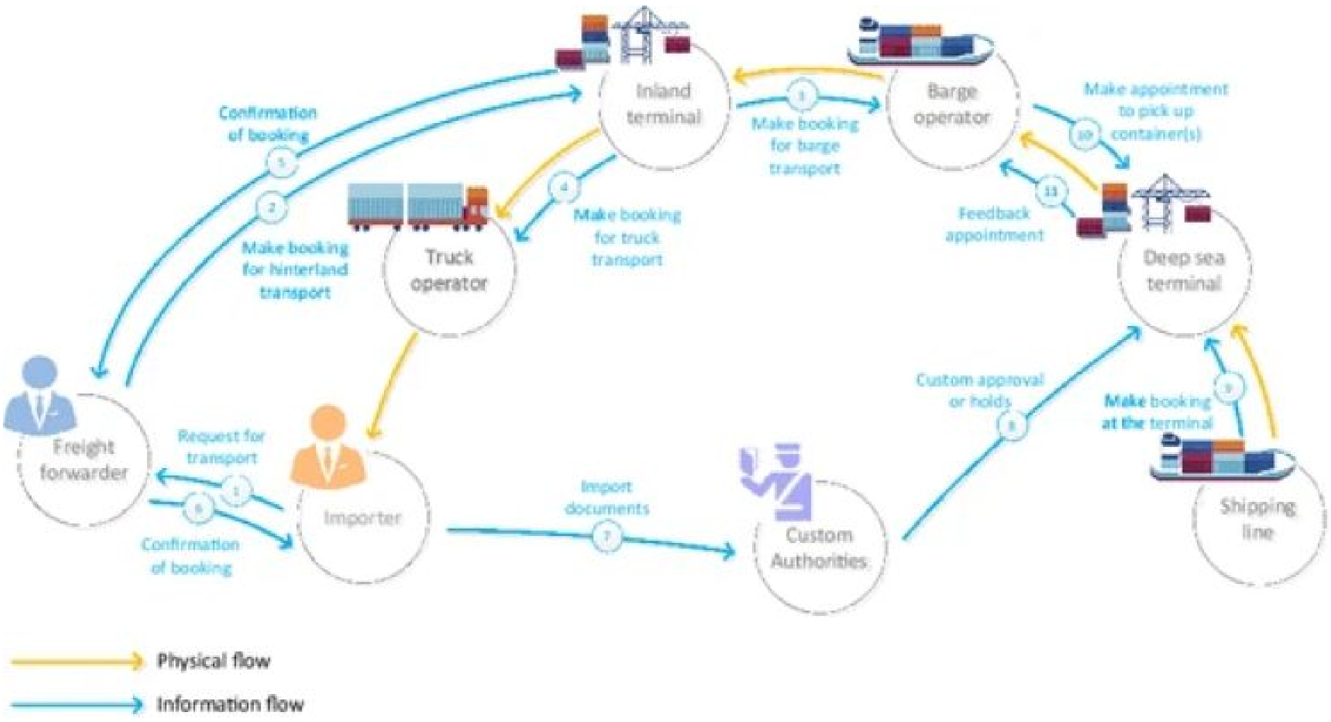


Figure 3.17: Interaction of Transporters,Ports and Terminals [96]

3.5.1. Physical Flow of Chain

The physical flow of containers is closely linked with how the information passes through all these entities.

- The shipping line assigns a ship from an international port to ship containers to the home port. The entire set of containers here will be considered as an order 3.4.1 which the deep sea ship delivers to the deep sea terminal of the home port.
- Once the ship is loaded at the international port, it is dispatched to the home port where goods are sorted for inter-terminal transport and hinterland transport. Each port will have a separate distribution of hinterland and ITT containers.
- Since this work is concerned only with the hinterland, the concerned hinterland containers unloaded from the deep sea vessel at the deep sea terminal are transferred to the barge berths within the same terminal. This is done through trucks/AGVs (2 TEU) which transport containers to the concerned berths by land.
- Now that the respective containers have been transported to the barge berths, the barges are loaded in call sizes of 50 TEU each.
- The loaded barges are now transported in batches of 50 TEU each to hinterland terminals. Here 50 TEU is taken as the maximum call size owing to the fact that both literature and industry corroborate with this figure[28] [33].
- Once the containers reach the respective inland terminals, it is unloaded and the fleet returns to the deep sea terminals to continue the transport cycle.

3.5.2. Information Flow

The information flow of this chain can be presented as follows

- Due to the presence of multiple actors in the process. Hinterland transport is often booked at the Hinterland terminal itself.
- Importer asks the freight forwarder to book the Hinterland Transport

- The Hinterland terminal books relevant barges and trucks to bring the hinterland transport to the respective inland terminals
- This also includes arranging the intermediary transfers such as container transfers from deep sea berths to barge berths within a deep sea terminal.
- Once the Barge transport is booked, a confirmation is sent from the Hinterland terminal to the freight forwarder
- It must be understood that a freight forwarder can also directly make an individual booking but in the case of Port of Rotterdam, it is common for Hinterland to book the transport.
- The freight forwarder notifies the importer regarding the same
- Thereafter importer sends documents notifying them of the recipient of the container and the confirmation of hinterland transportation.
- The shipping line communicates with the terminal regarding the commercial release of the Container. The Deep Sea terminal provides feedback on the appointment request
- When the container is released, it is transferred to the barge within deep-sea terminal and the trucks are arranged at the hinterland to collect the concerned containers.

3.5.3. Routing

The Routing in this process is done in the following ways:

- These routes follow the shortest path algorithm of Dijkstra, which find the shortest distances between nodes in a weighted graph [10].
- Essentially these routes are established between two set of GIS points representing the origin and destination. As mentioned earlier, both origin and destination are represented by agents.
- The routes in software form would be between the following list of arrays.

  1. *ArrayList <GISPoint > Origin Terminal = new ArrayList<GISPoint>();*
  2. *ArrayList <GISPoint > Destination Terminal = new ArrayList<GISPoint>();*

3.5.4. Parameters

The key parameters in the model are represented in the following table:

Table 3.7: Parameters, Variables and Objectives

Parameters	**Remarks**
Client	Stored in Transporter agent, directs transporter to Destination
Recipient	Stored in container agent, directs containers to destination, seize client
Barge Cranes	Number of Barge Cranes at DST/HT
Quay Cranes	Number of Quay Cranes at any DST
Mooring Min	Minimum Ship Mooring Time
Mooring Max	Maximum Ship Mooring Time
TEU Destination	20 ft containers scheduled for the next destination
ContainerPerTransporter	Call Size/Capacity of transporter
Port Efficiency	Grade of operational efficiency
Floating Terminal Transfer Time	Time to transfer containers overhead across RMG Crane
RMG Crane Min Speed	Minimum transfer time of RMG
RMG Crane Max Speed	Maximum transfer time of RMG
Max Moves/Hour	Maximum moves of BC/QC per hour
Min Moves/Hour	Minimum moves of BC/QC per hour
Variable	
numTransporter	Variable to be Optimized
Requirement	
Fleet Utilization Rate	85% Utilization rate for all fleets
Objective	
	Maximum Fleet Utilization

3.6. Agent-Based Modelling & Multi-Agent Network

Agent-based modelling refers to computer simulations that study the interaction between things, places and time. This is an important tool in the context of this simulation since agents can act independently of another agent or a process. They can also be defined in a wide range of functionality such as static or moving entities. This is handy for this research which is governed by multiple kinds of terminals, transporters and containers. Agent-based Modelling also provides the flexibility to conduct under extreme conditions, which is not always possible in optimization or discrete event simulations where infeasible solutions can not be explored further.

3.6.1. Agents in System

The agents in the system are the three respective entities in the system, namely *Ports&Terminals*, *Containers* and *Transporters*.

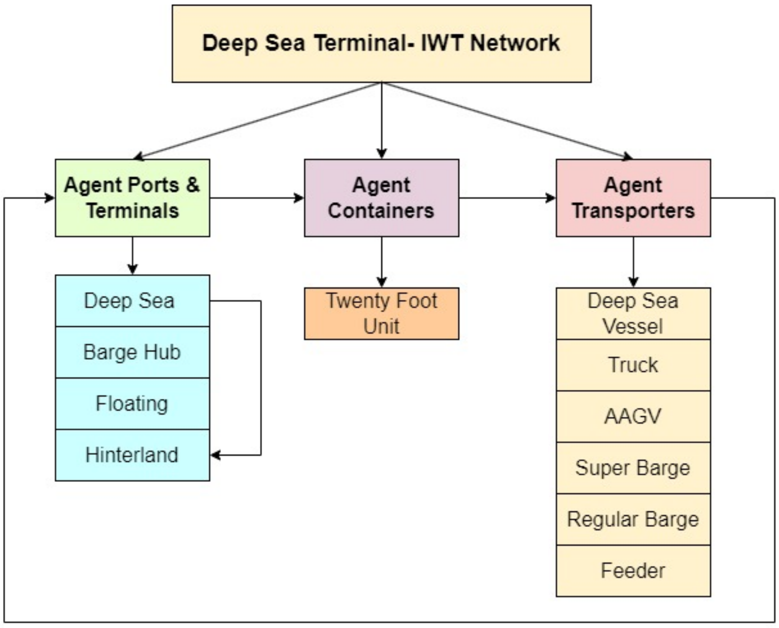


Figure 3.18: Reference Multi-Agent System

The three unique agents are sequentially linked with each other and also have some processes amongst themselves (example- on the left part of the figure 3.18, a process between Deep Sea Terminal and Hinterland is indicated. To reiterate, in agent based modelling, agents have their own autonomy and can also interact with other agents depicting their versatility.

3.6.2. Split Strategy Implementation

The simulation for all the scenarios will involve a split model simulation and analysis. This means that essentially if a process is made up of three steps, each step would have a simulation model of its own. This will then be cumulatively analysed in post-processing. An example of this idea is mentioned in figure 3.19 for the benchmark scenario.

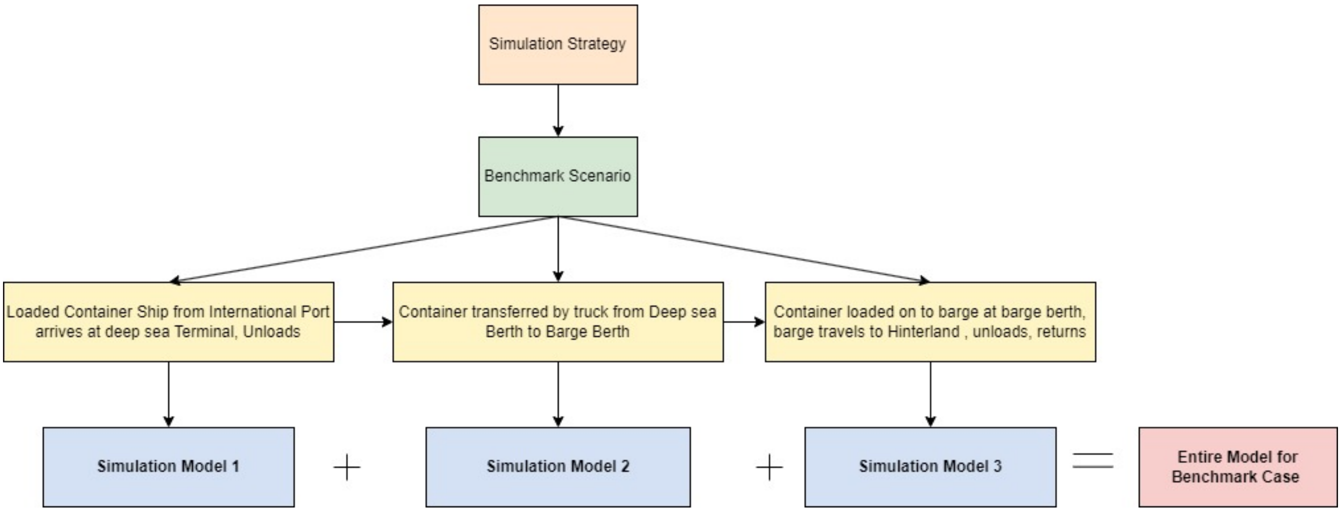


Figure 3.19: Split Simulation Model Strategy

As depicted, the benchmark case involves three main steps. First is the arrival of a deep sea ship from an international port to the deep sea terminal at home port where containers are unloaded. This will have a dedicated simulation model of its own that focuses solely on the deep-sea ship transporting containers. Subsequently, the containers unloaded from the ship will be transferred to a barge berth by a truck. This process too will involve a simulation model of its own. Finally, the barge transporting containers to the hinterland is also a simulation process of its own.

Cumulatively the three simulation models put together form the entire model for this benchmark case. Some reasons for this split model strategy are

- A split simulation allows for flexibility in flow rates of transporters and containers in the model
- Easier to Optimize individual fleet sizes for each simulation. Example- The first simulation step involves a deep sea ship, the second simulation step involves container transfer through trucks and the third simulation model involves a barge. These fleet sizes can be more accurately accomplished with separate simulation models.
- Certain software platforms limit the number of independent agents to 10. This makes the split model strategy more applicable across a variety of software platforms.
- The KPIs of the model such as congestion, throughput and time can be more accurately computed since each model has a different definition for a container order. For example- In deep-sea ship, one order is 4000 TEUs, while an order for a truck is 2 TEUs. Meanwhile, the order for a barge is 50 TEU.
- This helps replicate a behaviour similar to what actually takes place in a hinterland transport process

3.6.3. Process Logic

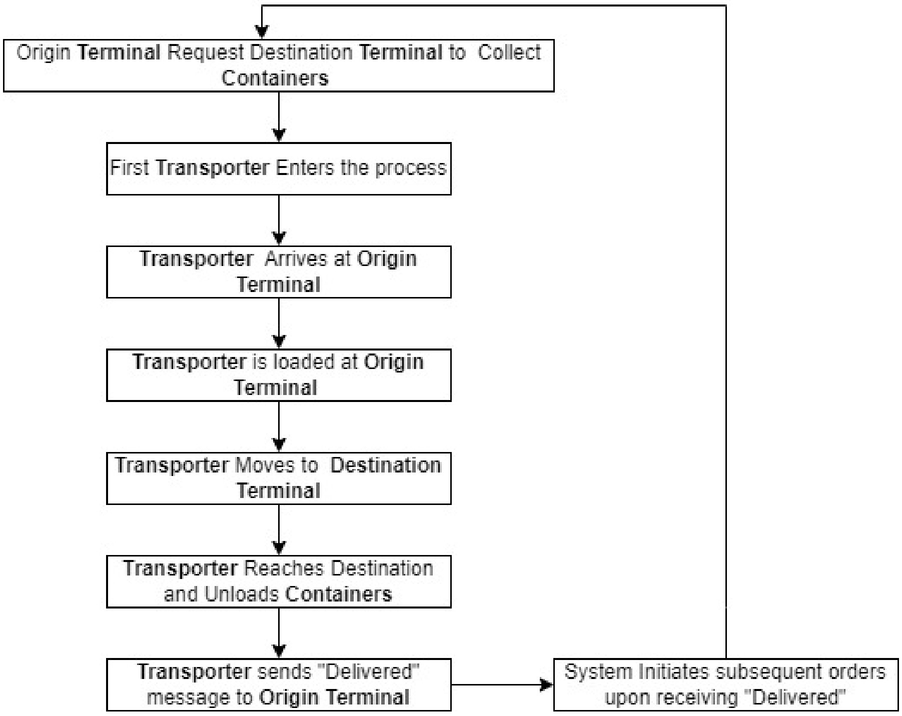


Figure 3.20: Process Flow and Logic

1. Extending the concepts of the previous section, every individual simulation model will follow a very similar process and it has been depicted in figure 3.20.
2. Every container mover has been generalised as a transporter.
3. The simulation is set in an environment where a transporter starts from a set origin and is directed to a preset destination along a pre-defined route and finally culminates with a return to the origin.
4. The process would start with a request from the origin terminal asking the destination terminal to collect its containers from the origin.
5. The process then continues and once a cycle of container delivery is completed, the destination terminal sends a ”Delivered” message to the origin.
6. Once this message is delivered, the origin terminal initiates the second round of orders/container delivery.
7. This idea is also applicable to the case where trucks deliver containers from one berth to another berth. The changes here would only be that the terminals are now called berths while the functionality and operability of the system largely remain the same.

3.6.4. Overview of Final Simulation Elements and Model

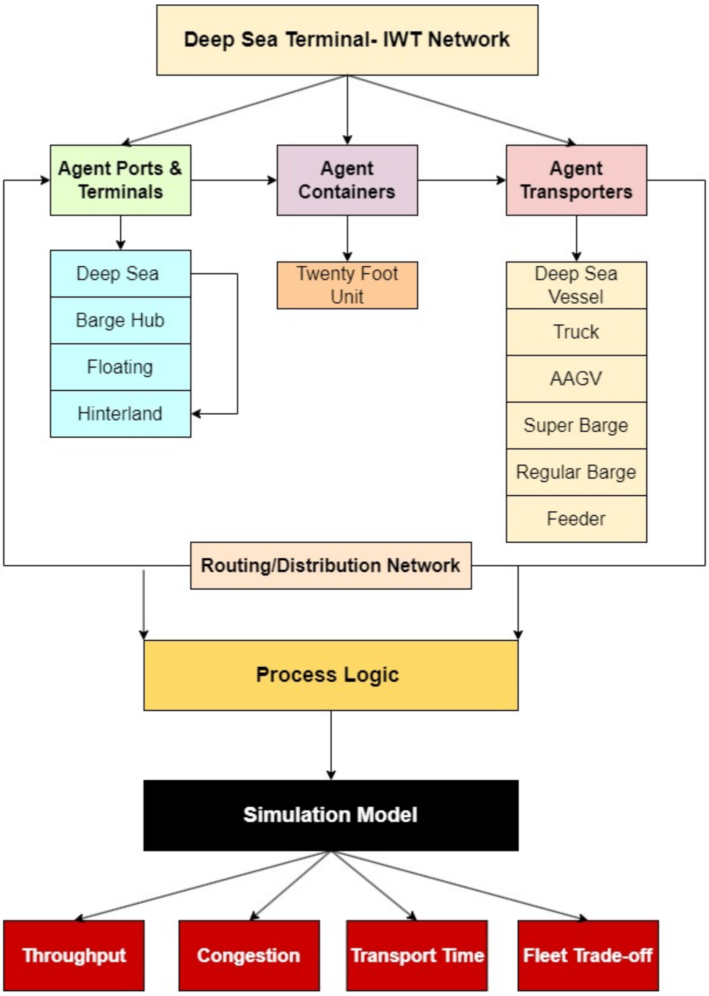


Figure 3.21: Simulation Model of Agents

The above model depicts a single-glance view of the major elements involved cumulatively in all cases. In essence, this is a complete expanded view of an already compact figure 3.18. The final simulation model will have an output element which is presented with the blocks Simulation,Process Logic and the Key Performance Indicators that are mentioned. Going by sequence, The first agents that are initiated in the system are the ports and terminal which house containers(second agent). Containers cam be accessed by both terminals that are storing them and the transporters which carry them between these terminals. A routing network with various point to point and hub and spoke strategies connect origins and destinations. The output of the model is the number of transporters that have carried containers during a specified period. With this information (plus the preset information on berths) will give us an idea of congestion, transport time and total containers transferred.The model is also supported by preset routing networks and vital parameters for each simulation model. Linking all these entities is the process logic which is defined by table 3.20

3.6.5. Software Platform

Software-based Simulation Model

The software platform of choice here is AnyLogic which is a specialised software for simulation in all major simulation techniques, Discrete Element Simulation, Agent Based Modelling and System Dynamics. The software itself is written in Java and is linked to optimization engines such as OptQuest and its own genetic algorithm engine[2].

Figure 3.22: AnyLogic[2]

The simulation model is divided into 2 parts. The first one is the initiation and sortation of container orders. This is defined by the state chart given in figure 3.24. Containers are first requested from the deep sea terminal, after which barges are initiated from Hinterland. The loading process is what "ContainerProcessing" stands for The second and major contributing part is the process itself (3.23). The process defined in 3.20 can be replicated by the aforementioned two-part process. It must also be reiterated again that the software simulation will follow the same split simulation strategy indicated in the figure 3.19.

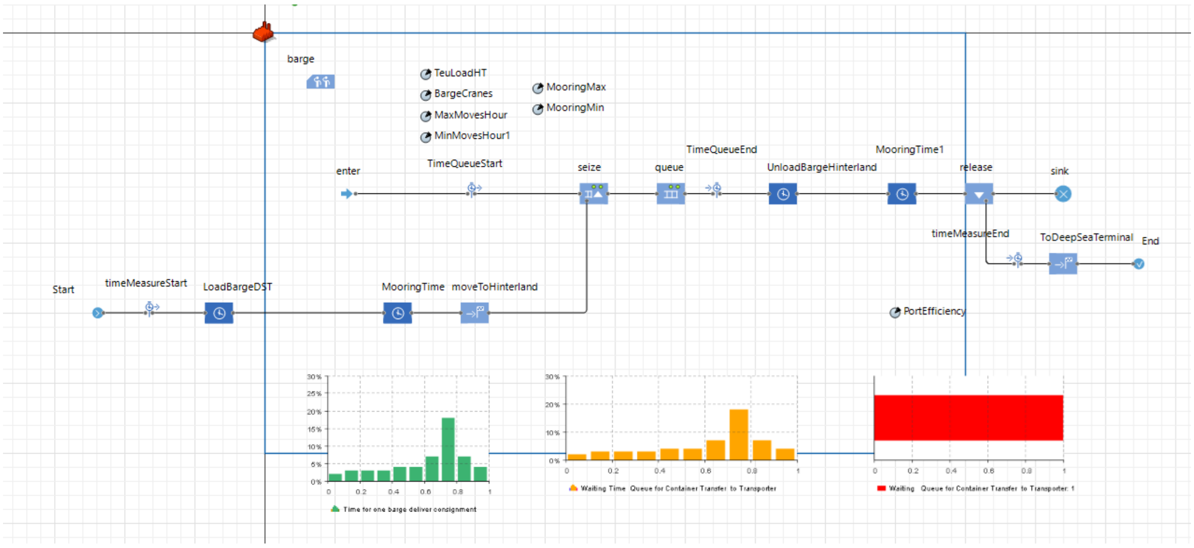
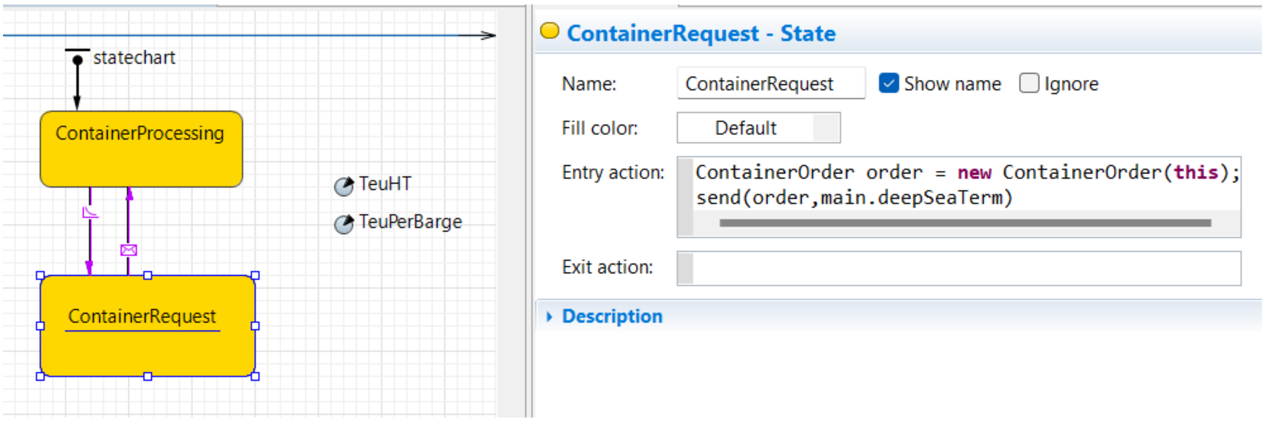


Figure 3.23: Process Logic replicated in Software



Name: ContainerRequest ☑ Show name ☐ Ignore

Fill color: Default

Entry action:

```
ContainerOrder order = new ContainerOrder(this);
send(order,main.deepSeaTerm)
```

Exit action:

Figure 3.24: Statechart to manage container orders and requests

3.7. Post Processing- By KPIs

Post-processing of the data and simulations in this research varies as per the key performance indicator. The four main key performance indicators here are congestion, Transport Time, throughput and fleet sizing.

3.7.1. Congestion

1. **Step 1-**The ”sink” of the process (ref 3.23) is studied and recorded. Every process in this research is studied for 3 months(92 days) following which the sink is recorded. The sink gives us data on the number of trucks, AAGVs, and Ships that have successfully completed their journey during the 92 day period. Period is marked in green while sink is marked in maroon.

   Transporters Per Day = Sink/Period Recorded
2. Step 2- This sink is now divided by the Period recorded(92 days)to give an idea of the footfall of transporters per day. Each simulation is done only for one route under the split strategy. Multiple Terminals would mean multiple simulations. Once information on berth is also input, we get the concerning berth-based congestion both for the point of origin terminal as well as the destination terminals.
3. For one berth,
   Transporters Per Day = Sink/Period Recorded
   This is the congestion of ships or barges or trucks for a single berth. This data is crucial to enlist impact of congestion.
   For multiple Berth,
   Transporters/Day for all Berths= **Transporters Per Day* Berths**
   This is congestion for the transporter moving from a set of berths at the origin to one destination, We now figure in congestion at all destinations cumulatively,
   Total Transporter Congestion = Transporters congestion per Day*Berths(Destination 1) + Transporters congestion per Day*Berths(Destination 2) +......
   This is the number of transporters involved in one process at that specific destination. Since this research is concerned only with the congestion of individual transporters(ships/barges), transporter congestion will not be added cumulatively.

3.7.2. Transport Time

1. The sink which gives us the number of transporters is recorded. Following it is divided by the period(92 Days). This gives us the footfall of transporters per day for that specific route and specific berth.
   Transporters Per Day = Sink/Period Recorded
   (for one route and berth)
2. In order to know the total number of containers transported, it is necessary to figure in the number of berths used in the entire process. Following this, the container capacity of each ship is multiplied. This gives us Throughput Per Day.
   Containers Per Day(throughput) = Transporters Per Day * Container Capacity*Berths *This research assumes a parallel processing which means multiple ships/other transporters are being loaded at the same time at different berths.*
3. The subsequent throughputs of each destination terminal is also added to give us a cumulative number. Eg- in the Benchmark case, barges have to deliver containers to four different terminals in Rotterdam. Therefore throughput of each specific terminal is calculated.
   Throughput/Day for 1 process= Containers/Day(destination 1) + Containers/Day(Destination2) +....Containers/Day(Destination n).

   This represents the overall system’s capability to transport containers per day.
4. Therefore the time in this process is defined as **Time in process(Hours) = (24 Hours* Throughput Required to be Transported)/(Throughput system capability)**.
5. As we know from earlier sections this used a split model strategy where multiple sub-models make up one big model. Therefore:
   Total Time to transport X containers (Hours) = Time(sub Model 1) + Time(sub Model 2) +...

3.7.3. Throughput

The cumulative throughput per day can be calculated by extending steps of the previous KPI on transport time

- It is given as follows:
  Total Containers/ Day = (24 Hours*Throughput to be Transported)/(Total Time to transport X containers)

3.7.4. Optimization & Fleet Sizing

The optimization experiment is needed for deriving optimum fleet sizes for each of the transporters used in the whole research. The optimization parameters, constraints and variables are given in table 3.8.

Optimization

Table 3.8: Optimization Parameter,Variables and Constraints

Objective	Maximize Utilization,U
Variables	
Total Transporters	N -[1,∞]
Transporters Used	T -[1,∞]
Utilization	T/N
Parameter	
Container Agent	Parameter as shown in table 3.7
Transporter Agent	Parameter as show in table 3.7
Terminals Agent	Parameters as shown in table 3.7
Constraints	
Utilization	T/N <0.85
Total Transporters	N>0
Transporters Used	T>0
Output	
Transporters Used	Optimum T

Fleet sizing is evaluated by an optimization algorithm used by the Anylogic Software platform[31].

1. The objective is set to maximize the utilization of transporters. The objective is given by-
   root.originTerminal.transporter.utilization()
2. The software uses a genetic algorithm and runs 500 iterations
3. The data and parameters used here is taken as it is from the simulation data used in each case. Therefore all parameters, and conditions defined for simulation hold true for optimization as well. Refer table 3.7
4. An experiment UI is created on AnyLogic.
5. The objective is subject to the constraint/requirements. The constraint here is that the utilization should not exceed 85 per cent.
6. The simulation is set to a stop condition, of 3 months(92 days) which is same as the simulation.
7. The optimization runs with the fleet sizing as output.

4

Current Operational Analysis

The current system of hinterland transport is a general mode of operation that can be seen in multiple inland waterway environments ranging from Rhine River [67] to the Hong Kong- China hinterland with the Pearl River delta [28]. This research will take Port of Rotterdam as an example because Rotterdam is the largest port in Europe by container throughput. During the literature phase of this work, port operations about Rotterdam, Antwerp and Hong Kong were looked at from perspectives of accessibility, growth potential and Hinterland connectivity. Rotterdam's Maasvlakte is set to expand by 200 per cent by 2040. The container capacity is projected to increase from the current 15 million TEU to 30 million TEU[81].

This opened up a lot of opportunities to investigate issues related to the Maasvlakte itself but a hidden aspect here is the hinterland terminals in Rotterdam. This is where the biggest opportunity lies since more than 60 per cent of import containers are directed through inland waterways and hinterland terminals to remote ports like Moerdijk and Dordrecht. Interestingly this route also links the waterways of Duisburg and Antwerp as well, the latter of which is the largest inland waterway port in the world.

4.1. Port of Rotterdam: A Case Study

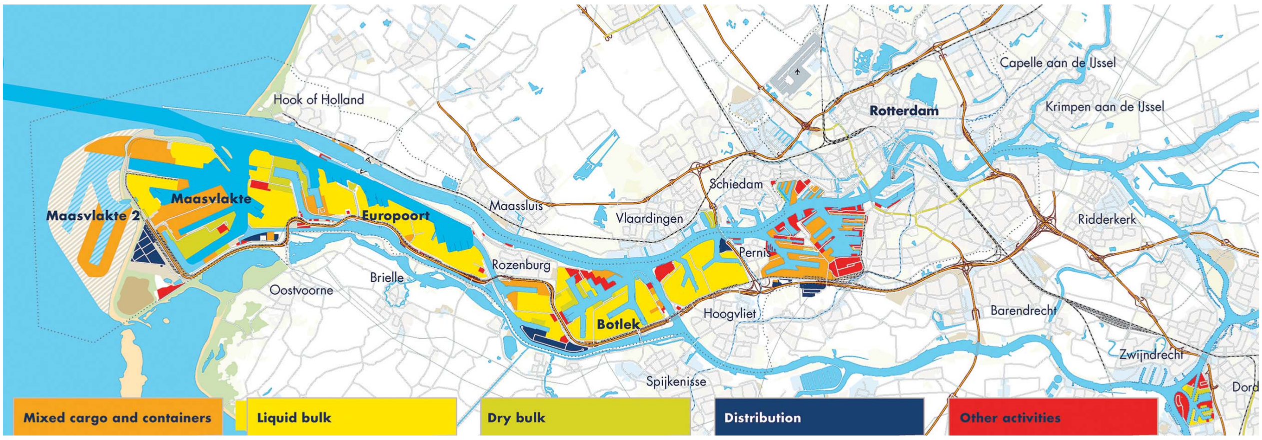


Figure 4.1: Port of Rotterdam[29]

Diving deep into the layout, the Port of Rotterdam has more than 30 container terminals including empty depots. These are distributed in three different areas

- **Deep Sea Terminals**- The major deep-sea terminals that handle ultra-large container vessels are located at Maasvlate 1 and 2. These terminals being at the tip of the Netherlands act as a gateway to Europe for feeder and container vessels.

  - **APM-T Maasvlakte II**- Annual container handling capacity of 2.7 million TEU[76]
  - **Hutchinson Euromax Terminals**- Annual Container Handling Capacity of 5 million TEU [21]
  - **ECT Delta Terminal**- Annual Container Handling Capacity of 6-7 million TEU when redeveloped [22]
  - **Rotterdam World Gateway Terminals** -Annual container handling capacity of 2.35 million TEU[76].
- **Hinterland Terminals 1**- The first set of hinterland terminals arrive at Botlek where Broekman Distri Port and Waalhaven Botlek terminal respectively are located. These are located approximately 22km away from the Maasvlakte. They are essentially container terminals capable of handling barges. They have a capacity of 120,000 and 200,000 TEU respectively [29]
- **Hinterland Terminals 2**- The final set of Hinterland terminals are located at Waalhaven/Eemhaven. Here Port of Rotterdam has four major terminals, namely Rotterdam Shortsea terminals, CTT Rotterdam, Barge Center Waalhaven and Matrans terminals. Cumulatively these four terminals can handle 2.2 million TEU annually making this an important area of Hinterland transport and interaction. These set of terminals are located 40km from the Maasvlate and are at the extreme end of Port of Rotterdam's Jurisdiction.

4.1.1. Account of Hinterland Traffic and Routes

Figure 4.2: Chain of Hinterland Transport[33]

The chain of container flow from Deep Sea Terminals at Maasvlakte to Hinterland is shown in the above image.

Deep Sea Routes and Operators
Several of these terminals have direct agreements with shipping lines owing to either parent company ownership or fixed contracts. It is prudent to point out here that only deep sea shipping lines/feeder lines have any contractual relationship with these deep-sea terminals. This is not applicable to barges, therefore barges don't necessarily have any financial obligations as well(such as berth fee and service fee) [83]. However, this also means that deep-sea ships or contracted shipping lines receive priority over barge lines at the Port of Rotterdam. Some of the major lines and routes include the following:

- **Maersk+MSC** Alliance: Rotterdam to Hmaburg,Bremen,Antwerp. This is also known as the 2M alliance[100]
- **The Alliance**: Rotterdam to Busan, Rotterdam to Yantian, Rotterdam to Singapore. This alliance of shipping lines exist between Yang Ming, ONE and Hapag Lloyd[100]
- **Ocean Alliance**: Rotterdam to Hong Kong, Rotterdam to Kaohsiung, Rotterdam to Shenzhen. Shipping alliance between OOCL,COSCO, CMA CGM and Evergreen[100].

Among these containers, several of them are directed to the hinterland of the Netherlands, Belgium and Germany. However, it must be noted that not all hinterland-bound containers are handled by barge As per 2022 statistics [76], 55% of hinterland-bound containers are handled by trucks, 10% handled by trains and the remaining. The port of Rotterdam envisages a rise in barge transport from 35% to 41% by 2030. This is done to reduce the reliance on trucks which are proven to have a higher rate of pollution per container transported. The summary of these statistics can be seen in figure 4.3.

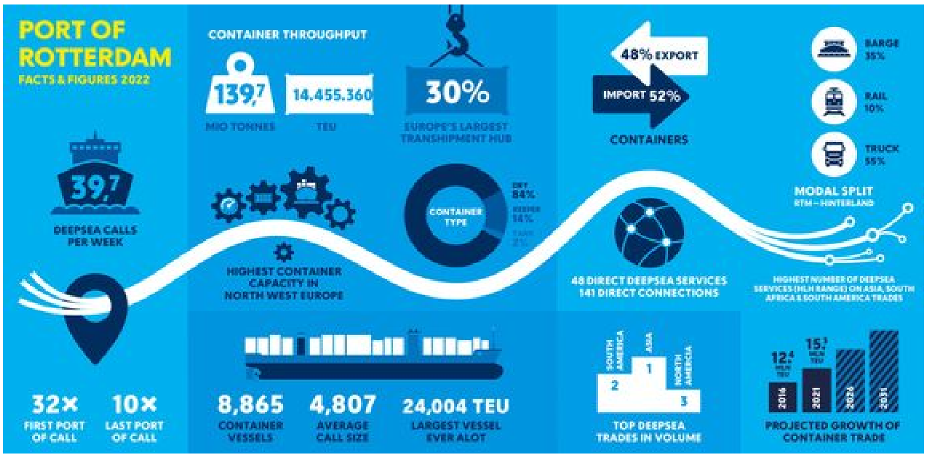


Figure 4.3: 2022 Port of Rotterdam Statistics[76]

The profile of ships that dock in the port of Rotterdam ranges from Panamax(>5000TEU) Ships to Ultra Large Container Vessel Ships(14501 TEU+).

Feeder Routes

The port of Rotterdam also has an extensive feeder network which is in place as well. This involves multiple operators and feeders on average having capacities ranging from 800-1500 TEU. Feeders that arrive in Rotterdam generally have Deep sea terminals as their first call before moving to the Hinterland. Some of the prominent feeder networks at the Deep Sea Terminals include the following:

- **Unifeeder**: Rotterdam to Antwerp, Rotterdam to Bremerhaven, and Rotterdam to Felixstowe[89]
- **Seago Line**: Rotterdam to Copenhagen, Rotterdam to Dublin, and Rotterdam to Oslo[52]
- **MacAndrews**: Rotterdam to Barcelona, Rotterdam to Genoa, and Rotterdam to Valencia[18].
- **X-Press Feeders**: Rotterdam to Dubai, Rotterdam to Jeddah, and Rotterdam to Karachi[25]
- **Niledutch**: Rotterdam to Alexandria, Rotterdam to Casablanca, and Rotterdam to Port Tangier Med[62]

Barge Routes

The barges that transport these containers themselves belong to different networks and the routes most commonly operated in the port of Rotterdam are as follows:

- **Rhine River**- The Rhine River represents one of the major chunks of hinterland traffic and accounts for 34% of total traffic.Region served is France, Germany and Switzerland[43]..
- **Rotterdam- Antwerp**- The Rotterdam - Antwerp traffic is also another major point of contention as this set of inland waterways supports numerous local businesses and families that own barges. This accounts for 23% of the barge traffic.
- **Domestic Traffic**- Domestic traffic in the Netherlands is connections from deep-sea terminals in Maasvlakte to Dordrecht, Nijmegen, Moerdijk and Hengelo. These are centres of industrial production and electronics. The domestic trade accounts for 36% of hinterland trade.
- **Belgium and Northern France**- The last 7 per cent of hinterland traffic is predominantly seen in the inland waterways to Zeebrugge, Gent and Port of Le Havre(France).

Hinterland Barge types

The literature of Rob Konings[43] and Martin Van Der Horst[33] has very well discussed the call size situation at Port of Rotterdam which varies sporadically both with terminal as well as barge size. Based on the individual capacity and call size data, a correlation has been assumed and they have been presented in table 4.1 [68].

Table 4.1: Barge Types and Statistics[67]

Barge Type	Length	Capacity	Quay Cranes/Barge	Call Size/Terminal (TEU)
Kempenaar Class	63m	32 TEU	1	6
Johann Welker Class	85m	60 TEU	1	24
STB 105	105m	300TEU	1-2	51
CEMT Class Va	110m	200 TEU	1	33.3
CEMT Class Vb	135m	470 TEU/500 TEU	1-2	51

4.1.2. Data and Information of Integrated Deep Sea- Hinterland Network in Port of Rotterdam

Deep Sea Terminal

In order to understand the complexities of hinterland transport and replicate the process at Rotterdam, a two-week data of deep-sea terminals was studied along with their distribution of Transporters.The deep sea terminal of choice was APM Terminals at Maasvlakte 2. A reason for this choice is that among all the other deep-sea terminals at the Maasvlakte, APM-T is the one that is projected to expand the most by 2035 from the current 2.7 million TEU annual throughput, growing to an estimated 4.7 million TEU in 2026 and finally saturating at 7.5 million TEU by 2035[5]. The period observed was from the 20th of June 2023-4th July 2023. The data obtained was as follows-

Table 4.2: Barge Types and Statistics[67]

S.No	Ship Category	Ship Type	Period(Days)	Ships Recorded	%
1	Kempenaar Class	Barge	14	2	1.87
2	Johann Welker	Barge	14	5	4.67
3	STB 105	Barge	14	2	1.87
4	Large Rhine CEMT Va	Barge	14	36	33.65
5	Large Rhine CEMT Vb	Barge	14	29	27.1
6	Feeder Ship	Feeder	14	13	12.15
7	Panamax Ship	Deep Sea Ship	14	8	7.48
8	Ultra Large Container Vessel	Deep Sea Ship	14	6	5.61
9	Miscallaneous Ship	Mix	14	6	5.6
	Total			107	100

The data for this can be accessed in this **Data Sheet** The data reveals the following:

- **Main Barges**- It is clear from the table that the three most prominent categories of barges are the Large Rhine CEMT Va and Vb accounting for 33.6% and 27.1% respectively. The smaller Johann Welker class accounts for about 4.7% of barges that arrived during this 2-week period.
- **Interesting Barge Capacity: Call Size ratio**- Interestingly, the smaller set of barges such as the Kempenaar class only account for 2% of the total 14-day traffic.This insight is important as it proves that most of the large barges also carry lower call sizes despite their large capacity.
- **Data on Feeders**-When it comes to the footfall of feeders, it stays constant at approximately 1 feeder ship per day over the 2-week period. The most frequent route is the United kingdom route with Unifeeder operating from **Rotterdam to Felixstowe**.
- **Findings on Deep Sea Ships**-
- Similar comments also apply to the deep sea ships(1 per day), but it is prudent to notice that the number of Ultra Large Container Vessels(14501 TEU+) is nearly equal to the number of Panamax Vessels(3000-5000 TEU) during this same period. This also matches the port of Rotterdam data which states that 5000 TEU arrive daily per deep sea terminal[76]. This signifies that a mix of deep sea and feeder traffic are seen at APM-T Maasvlakte. The most common origins of Deep sea Ships are **Bremerhaven/Hamburg**.
- **Barge Findings**-Therefore, on a real operational day when barge arrivals are known, it can be logically assumed that about 20-22 barges make footfall at APM-T Maasvlakte.

Hinterland Terminals

This also uses the same reference **Data Sheet**

- **Hinteland Terminal Set 1 versus Set 2**- From the datasheet, it can be observed that for 2 weeks, 26 barges originated from the second hinterland terminal set versus only 18 from the first set of terminals. Similarly, on the return journey, 9 barges were directed to Waalhaven/Eemhaven terminals while only 4 were directed towards Botlek.Note- these journeys only concern the domestic barge trade.
- **Importance of Rotterdam Shortsea Terminals and 2nd set of Terminals**- It has to be noted that all barge journeys to Duisburg, Antwerp and deeper parts of the Netherlands generally make a stop at Rotterdam Shortsea Terminals located at Waalhaven/Eemhaven as this is one of the biggest shortsea and hinterland hubs in Europe with an individual handling capacity of 1.84 million TEU[79].
- **Importance of Other Terminals at Waalhaven**-The other hinterland connections in Waalhaven such as CTT Rotterdam, Barge Center Waalhaven and Matrans Rotterdam have barge connections to Northern Europe. Terminals such as and also serve as combi Terminals(Handling both bulk cargo and containers).
- **Final Focus Terminals**-Therefore in view of the visible demand of containers either towards or from Waalhaven/Eemhaven, this research will focus on the transport of containers from APM-T Maasvlakte to the second set of Hinterland Terminals. The research also recognizes the higher complexity associated with this longer stretch compared to Botlek.

4.1.3. Important terminal/transporter based data, parameters and demand

Deep Sea Terminal

APM-Terminals Maasvlakte 2 has the following specifications which will be used in the model as it is. The location of barge berths and deep sea berths have been marked in red and yellow ticks respectively in figure 4.4. The important and necessary specifications are explained in the table B.2.

Figure 4.4: Locations of APM-T and Berths[30]

All parameters for ships, barges and crane allocation are based on APM-T's published data[4]. Triangular distribution has been assumed for the loading and unloading process in deep-sea ships, trucks and barges[57].

Hinterland Terminals

The location of the Hinterland terminals is shown with red ticks in figure 4.5. Among these, the largest terminal is Rotterdam Shortsea Terminals which has an annual output of 2 million TEU. The terminals are:

- CTT Rotterdam- Terminal Marked in yellow tick with berths shown in yellow-green accents
- Rotterdam Shortsea Terminals- Terminal marked in blue, the three barge berths marked in purple.

- Barge Center Waalhaven- Terminal marked in green, berths in green
- Matrans Terminal- Terminal marked in red, berths in red.

Figure 4.5: Locations of Hinterland Terminals and Berths[30]

Demand,Speed and Container Distributions

The table 4.3 shows the intricate details of the current setup at the Port of Rotterdam. Details such as modal split are from the latest Port of Rotterdam 2022 statistics [76]. Each transporter has a designated speed profile and limits issued by port authorities and the local government. The speeds of the Amphibious AGV as such have been based on the current truck speeds and barge speeds issued by the Port of Rotterdam[77] and other ports of similar scale in Europe such as Hamburg[6] and Antwerp [82].

The major assumption made here is a split of the 5000 TEU demand coming in daily. Taking into account typical call sizes of Deep sea Vessels and Feeders, Deep Sea ships are assumed to bring in a call size of 4000 TEU and feeders- 1000 TEU. With regard to barges and their call sizes at Port of Rotterdam, literature works of Shobayo&Hassel [83] and Van Der Horst[33] present ranges from pessimistic values of 6 TEU in some instances to an optimistic value of 51 TEU that have been recorded for hinterland transport between the Maasvlakte and Waalhaven/Eemhaven. While our research considers the terminating hinterland terminals at Waalhave/Eemhaven, it is also logically assumed that all containers from there will be transferred to deeper hinterland Ports. Therefore the maximum call size of 50 TEU (51 in the literature) is considered per every barge that travels along the Maasvlakte-Waalhaven/Eemhaven Route. Correlating the aforementioned literature and Terminal Data[4], a footfall of around 20 barges is assumed to transport 1050 containers (Refer table 4.3, row 7) to the hinterland.

Table 4.3: Important Specifications of Vehicles/Containers in Port

Parameter	Entity	Value
Modal Split	1. Truck 2. Barge 3. Rail	55% 35% 10%
Truck Speed	1. Within Terminal 2. Turns 3.On Road	20Km/hr 10Km/hr 60Km/hr
AAGV Speed	1. Within Terminal 2. On Road 3.Average Speed	11Km/Hr 11Km/hr 13Km/hr
Container Split	1.Hinterland 2.Inter-Terminal	60% 40%
Demand	Feeder+Deep Sea Veesel	4807 TEU
Demand Split	1.Feeder Ship 2.Deep Sea Vessel 3.Total	1000 TEU 4000 TEU 5000 TEU
Daily Hinterland Demand	Daily Footfall- 5000 TEU Hinterland- 60% Barge-35%	1050 TEU

4.2. Simulation and Modelling of Current Operations

The current port operation can be described based on the infographic below. Right now, any deep sea ship or international feeder lines first dock at the Deep Sea Terminal to drop the imports at the deep sea berths. Here fleets of trucks/AGVs wait to receive containers from these deep-sea ships, they are subsequently transferred to barge berths within the Deep Sea Terminals. A fleet of barges originating from the Rotterdam/Moerdijk/ Non-NL hinterland arrives at the respective barge berths at request of deep-sea terminals. Here each barge is served by one QuayCrane/Barge Crane that loads the containers to the respective barges. These barges then transport the containers to the hinterland terminals. [96].

4.2.1. Ports and Terminal Agents

The actors involved here are based on the existing infrastructure that we have in ports today. They are as follows-

- **International Port**- The Ports of Hamburg and Felixstowe serve as the International Ports which send in respective deep-sea vessels.
- **Deep Sea Terminal**- APM-T Maasvlakte Rotterdam is the Deep sea Terminal where feeders, Deep Sea Vessels Dock
- **Hinterland Terminals**- This is the final point in the entire chain where containers need to be eventually delivered. In Port of Rotterdam's Waalhaven Hinterland, 4 terminals are present,namely-
    1. CTT Rotterdam
    2. Rotterdam Shortsea Terminals
    3. Matrans Terminals
    4. Barge Center Waalhaven

The hinterland terminals are modelled as a population of static agents.

4.2.2. Transporter Agents

- **Deep Sea Ship**- Origin from Port of Hamburg
- **Feeder**- Origin from Port of Felixtsowe.
- **Trucks at Deep Sea Terminal**- Trucks or AGVs transport containers scheduled for hinterland from the deep sea berths to super Barge berths. Trucks
- **Regular Barge**- These are used to transfer containers from the deep sea terminal directly to hinterland terminals.

4.2.3. Process Flow

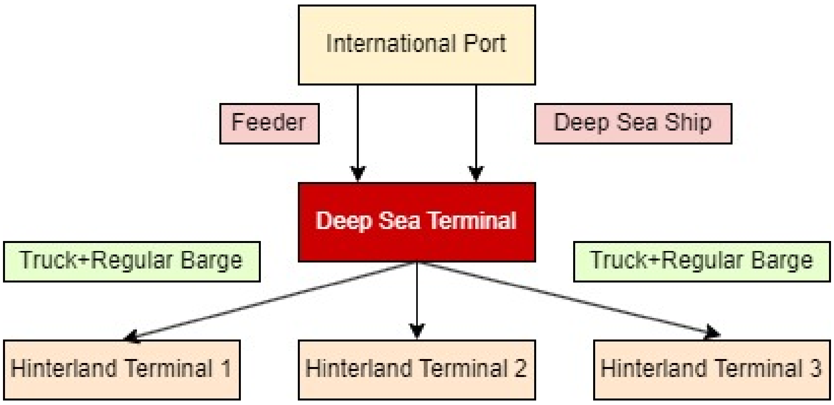


Figure 4.6: Benchmark Case

- **International Port to Deep Sea Terminals**- Feeders and Deep Sea Vessel(DSV) from Felixstowe(1000TEU call size) and Hamburg(4000TEU call size) arrive at APM-II deep sea terminal. An Overview is given in the image below.
- **Deep Sea Berth to Barge berth within deep sea terminal**- The containers from both ships are unloaded to trucks which transfer these containers between the deep sea berth and barge berth.
- **Deep Sea Terminal to Hinterland Terminals**- The barges take in small call sizes and transfer the consignments of 50 TEU to the hinterland.

Each of the above processes is defined by the same logic 3.20 described in Chapter 3. A transporter is requested by the origin terminal, arrives at the origin picks up containers, leaves and reaches the destination terminal. When it reaches the destination, a ”Delivered” message is sent to the origin where another order is initiated. As mentioned earlier the model is extremely similar to what’s mentioned in figure 3.23

Figure 4.7: international Port Routes[30]

4.3. Setup

The benchmark setup can be implemented in the Port as follows

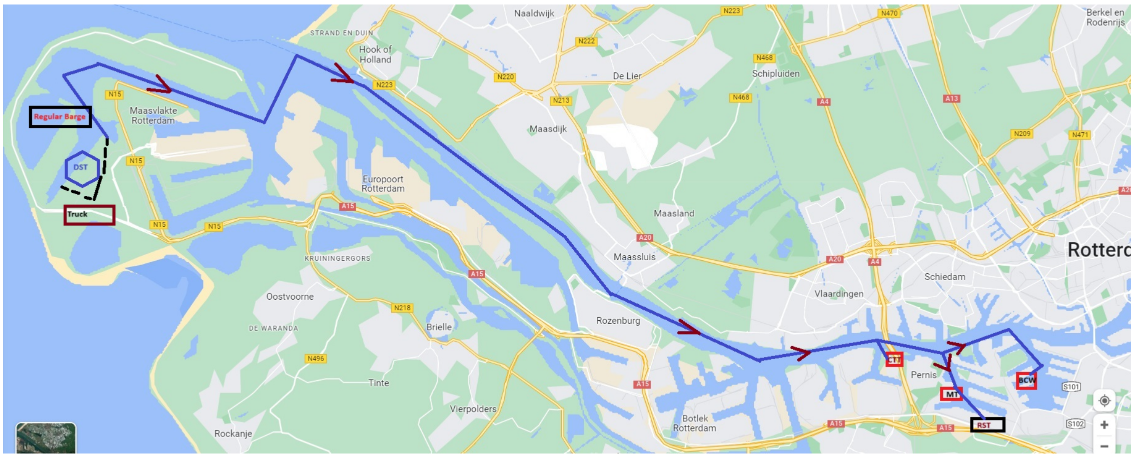


Figure 4.8: Benchmark Case in Rotterdam[30]

4.3.1. Brief Remarks

1. The congestion at deep sea terminals has been well established, with over 8 barges occupying each of the three berths on a daily basis.
2. The second base case employed a larger call size(100 TEU). The resulting congestion was 42 per cent lower than the current 50 TEU call size and 7 per cent lower transport time. This motivates the research to experiment with concepts that can transfer higher call sizes since the above experiment assures a similar or better transport time/ Throughput rate.
3. The base cases also show that Trucks are still very efficient despite their low capacity. This implies similar low-container-capacity concepts might also be useful over short distances(such as inter-terminal transport).
4. The above results validate the first set of research questions that focus on quantifying the congestion and current operations.

5

Proposed Solutions

5.1. Proposed Operational Solutions for Hinterland Transport

The solutions proposed to address this part of the research focus on a combination of transshipment concepts. The solutions have been arranged in such a way that they can be employed across a range of timelines

1. Short-Term Solution- Uses Existing Transshipment Infrastructure and introduces the concept of a Super Barge. This can be envisioned within the next five years due to low requirements of new infrastructure
2. Short-Medium Term Solution- A solution similar to the short-term solution but regular barges are replaced with Amphibious AGVs. This can be envisioned within the next 10 years
3. Medium Term Solution- This can be seen as a parallel to the benchmark case. The changes here are the introduction of floating terminals and Amphibious AGVs. Parallels with a benchmark- Trucks replaced by AAGVs, Regular barges remain common between both benchmark cases and this, lastly instead of barges docking at deep sea terminals, they dock at floating terminals.An implementation period of 10-15 years can be expected.
4. Long Term Solution 1 - This uses a combination of transshipment concepts such as barge hub, floating terminals and the AAGVs. This can be envisioned to be implemented in the next 15 years.

Table 5.1: Elements of Proposed Solutions

Solutions	Terminal Actors	Transporters	Change From Benchmark
Benchmark Case	1. International Port 2. Deep Sea 3. Hinterland	1. Deep Sea Ship 2. Feeder 3. Regular Barge 4. Truck	
Short Term Solution	1. International Port 2. Deep Sea 3. Barge Hub 4. Hinterland	1. Deep Sea Ship 2. Feeder 3. Super Barge 4. Truck 5. Regular Barge	Barge Hub, Super Barge
Short-Medium Term Solution	1. International Port 2. Deep Sea 3. Barge Hub 4. Hinterland	1. Deep Sea Ship 2. Feeder 3. Super Barge 4. AAGV 5.Truck	Barge Hub Super Barge AAGV
Medium Term Solution	1. International Port 2. Deep Sea 3. Floating Terminal 4. Hinterland	1. Deep Sea Ship 2. Feeder 3. AAGV 4. Regular Barge	Floating Terminal AAGV
Long Term Solution	1. International Port 2. Deep Sea 3. Floating Terminal 4. Barge Hub 5. Hinterland	1.Deep Sea Ship 2. Feeder 3. AAGV 4. Super Barge	Floating Terminal AAGV Barge Hub Super Barge
Final Chain Solution	1. International Port 2. Deep Sea 3. Floating Terminal 4. Hinterland	1. Deep Sea Ship 2. Feeder 3. AAGV 4. Super Barge	Floating Terminal AAGV Super Barge

5.2. Short Term Solution- Use of Existing Infrastructure

The short-term solution is formulated by looking at the next five years. It can be assumed that no new invention or innovation would be desired or be introduced in such a short span of time. Thereby the transshipment network will use existing infrastructure. The exception here is Super Barge since high-density e-barge concepts do exist in ports like Shanghai and a technology transfer can be assumed for a Super Barge to be a reality within the next five years.

5.2.1. Terminal Agents

The actors involved here are based on the existing infrastructure that we have in ports today. They are as follows-

1. **International Port**- The Ports of Hamburg and Felixstowe send in Feeders and Deep sea Vessels respectively at the rate one one vessel per day each.
2. **Deep Sea Terminal**- APM-T Maasvlakte
3. **BargeHub**- Barge Hub is a hub located in hinterland for barges to drop off containers. The centre of congestion is therefore diverted from the deep sea terminal to the barge hub.

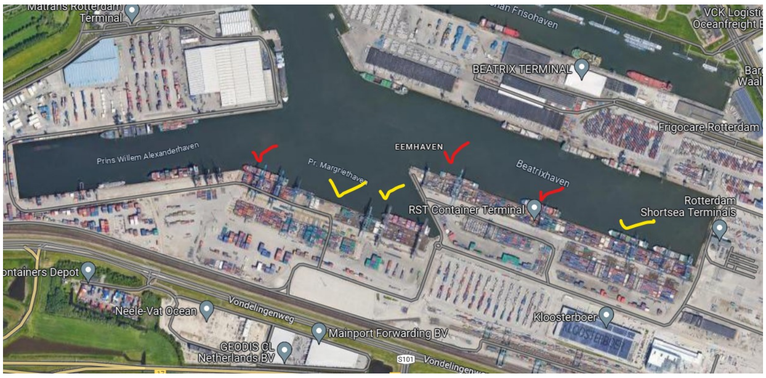


Figure 5.1: Barge Hub- Rotterdam Shortsea Terminals

4. **Hinterland Terminal**s- This is the final point in the entire chain where containers need to be eventually delivered,

5.2.2. Transporter Agents

1. **Deep Sea Ship**- Brings in containers from deep sea ports such as Hamburg/Bremerhaven to Port of Rotterdam.(Arrives once a day)
2. **Feeder**- Feeder ships bring in containers from Felixstowe to Rotterdam. (Arrives Once a day)
3. **Trucks at Deep Sea Terminal**- Trucks or AGVs transport containers scheduled for hinterland from the deep sea berths to super Barge berths.
4. **Super Barge**(larger call sizes)- The super barge is an exploratory concept employing larger call sizes(400-700 TEU).

   The super barge will access the same berths at the Deep Sea Terminal as the regular barge 4.4.
5. **Trucks at Barge Hub**- The trucks at Barge Hub transport containers from the berth where the super barge docks to the berths from where the small barges depart.
6. **Regular Small Barge**(Small-Medium Call Sizes)- Similar to the barges used in the base benchmark case.

5.2.3. Process Flow

Strategy- Deep sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke).

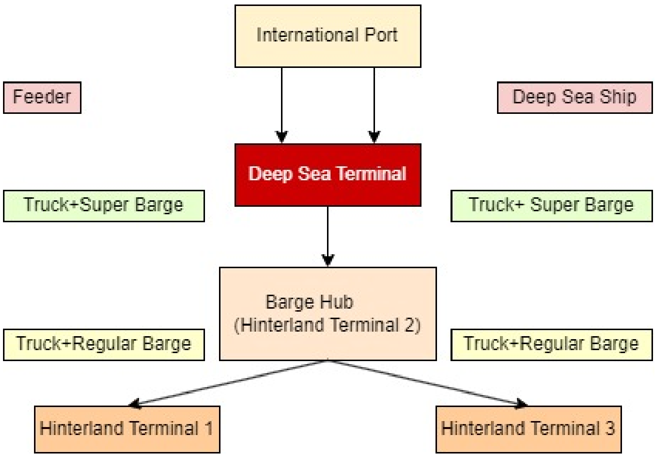


Figure 5.2: Short-term Goal- Use of Existing Infrastructure

1. **International Port to Deep Sea Terminal(APM-II)**- Respective deep sea ships and feeder ships from Hamburg and Felixstowe arrive at the rate of 1 ship per day. This scenario is common for current, short, medium and long-term cases.

2. **Deep sea Terminal's Deep sea berth transfer to barge berth**- Once a deep ship/feeder ship arrives at at deep sea terminal berth, it has to be unloaded and transferred to a barge berth. This is done by the fleet of trucks and AGVs that execute these intra-terminal transfers.
3. **Deep Sea Terminal'S Barge Berth to Barge Hub**- Once the Containers arrive at the barge berths, they are loaded onto the super barge. Containers common to all hinterland terminals are loaded onto this Super Barge(This makes the overall cost cheaper). Once loaded the super barge travels to the barge hub where it completes 2 actions- 1) Unloads the container consignment which ends at Barge Hub(Rotterdam shortsea terminals) and 2) unloads the remaining containers that are to be transferred to the hinterland.
4. **Transfer between Barge Hub's Super Barge Berth to Barge Hub's Regular Barge berth**- As indicated earlier, the consignments from super barge are split into two, one destined for the barge hub itself and others intended for the hinterland. Only those intended for the hinterland are transferred by trucks to the regular barge berths at the hub.
5. **Barge Hub to Hinterland Terminals Transfer**- From here the smaller call size barges transport the remaining containers to the three other hinterland terminals

5.2.4. Setup

- Total Containers to be transported- 1050 TEU
- Containers to be transported from barge hub to hinterland- 788(one-fourth load drops off barge hub, Rotterdam Shortsea Terminals)
- Super Barge Call Sizes range-(400,500,600,700) TEU
- Regular Barge Call Size- 50 TEU

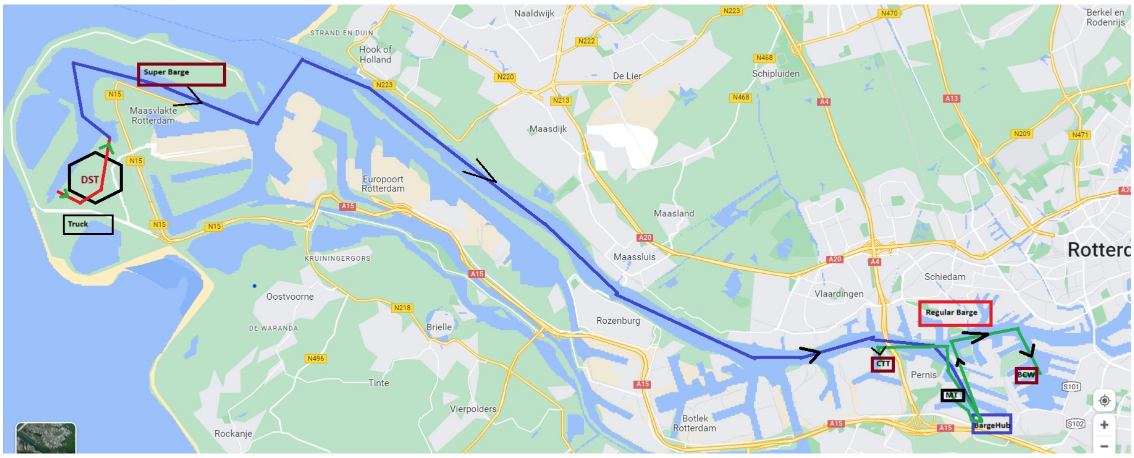


Figure 5.3: Short Term Case in Rotterdam[30]

5.2.5. Remarks

- Number of handling points is too high
- Multiple kinds of transporters are used, this is not good for operations.
- While barges have gone down in the fleet, the number of trucks has gone up. This makes sense from a business angle since 6 extra trucks is better than 15 extra barges.

5.3. Short-Medium Term Solution-Introduction of Amphibious AGVs

The short to medium-term solution is envisaged in the next 10 years. It is done with the assumption that amphibious AGVs can be developed within this 10-year time period due to their presence in literature. Essentially it replicates the previous short-term scenario but replaces the final truck+barge travel leg with an unimodal AAGV transport.

5.3.1. Terminal Agents

1. **International Port**- Deep Sea Ship from Hamburg to Rotterdam(call size- 4000TEU) and Feeder Vessel from Felixstowe to Rotterdam (call size- 1000TEU).
2. Deep Sea Terminal
3. **Barge Hub**-The barge hub is located at Rotterdam Shortsea Terminals as indicated before. Barge Hub receives the super barge and also houses AAGVs to amphibiously transfer containers to the hinterland. The amphibious AGV necessitates the use of a ramp to traverse between land and water. The location of the ramps is given in the figure below. Since Super barge berths can be on both the west and east parts of Rotterdam Short Sea Terminals, there will be two ramps to assist the entry and exit of AAGVs

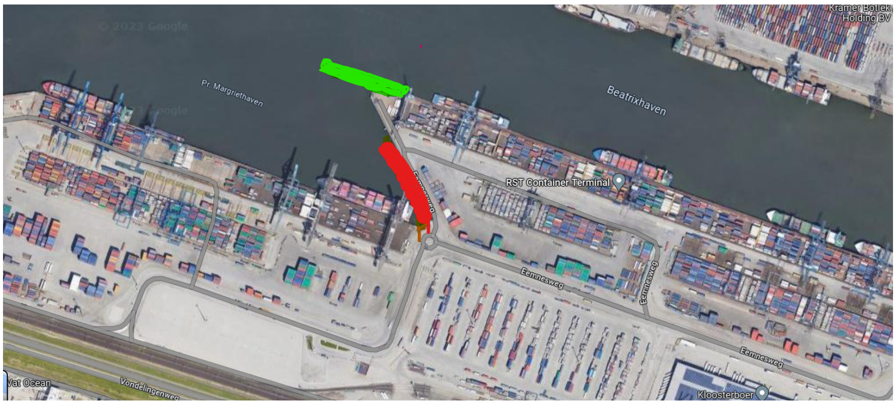


Figure 5.4: AAGV Ramp at Barge Hub[30]

The ramps have to be designed as per the quay height and incline. The calculation is given below-

- Quay Height + Buffer = 5m[79]
- Suggested ramp include angle= 3 degrees[20]
- Therefore Ramp length- 95.53m approximated to 100m.
- Ramp Width- 5m If a 100% safety margin is considered, then the width will be 2 times the width of a TEU[1] container which is approximately 5 metres.
- Typical Roll on Speed/Roll-Off Speed= 9km/hr[20]
- Time Traversed on Ramp- 40 seconds
- Time to release and retract pontoons- 30 seconds(This is a logical assumption).
- Time to inflate Pontoons- 10 seconds[51]
- Approximate Ramp Time Delay- 1.5 to 2.5 mins.
  The roll-on, and roll-off operations are based on a triangular distribution[64].

4. **Hinterland Terminals**- The final point in the container transport chain. AAGVs bring in the containers from the barge hub to hinterland terminals. The terminals here will be the same as the previous case, wherein the final recipients are CTT Rotterdam, Matrans Terminal and Barge Center Waalhaven. Ramps are marked for CTT and Matrans Terminals5.5.

Figure 5.5: AAGV Ramps at CTT,Matrans Terminals[30]

The ramp measurements will corroborate with the measurements done for ramps at the barge hub.

5.3.2. Transporter Agents

1. **Deep Sea Ship**
2. **Feeder**
3. **Trucks at Deep Sea Terminal**- Same actions as previous cases.
4. **Super Barge**-Same Action as previous Cases

5.3.3. Process Flow

Strategy- Deep Sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke)

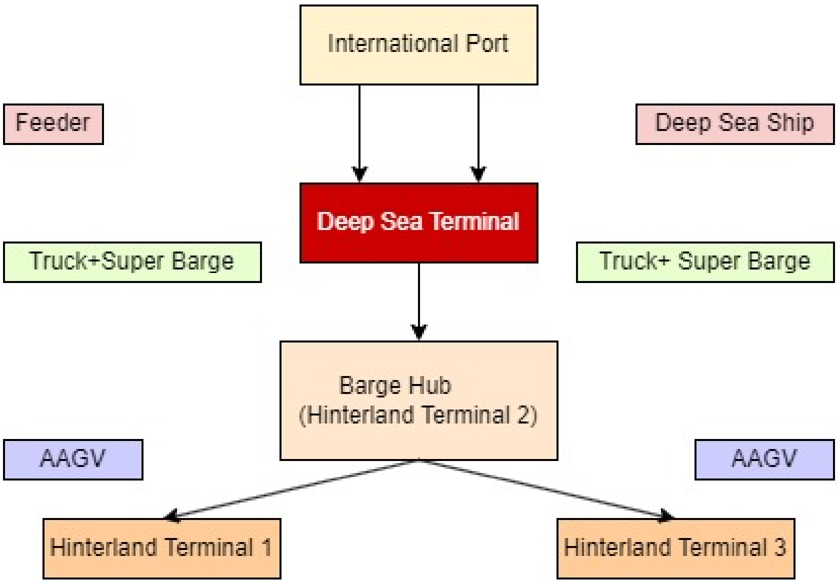


Figure 5.6: Medium-Term Goal- Introduction of Amphibious AGVs

1. **International Port to Deep Sea Terminal(APM-II)**- Respective deep sea ships and feeder ships from Hamburg and Felixstowe arrive at the rate of 1 ship per day.
2. **Deep sea Terminal's Deep sea berth transfer to barge berth**- Once a deep ship/feeder ship arrives at at deep sea terminal berth, it has to be unloaded and transferred to a barge berth. This is done by the fleet of trucks.

3. **Deep Sea Terminal'S Barge Berth to Barge Hub**- Once the Containers arrive at the barge berths, they are loaded onto the super barge that travels to hinterland. Similar to previous section, containers common to all terminals are loaded at once to a super barge to make process more efficient. This process follows the same procedure as the short-term case.
4. **Barge Hub to Hinterland**- The remaining 75 per cent of the containers are now transferred to the three remaining hinterland terminals via Amphibious AGVs which are stationed near the three Super Barge Berths as shown.

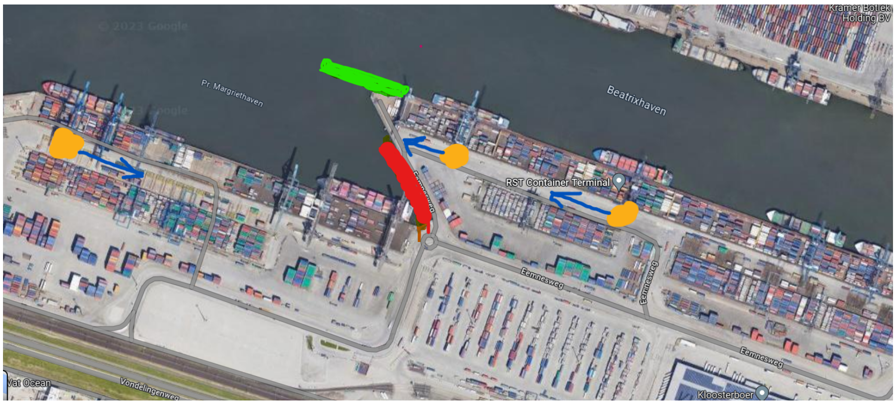


Figure 5.7: AAGV access points in Barge Hub and Ramps[30]

5.3.4. Setup

The setup of this solution matches an earlier section 5.2.4. The following image summarises the whole process.

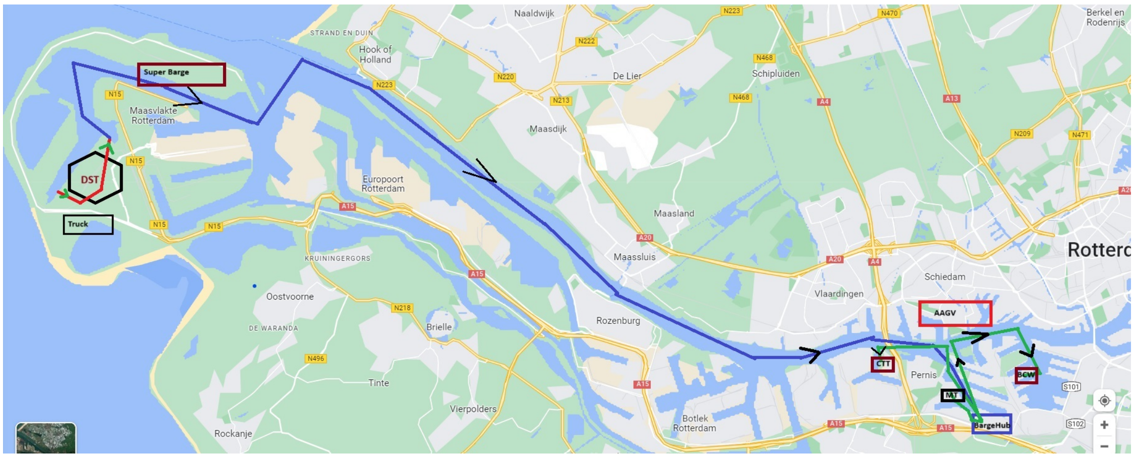


Figure 5.8: Short-Medium Term Case in Rotterdam[30]

5.3.5. Remarks

- Amphibious AGVs ensure faster container transfer with fewer handling points. Time savings of 13 per cent were recorded in comparison to the short-term case
- Number of Transporters is lower than the benchmark case despite the addition of 18 AAGVs to the system.
- Higher call size can increase the flow rate of containers but the barge itself suffers from bad utilisation.However this can be addressed with higher demands(greater than 1050 TEU)

5.4. Medium Term Solution- Introduction and use of Floating Terminals & AAGVs

The medium-term solution is something that can be envisaged in the next 10-15 years. By this time, it can be expected that both floating terminals and Amphibious AGVs will be in active use. This solution is akin to the benchmark case since the number of handling points remains the same.

5.4.1. Terminal Agents

1. **International Port**- Deep Sea Ship from Hamburg, Feeder Ship from Felixstowe
2. **Deep Sea Terminal**- First Points of arrival for feeders and deep sea ships. Also, this is the location of AAGVs.
3. **Floating Terminal**- Container Exchange between barges and AAGVs. Barges wait at the floating terminal to collect containers from AAGVs.
4. **Hinterland Terminals**-Final point of delivery

5.4.2. Transporter Agents

1. **Deep Sea Ship**
2. **Feeder Ship**
3. **Amphibious AGV**- Located at Deep sea Terminal. Transfers from deep sea quay to floating terminal berths.
4. **Regular Barge** - With small call sizes.

5.4.3. Process flow

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke)

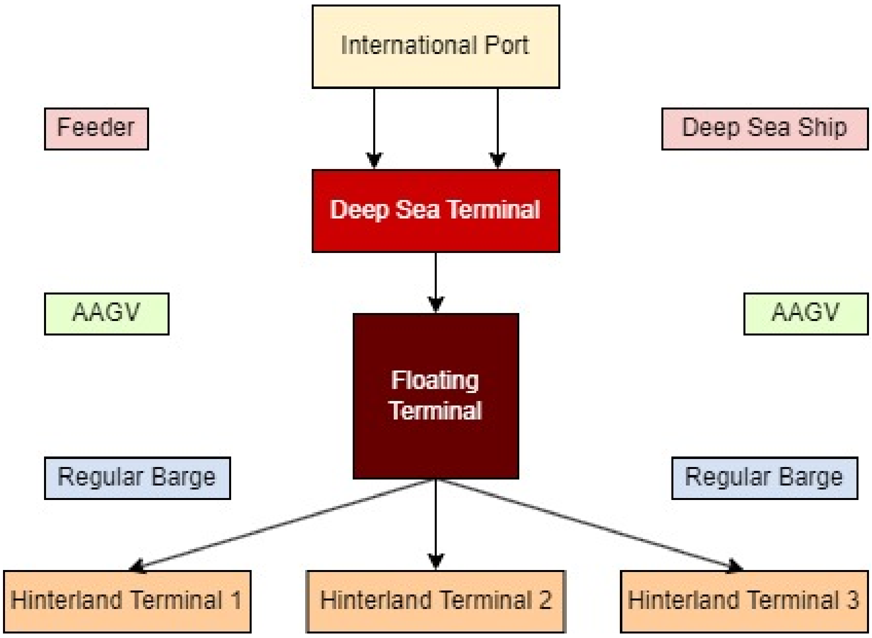


Figure 5.9: Medium Term- Use of Floating Terminals

1. **International Port to Deep Sea Terminal**- Both Feeders and deep sea ships arrive and are unloaded to AAGVs at the deep sea terminal.
2. **Deep Sea Terminal to Floating Terminal** -The amphibious AGVs transfer the hinterland scheduled containers to the floating terminal. The concerned containers are directly unloaded to the AAGVs from the deep sea ships and they exit the terminal through ramps to travel on sea to the floating terminal.The location of the ramp at the deep sea terminal is shown below:

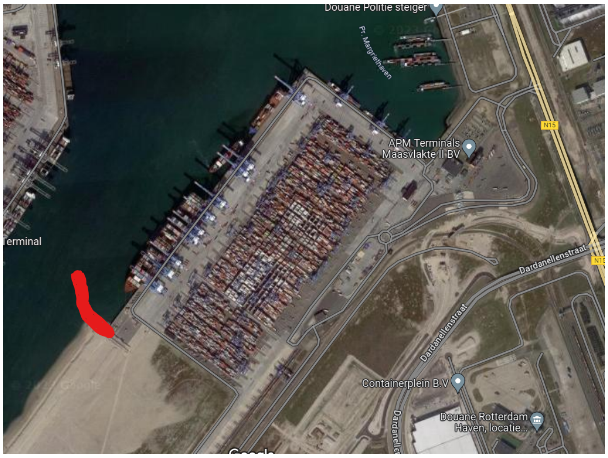
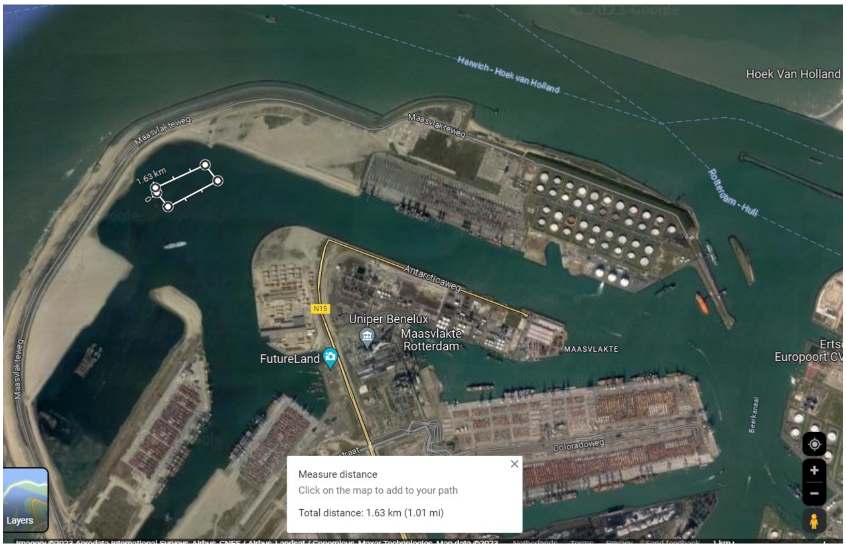


Figure 5.10: Location of the Ramp at APM- Terminals[30]

3. **Floating Terminal to Hinterland**- The hinterland scheduled containers are taken to the hinterland via the regular system of barges that are low on-call sizes. Similar to the current system, this is a direct transfer from the floating terminal to the hinterland.

5.4.4. Floating Terminal location- Relevance and Need

. The floating terminal will be located in the area as shown in the map below. The floating terminal will be located near the Container Exchange Route which is a strategic location for future connections and also is in line with what hinterland actors are looking at[99]. From a relevance angle, hinterland actors such as the Waalhaven group and Terminals such as CTT Rotterdam, Barge Center Waalhaven and Matrans Terminals are looking to expand their presence in Maasvlakte with a terminal exclusively for Barge/Feeder traffic along with the ability to handle empty containers as well. The cited article[99] also states that they wish to prevent unnecessary low-call size trips of Feeder ships to the Hinterland. From a strategic angle, the requirement is only for an entity to exchange containers and store empty containers. **This can be performed in entirety by a floating terminal which can be a more cost-effective alternative to the proposed terminal**. The location for this floating terminal 5.11 will be at the North West Corner of the Maasvlakte as shown. This is also close to the proposed location of the new barge/feeder terminal.



Measure distance
Click on the map to add to your path
Total distance: 1.63 km (1.01 mi)

Figure 5.11: Proposed location for floating terminal[30]

5.4.5. Floating Terminal Specifications

The design of the floating terminal used for these simulations will be the smaller version 3.5. This will be used in various combinations of berths as shown in 3.5 and also specific to each of the solutions.

5.4.6. Setup

- Containers to be transported- 1050 TEU
- Barge call size from the floating terminal- 50 TEU
- Barge Berths at Floating Terminal- 3
- AAGV berths at the floating terminal- 5
- Twin Spreader at Floating Terminal- Dual Loading of Containers.

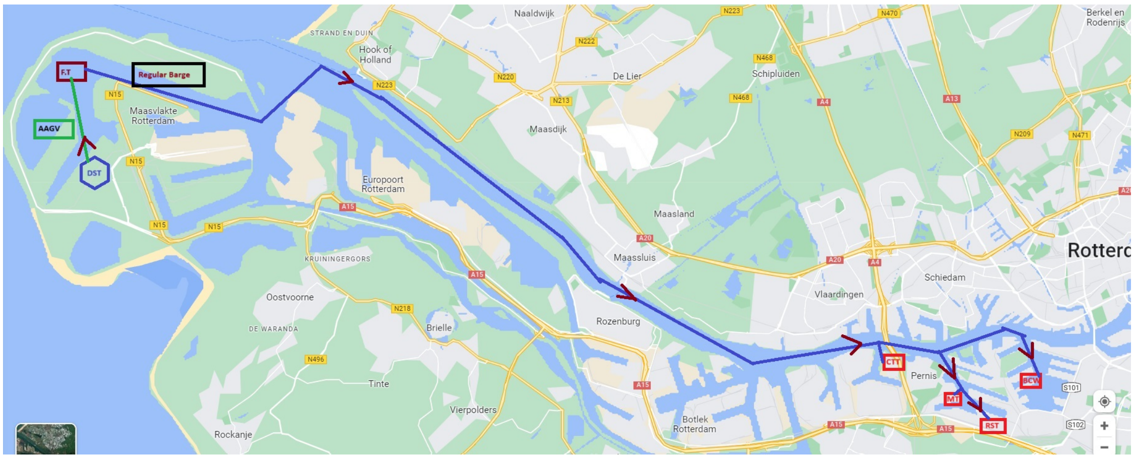


Figure 5.12: Medium Term Case in Rotterdam[30]

5.4.7. Remarks

- One of the fastest solutions at a transport time of 46 hours.
- Number of transporters however rise to 64 from 48 in the benchmark case.
- Congestion of barges still remains extremely high.
- AAGVs ae constrained by speed limits of ports.
- While barge congestion is reduced to 5 per berth, not good for future floating terminal productivity.

5.5. Long Term Solution I - Combination of Transshipment Concepts

The combination of various transhipment concepts can be envisaged as a long-term project if it gives the desired operational benefits. But realistically this could take over 15 years to materialize given the operational complexity. This will essentially combine all the transhipment concepts considered above and incorporate them into this one case, namely barge hub, floating terminal, amphibious AGV and super barge all in one case. This solution can also be seen as a parallel and extension to the short-term and short-medium-term cases.

5.5.1. Terminal Agents

1. **International Port**- Hamburg, Felixstowe
2. **Deep Sea Terminal**- APM-II, Houses Amphibious AAGVs
3. **Floating Terminal**- Receives AAGVs from deep sea terminal. Also acts as a centre for container exchange between AAGV and super barge.
4. **Barge Hub**- Receives Super Barge, also houses AAGVs for the hinterland.
5. **Hinterland Terminals**- Final point in the chain

5.5.2. Transporter Agents

1. **Deep Sea Ship**
2. **Feeder**
3. **Amphibious AGV at Deep Sea Terminal**
4. **Super Barge**- Moves containers from floating terminal to barge hub.
5. **Amphibious AGV at barge hub**- Moves containers from barge hub to hinterland.

5.5.3. Process Flow

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland Terminals(Hub and Spoke)

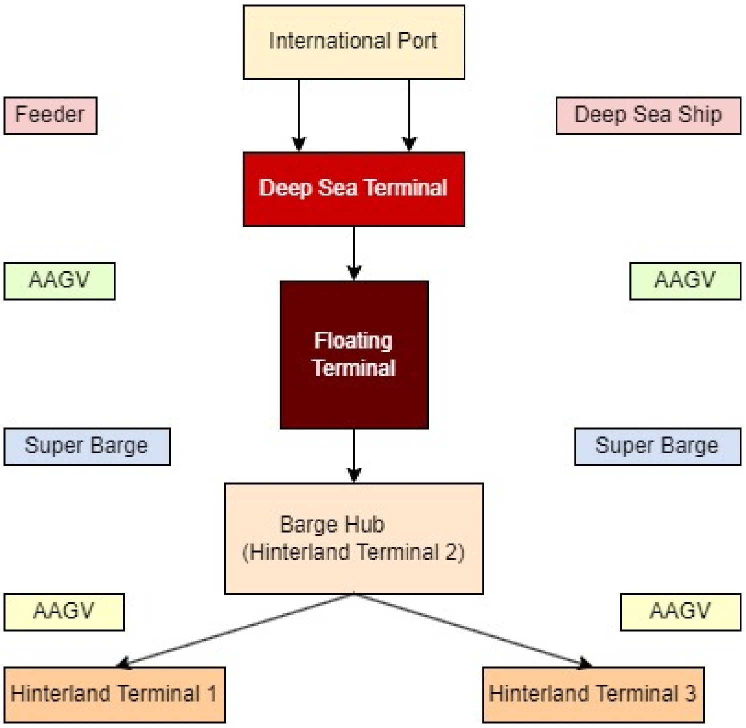


Figure 5.13: Long Term- Combination of Transshipment Concepts

1. **International Port to Deep Sea Terminal**- The feeders and deep sea ships arrive at the deep sea terminal berths like in previous cases.
2. **Deep Sea Terminal to Floating Terminal**- The containers bound for the hinterland are transferred to the floating terminal via amphibious AGVs upon which containers from deep sea ships and feeders are directly loaded. The AAGVs arrive at the berths of the floating terminal.
3. **Floating Terminal to Barge Hub**-The hinterland container consignments are transferred from the floating terminal to the barge hub via the super barge which can carry between 400 and 700 TEU in one go. At the barge hub, containers destined for the barge hub itself are unloaded while the rest are taken over by AAGVs.
4. **Barge Hub to Hinterland**-The remaining 75 per cent of the containers are now transferred to the three remaining hinterland terminals via Amphibious AGVs which are stationed near the three Super Barge Berths as shown.Similar to previous section, containers common to all terminals are loaded at once to a super barge to make process more efficient.The amphibious AGVs use the same access points and barge hub configuration as the short-medium term case 5.7.

It must be noted all configurations related to deep sea terminals, barge hubs and floating terminals will repeat and be relevant in this case as well.

5.5.4. Setup

- Containers to be transferred to hinterland- 1050
- Containers to be transferred from barge hub to hinterland- 75% TEU.
- Amphibious AGV berths at Floating Terminal-5
- Super Barge berths at Floating Terminal- 2 individual berths with 2 Cranes each, 1 berth with just 1 crane.

The setup when implemented in the port of Rotterdam will resemble the configuration given below.

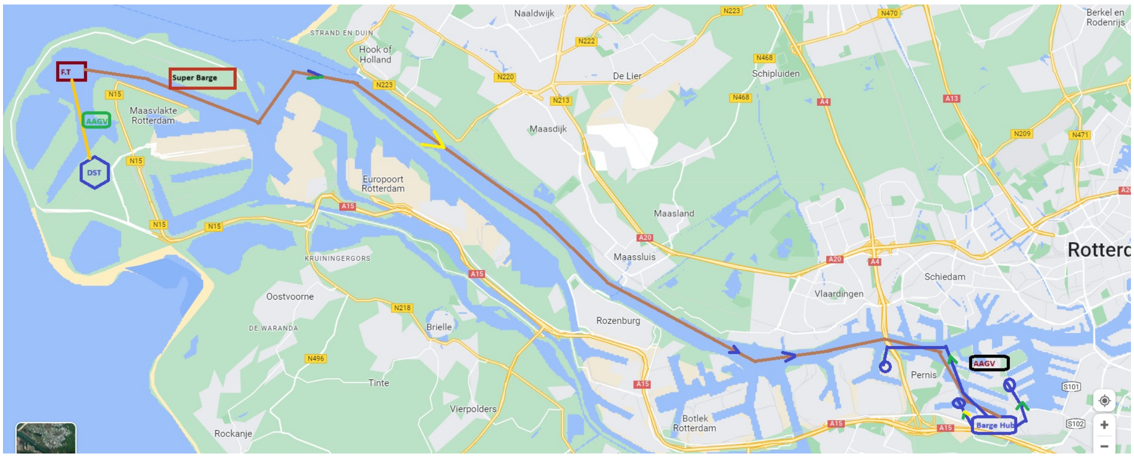


Figure 5.14: Long Term 1 Case in Rotterdam[30]

5.5.5. Remarks

- Number of handling points too high
- Simulation reveals that demand is not large enough to use higher call size barges.
- While this case ensures maximum barge reduction, it comes at the cost of congesting water and land lines through 58 AAGVs.

5.6. Long Term Solution II- The Final Chain

The final chain solution is envisioned as a framework that can be applied in the long term. From earlier solutions, it is very clear that there needs to be a reduction in transporters as well as the number of handling points from a barge perspective as well as an AAGV/truck perspective. Therefore the load on AAGVs are reduced by shifting the feeder traffic to the floating terminal while the deep sea ship remains as it is at the deep sea terminal. This can however be seen as an opportunity since this would ensure that AAGVs are better utilised and do not just travel one way.

Terminal Agents

1. International Ship
2. Deep Sea Ship
3. Floating Terminal
4. Hinterland Terminals

Transporter Agents

1. **Deep Sea Ship**
2. **Feeder Ship**
3. **Round Trip AAGVs**- AAGVs between deep-sea terminal and floating terminal will have containers on both to and fro trips. One journey carries hinterland-bound containers to floating terminal while another journey carries inter-terminal transport bound containers
4. **Super Barge**

5.6.1. Process Flow

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke)

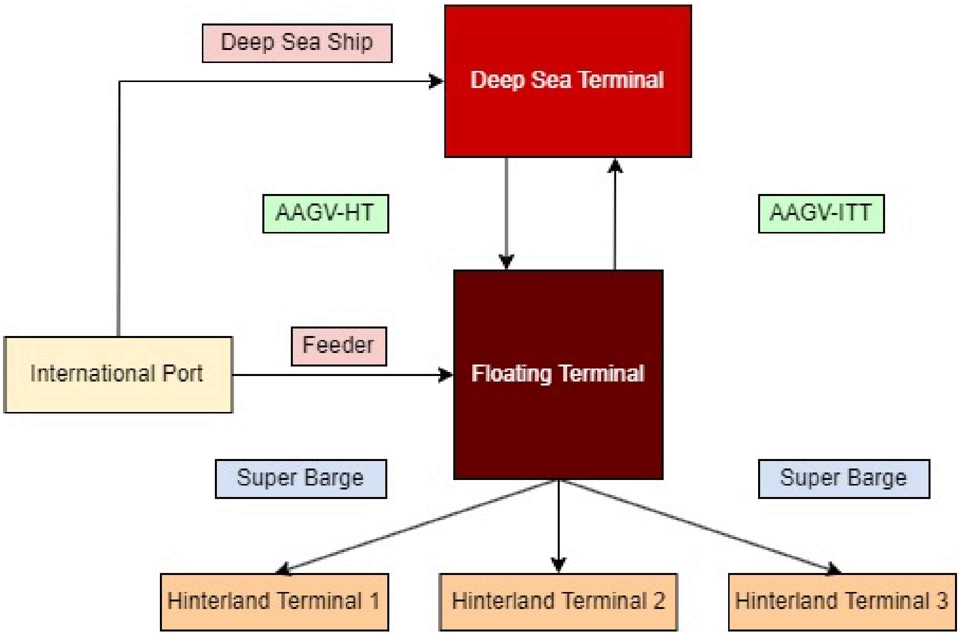


Figure 5.15: Long Term- Final Chain

This scenario has been built as a result of the shortcomings noted in previous scenarios. The issues seen predominantly relate to congestion due to AAGVs in both floating terminals and barge hubs. It is therefore decided that feeder traffic will be shifted to ensure a tangible outcome in congestion reduction at deep sea terminals.

1. **International Port's Feeder Ship to Floating Terminal**-In this final chain, the UK feeder ship transfers directly to the floating terminal instead of the deep sea terminal. Thereby providing an opportunity to have one more deep-sea ship in place of the feeder.
2. **International Port's Deep Sea Vessel to Deep Sea Terminal**- The deep sea vessel from Hamburg docks at deep sea terminal like in all cases
3. **AAGV' Hinterland TEU to Floating Terminal**-The container consignments scheduled for the hinterland are transferred from the deep sea terminal to the floating terminal.
4. **AAGV' ITT containers to Deep Sea Terminal**- The container consignments from feeder ships that are scheduled for inter-terminal transport are transferred to the deep sea terminal. The AAGVs in this case have better utilization since they cover a round trip where both trips run under full load.
5. **Hinterland Containers transport From Floating Terminal to Hinterland Terminals**- The containers scheduled for hinterland are now transferred via Super Barges. This is a direct transfer to all individual hinterland terminals from the floating terminal, thereby ensuring fewer trips.**It must also be noted that the feeder will have containers under the modal split of truck and train as well. Therefore the flow rate will have to factor in the entire hinterland consignment.**

5.6.2. Setup

- Super Barge Call Size- (400,500,600,700) TEU
- Super Barge Berths at Floating Terminal- 3
- AAGV berths at Floating Terminal- 3
- Feeder berth at Floating Terminal- 1

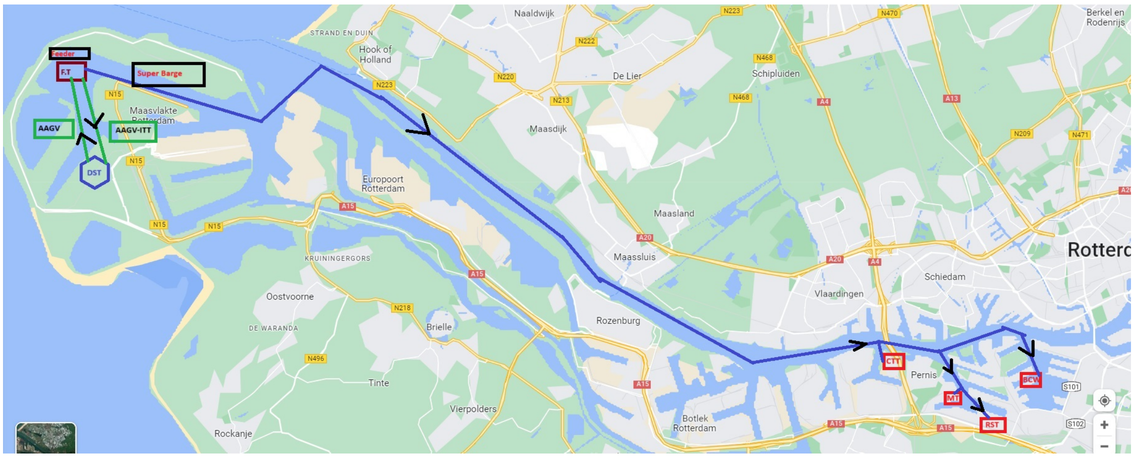


Figure 5.16: The Final Chain Case in Rotterdam[30]

5.7. General Remarks

When the base demands were compared for all cases, it is sufficiently clear that only one solution balances and exceeds the benchmark case in terms of congestion, transport time, container transfer rate and fleets. That is the long-term final chain solution which ensures all major concerns are solved, them being :

1. Diversion of barge traffic to a new transhipment hub- floating terminal.
2. Reduction in congestion at the Floating terminal- Achieved with footfall of 2-3 super barges per day. Benchmark case recorded 24 barges a day at a berth occupation of 8 ships/berth/day.
3. 452 AAGV trips per day, this is a lower congestion figure than the benchmark which saw 472 truck trips a day.
4. 14 per cent higher container throughput rates
5. 12 per cent reduction in transport time.

This motivates the author to conduct more experiments to validate the effectiveness and global applicability of the Final chain solution.

6

Experiments

6.1. Need for Experiments

Once an optimum solution is identified, various experiments are performed that take into account the various non-linearities in demand and throughput. These non-linearities can be seen predominantly in the three main assumptions that were made in the current operational analysis i.e.

- Modal Split- Currently 35% of Hinterland bound containers are transported by barges but this could increase in future owing to emission advantages barges hold over trucks.
- Hinterland Share- The assumption made in this work is that 60% of all containers that arrive in the current operational setup are bound for the hinterland. With the increased use of waterways projected for hinterland transport within the same nation and between other countries[44], it can be assumed that this number can and will go up.
- Berths and Demand- With greater demand, terminals need to be more flexible with berths and their allocation for different kinds of ships. Currently it is assumed that current operation in Rotterdam faces 1 deep sea ship and 1 feeder per day.

6.2. The Experiments

Taking cue from the current state of affairs, the experiment have been designed to simulate growth and flexibility and are as follows.

1. **Modal Split Experiment**- With regions such as Europe, China and the USA doubling down on barging, they intend to raise the share of barging to 45% from the existing 35% [33]. This experiment will test two situations, 45% and 55% while keeping demand Constant
2. **Hinterland- Inter Terminal Container Distribution**- Ships generally bring in a consignment of containers scheduled for hinterland as well as inter-terminal transport. While the base demand has used the current 60 per cent distribution towards the hinterland and 40 per cent towards inter-terminal transport, studies with 2030 as an outlook[84] have considered hinterland proportions of 70 per cent and more. This experiment will be done keeping modal split constant and demand constant while varying the HT-ITT distribution between 70-30 and 80-20 proportions.
3. **Berths&Demand Experiment**-Anticipating future demand, the number of feeders and deep sea vessels are alternatively increased to see how it affects the final chain and benchmark cases.
4. **Special Case**- This is a worst-case scenario where the maximum modal split, maximum hinterland transport and maximum demand/berths are applied to the benchmark case and final chain case.

The experiments have only been computed for the best-performing case and its comparison with the benchmark. This will subsequently be seen in the results Chapter 7 of this work where it is proven that **the final chain** produces the most optimal range of solutions across congestion, throughput, transport time and fleet. The KPIs measured here across the range of experiments are the same as before- Throughput, Fleet, Congestion and Transport Time.

6.3. Transporter Modal Split Experiment

The modal split is defined as the split between modes of transport to perform a certain task. In this case, it is hinterland transport. For the last many years ports around the world have strived to increase the proportion of barging owing to the fact that barging can provide reliable transport with lesser emissions per TEU[33]. Apart from ports like Rotterdam and Shanghai, Ports in the USA also wish to exploit their inland waterway network to support Medium, small and micro industries along the hinterland. Rotterdam, Antwerp and Hamburg have set targets of 45% modal split in favour of barge by 2030.

6.3.1. Experimental Conditions

The experimental conditions here will be a constant demand, a constant hinterland container proportion but with varying modal splits. The data can be accessed here **by clicking this**. A summary of the specific data used is given below

Table 6.1: Modal Split Configurations

Category	**45% Modality**	**55% Modality**
Containers/ Day	4000(Deep Sea Vessel) 1000(Feeder)	4000(Deep Sea Vessel) 1000(Feeder)
Hinterland Container Share	60%	60%
Modal Split for Barge	45%	55%
Total Hinterland Demand	1350 TEU	1650 TEU
Containers for ITT(Feeder Only)	400 TEU (Floating Terminal)	400 TEU (Floating Terminal)

6.4. Hinterland-Inter Terminal Distribution Experiment

6.4.1. Background

Container vessels generally arrive with a mix of containers, some scheduled for hinterland while the others are exchanged between deep-sea terminals. In the context of the port of Rotterdam, this means containers are either exchanged within terminals at Maasvlakte(Inter-terminal transport) or it is shipped to the hinterland to areas such as Waalhaven and Eemhaven. From various sources of literature [81], it is clear that hinterland transport has the potential to grow massively. 2030 simulations[84] have declared hinterland shares in excess of 70 per cent in Port of Rotterdam and specifically aiming at the Waalhaven-Eemhaven region. The data can be accessed here **by clicking this**

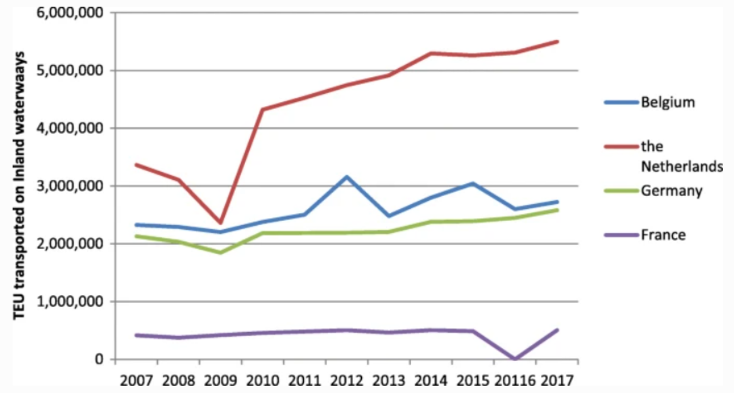


Figure 6.1: Growth of Inland Shipping in Europe[83]

Looking at the growth trajectory of the Netherlands, it is highly possible that Rotterdam and other major ports in Europe could end up being major hubs of hinterland traffic as well. As stated in literature [84], traffic at major ports around the world could grow anywhere between 10% and 100% by 2030. Therefore this section will deal with 70-30 and 80-20 proportions for hinterland transport.

Table 6.3: Berth:Demand Experiment Data

Category	**2 DSV 1 Feeder**	**2 DSV 2 Feeder**	**1 DSV 2 Feeder**
Containers/ Day	2 DSV- 8000 TEU 1 Feeder- 1000 TEU	2 DSV- 8000 TEU 2 Feeder- 2000 TEU	1 DSV- 4000 TEU 2 Feeder- 2000 TEU
Hinterland Container Share	60%	60%	60%
Modal Split for Barge	35%	35%	35%
Total Hinterland Demand	1890 TEU	2100 TEU	1260 TEU
Containers for ITT(Feeder Only)	400 TEU (Floating Terminal)	800 TEU (Floating Terminal)	800 TEU (Floating Termina)

6.4.2. Experimental Conditions

The experiment keeps the daily demand of 5000 TEU constant along with keeping the modal split constant. The hinterland- Inter Terminal transport proportions alone change as mentioned in the following scenarios. The simulations here are done as per previous scenarios and run for a period of 92 days. Analysing this from a mathematical perspective tells us that results should be different from the initial benchmark case(60% Hinterland,35% modality). This is because, unlike the modal split experiment, the distribution here changes between the hinterland and inter-terminal container consignments. This implies that a linearity in the process is lost.

Table 6.2: Hinterland Share Configurations

Category	**70% Hinterland Share**	**80% Hinterland Share**
Hinterland Container Share	4000(Deep Sea Vessel) 1000(Feeder)	4000(Deep Sea Vessel) 1000(Feeder)
Modal Split for Barge	70%	80%
Total Hinterland Demand	35%	35%
Total Hinterland Demand	1225 TEU	1400 TEU
Containers for ITT(Feeder Only)	300 TEU (Floating Terminal)	200 TEU (Floating Terminal)

6.5. Demand: Berths Experiment

6.5.1. Background

In order to simulate future demand, it is important to understand how a deep sea terminal would develop to accommodate more ships and hence higher throughput. It is clear that APM-T Maasvlakte is planning to increase its quay from the current 1km to 2km by 2026[5]. This means the berth configurations and demand configurations will change. Currently, we have one deep-sea ship and one feeder ship coming daily to the Port of Rotterdam. It can be expected that will change in the next few years and those scenarios are as follows-

- 2 Deep Sea vessel and 1 feeder ship on a daily basis
- 2 Deep Sea Vessel and 2 Feeder Ships on a daily basis.
- 1 Deep Sea Vessel and 2 Feeder Ships on a Daily Basis

6.5.2. Experimental Conditions

Here demand will be varied keeping the modal split and hinterland-inter terminal container distribution consistent. The data can be accessed here **by clicking this**

The table above depicts how the demand changes with increasing/decreasing number of ships per day.

6.5.3. Location of Berths in the Expanded Terminal

The berth configurations are subject to change at deep sea terminals when expansion takes place. A logical assumption is presented in the figures below, for the benchmark as well as final chain cases.

Figure 6.2: Berth Configurations for Benchmark[30]

As depicted in the above mentioned figure, the expansion of the terminal will take place towards the south of the current terminal complex. This will open the space for at least two more new deep sea berths down south(marked in yellow and light green) in addition to the existing berths (red and blue). Furthermore if the benchmark case(current operation is considered), then the area to right of the red berth i.e. barge berths will still function as done in current cases. This expanded terminal will accommodate the different configurations mentioned in 6.3.

Figure 6.3: Berth Configurations for Final Chain Case[30]

When the final chain case was discussed in the previous chapter, one of the main target points was to make sure that deep sea terminals have enough space to serve deep-sea ships. This was only possible by diverting the feeder traffic(partly) to either the floating terminal berths or the current barge berths. In the aforementioned figure, we accommodate 2 deep-sea ships and 2 feeders within the same existing canvas as used currently (in non-expanded mode). This is achieved in the following ways-

- One of the feeder Ships, will now dock at the floating terminal while the other feeder docks at the barge berths which are now unused.
- The remaining two deep sea ships can be accommodated in the existing two berths at APM-T.
- Therefore the final chain solution employs the current resources used at the deep sea terminals without the need of any extra space.
- The final chain case opens up opportunities for more Ships to be accommodated at the expanded area in future years (2 Deep Sea Ships or 1 Deep Sea Ship + 2 Feeders).

6.6. Special Case Experiment

The Special case experiment would involve a combination of parameters potentially shooting up the demand. This translates to a footfall of 4 Ships/Day(2 feeder ships + 2 deep sea vessels). Additionally, if we multiply this with a higher hinterland share of 80% and a barge modal transfer of 55%, the demand parameters are as follows-

Table 6.4: Special Case Data

Category	**Maximum Demand Case**
Containers/Day(Arrival)	2 DSV- 8000 TEU 2 Feeder- 2000 TEU
Hinterland Container Share	80%
Modal Split for Barge	55%
Total Hinterland Demand	4400 TEU
Containers for Inter Terminal Transport (Floating Terminal)	200 TEU

7
Results and Comparison

7.1. General Results

The general results focus on the comparison of the main KPIs of this research- congestion, transport time and throughput. This has been done for all proposed solutions. The link for the data-sheet can be found **by clicking this**

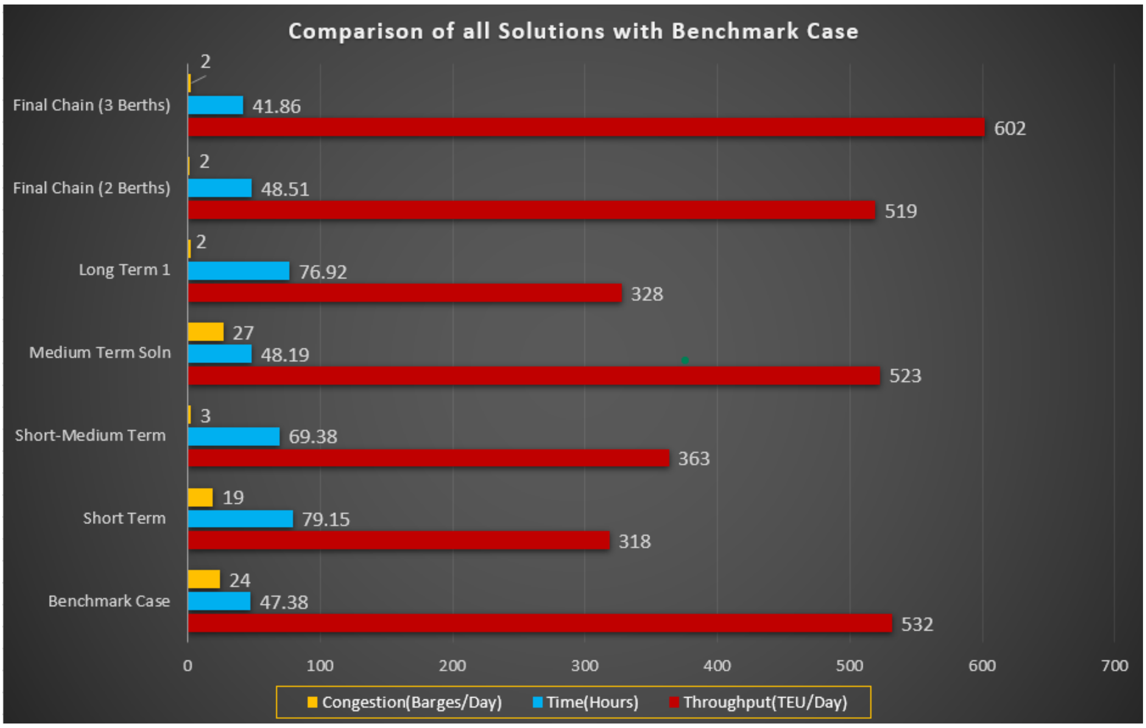


Figure 7.1: Statistics of all Results

7.1.1. Congestion

Diving into the general results, it becomes clear that the benchmark records a staggering 24 barges/-day. This corroborates with APM-Terminals data[5] of 22 barges per day. There are 3 barge berths at APM Terminals Rotterdam and this roughly translates to 8 barges/ berth. This also validates the first set of research questions which focus on barge congestion in ports. This is again a testament that low call sizes on barges (50 TEU and lesser) can cause bottlenecks in the overall system. This essentially also brings a risk for deep sea terminal operators who might be left with no choice but to accommodate barges at their deep sea berths, blocking queued ships. The strategy used in most of the solutions is to either divert the centre of congestion or use larger call sizes or both. This section of work does not discuss the congestion of AAGVs and Trucks. This will be discussed in section 8.3.1.

When this is compared to the other five proposed solutions, it is clear that there are multiple candidates which recorded reduced levels of congestion. These solutions are the *short-medium term solution, long-term 1 and the final chain solution*. The commonality between these three solutions is the use of Super-barge which transports higher call sizes per trip (ranging from 400-700 TEU). This has seen the level of congestion reduce to about 2-3 super barges a day from the current 24 barges experienced by current deep-sea terminals. These solutions have also employed the strategy of diverting the centre of congestion(from deep-sea terminal to either the floating terminal or the barge hub) and the strategy of using heavier call sizes. The barge hub and floating terminal are points of contact for amphibious AGVs,super-barge and even regular barges depending on scenario. Moving to one of the worse cases, the short-term case performs worse than expected, recording 19 barges/day. This is a mixture of 3 super barge trips (DST-BH) and 16 regular barge trips (BH-HT). While this shifts the congestion centre to the barge hub, it begins to clog the barge berths massively and also due to multiple handling points in process(DST,BH,HT,Berth transfers), the transport time also goes up massively as will be seen later. When the same short-term scenario has two of its final journey(truck+barge) legs replaced by Amphibious AGVs in the short-medium term solution, it eliminates this berth congestion entirely.

Containers are unloaded onto Amphibious AGVs from super barges just like they are done on trucks and AAGVs exit/enter through ramps. The congestion therefore in this short-medium for sea-going vessels is substantially better due to elimination of double-handling. When we go on to the long-term solution 1, it pretty much mimics the short term scenario except that AAGVs and floating terminals come into play. This has employed a maximum barge reduction policy by only using a super barge but the number of change points are much higher (DST,FT,BH.HT). This could imply congestion of vehicles other than barges at these change points so therefore is not fail-safe. Another promising solution here is the final chain solution which employs AAGV, super barge and floating terminal. The number of handling/change points are only three and the sea-going congestion is 2-3 Super barges/day like other cases. Therefore, this becomes a candidate to consider. Lastly, one of the worst-performing solutions in congestion was the medium-term solution which mimics the benchmark solution itself in setup but suffers even more severe congestion at the floating terminal to the tune of 26 barges/day(9 barges/berth).However,as will be seen later this solution is competitive in time.

1. **Congestion Reducing Solution**s- Short Term, Short-Medium,Long Term 1 and Final Chain
2. **Promising Solutions**- Short-Medium Term Solutions, Final Chain Solution
3. **Worst Performing Solution**- Medium Term Solution

7.1.2. Transport Time

The transport time of hinterland container consignments is dependent on multiple factors such as handling points, call sizes and equipment used to transfer. A quick glance at the transfer time graph reveals the effectiveness of the current setup despite congestion issues. The benchmark records a transport time of 47.37 hours. This also explains why operators seem okay with the added congestion since this is still among the fastest transport methods.The best solution that comes close to and also beats the benchmark is the final chain solution with three berths at the floating terminal. This records a transport time of 41.8 hours on average compared to the 47.37 hours recorded in the benchmark case. This is a 12% improvement over the benchmark case. The main contributing reason for this time improvement are the AAGVs. AAGVs are more productive per kilometre compared to truck and therefore transport container consignments faster than trucks do for inter berth transfers. Another contributing factor is the Super barge, where bulk call sizes are employed to reduce congestion and move containers faster. The floating terminal also incorporates a twin spreader which allows two twenty-foot containers to be loaded at once. This also contributes to the reduction in the overall loading and unloading cycle time of the barges.

A close second-best solution can also be found in the medium-term solution and the final chain solution with 2 floating terminal berths. They recorded 48.19 and 48.15 hours. Coming to the medium-term solution, as seen in the congestion section, the number of barges that make daily footfall is 26. This invariably will lead to a higher throughput. It can also be pointed out that this medium-term solution is a straight parallel of the benchmark case itself, which in a way self explains why this solution is also fast. To reiterate, while amphibious AGVs are limited in speed, they are still efficient enough to transport containers in the medium-term and final chain solutions faster or equal to that of the benchmark, therefore this is a good motivation for future prospects of AAGV. The final chain solution with 2 FT berths is also time effective and with slightly lesser congestion as seen before.Looking at some of the worst solutions, it can unanimously be seen that solutions with extra handling points suffer the most in transport time. These solutions are Short Term Solution, Short-Medium Term Solution and the Long Term-1 and record transport times of 79,69 and 76 hours respectively. Especially in the long term 1 solution, amphibious AGV's benefits are masked by the extra handling point at the Floating terminal.

In common, all three solutions employ the barge hub concept with the idea of shifting the hinterland traffic to the barge hub while ensuring that barge traffic is reduced by the use of a Super Barge. The major time loss in the process occurs at the barge hub where containers need to be unloaded again onto either AAGVs or regular barges in order to reach their destination.An encouraging signal for the future can be seen in the short-medium term solution. The use of Amphibious AGVs in the last leg of hinterland container transport instead of the double truck+barge transport reduced the overall time by 10 hours. Despite this, in solutions like the long-term-1 concept, time was also lost in transferring containers from the deep sea terminal to the floating terminal. This again can be attributed to the fact that Amphibious AGVs are limited by speed constraints. In a way this also motivates future research to explore further AAGV applications for inland waterways.

1. **Best Performing Solutions**- Medium Term Solution, Final Chain Solution (2 Berths & 3 Berths)
2. **Worst Performing Solution**-Short Term Solution, Short-Medium Term Solution, Long Term 1.
3. **Promising/Realistic Solution**- Final Chain Solution (2 berths & 3 berths solution)

7.1.3. Throughput

The throughput performance is also very similar to transport time since both are heavily interlinked. Akin to what was seen before, the benchmark case is still extremely effective with a transfer rate of 532 TEU/Day. This is attributed to the fast in-fast out concept employed by the current hinterland transport system via the use of small call-size barges. Another major reason for small call sizes is also stability since there is certainty of receiving 50 containers continuously over 400 containers. The best solution that can stack up against the benchmark case is the Final Chain Solution with 3 FT Berths. Understandably this has leveraged the twin spreader technology to transfer containers at twice the speed while also using the last berth to improve productivity. Expectedly the second on the list is the medium term solution and final chain-2 FT berth solution. All solutions follow the exact trend as the previous section on Transport time with also the same reasons for why the behaviour is as such. Both the time and throughput data reveal, that indeed there is a massive times loss when handling points increase. While this might reduce congestion of sea-going vessels significantly, it also causes problems in information flow and accountability from actor to actor. While this research does not want to unanimously advise against the use, it must be pointed out that solutions like short-medium term might be more useful as a filler solution until new technology is brought about. Furthermore, also if terminals are more interested in reducing congestion than time then the short-medium term solution might be more beneficial. For ports that do not deal with intense traffic, this very short-medium term solution could be a cost-effective one. But overall if performance is the only benchmark then the final chain solution should be preferred.

1. **Best Performing Solutions**- Medium Term Solution, Final Chain Solution (2 Berths & 3 Berths)
2. **Worst Performing Solution**-Short Term Solution, Short-Medium Term Solution, Long Term 1.
3. **Promising/Realistic Solution**- Final Chain Solution (2 berths & 3 berths solution), Short- Medium Term Solution(for low-cost port applications)

7.1.4. Fleet

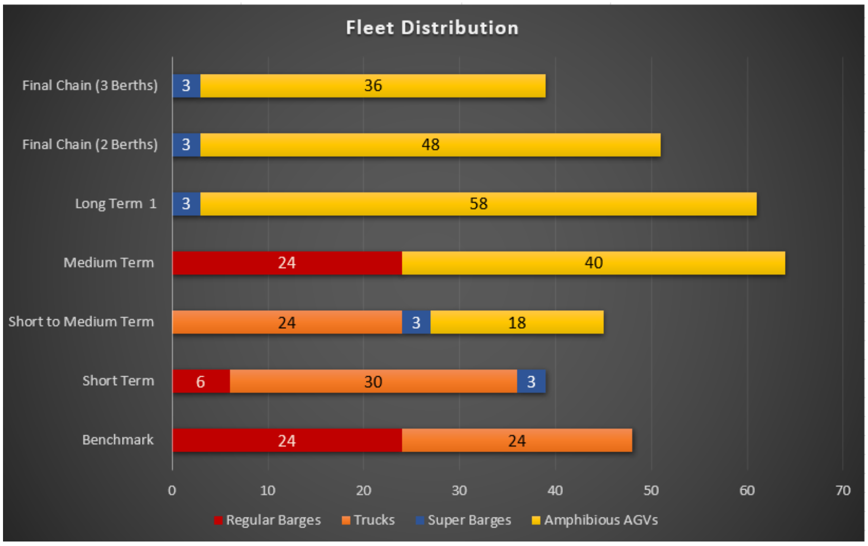


Figure 7.2: Fleet Distribution

A major contributor to achieve the end-goal of this project is to also control fleet sizes for the future. This will also encourage lower congestion, while using resources sparingly. For starters, the benchmark case accounts for 24 regular barges and 24 trucks. The fleet is also a testament to the congestion experienced on a daily basis. Going by chronology, the short term solution uses two sets of trucks(one for deep sea terminals, one for hinterland), a set of super barge (Deep sea - barge hub transfer) and a set of regular barges for hinterland transfer. Here despite the huge number of handling points and transporter types, the whole hinterland transportation process can conclude within 39 transporters which is 20% better than the benchmark. The super barges(3) are 700% lower than the benchmark case. For the short-medium term case, the last two legs seen in the short-term case (barge +truck) are replaced by the AAGV. While the overall fleet size goes up to 45, it comes with the advantage of being 10 hours faster overall compared to the previous short-term scenario. This also becomes a very good candidate if fleet reduction is the only bar. The next solution, i.e. the medium term solution sees a fleet size of 64 against the benchmark 48. This rise in fleet size is predominantly due to the AAGV container transfer from deep-sea terminal to the floating terminal. Again a question could be asked on whether AAGVs are useful, after-all 40 out of 64 transporters are AAGVs but as will be seen later 8.3.1, AAGVs are more productive than trucks. The increase in fleet is due to the distance between floating terminal and deep-sea terminal. The long-term solutions involve a combination of transshipment concepts and since this focuses on maximum barge reduction, it shoots up the fleet size to 61. Also by analysing the throughput and time, it is clear that despite the large fleet size, it cannot match the existing benchmark despite lower sea-going congestion. The final chain solution(3 berths at FT) gives a fleet size of 39 and matches with some of the earlier solutions. This solution can also be seen as reliable since it has given competitive figures for transport time and throughput as well.

1. **Best Performing Solutions**- Short-Term Solution, Short-Medium Term Solutions, Final Chain Solution(3 Berths).
2. **Worst Performing Solution**-Medium Term Solution, Long- Term Solution 1
3. **Promising/Realistic Solution**- Final Chain Solution(3 Berths FT).

7.1.5. Inferences from General Results

The comparison of general results showed us a variety of results that can be looked at from a critical and financial stand-point. If investment is the concern then the long-term solution would be the one that needs the most investment while short-term/short-medium-term solution would need low investment. If time-line is the concern then again short-term/short-medium-term solutions could be considered. For congestion, transport time, throughput and fleet, there are a variety of solutions that meets requirements.

The best solutions that were common among all the key performance indicators are the Final chain (3 berth FT) solution and the short-medium term solution. Final-Chain solution is chosen purely in terms of performance while short-medium-term is a low-cost solution that can be applied across a variety of ports. Since this research focuses predominantly on performance, **the final chain solution will be the subject of experiments and cases studied henceforth**, with due comparisons being made with the benchmark case.

7.2. Experiment Based Results

As stated earlier the experiment is performed for only the benchmark and the best-performing solution which is the final chain solution.

7.2.1. Modal Split Experiment

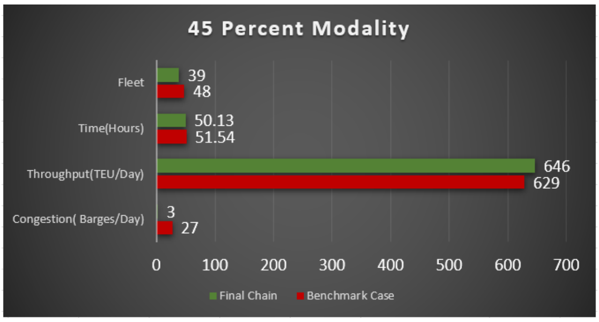


Figure 7.3: Modal Split Experiment-45%

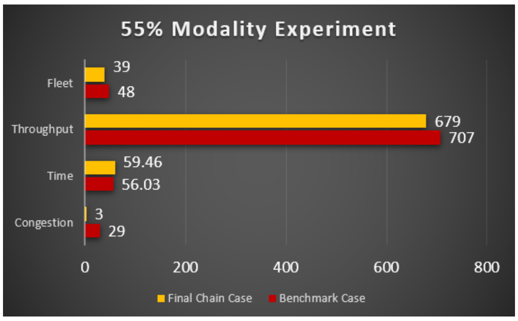


Figure 7.4: Modal Experiment- 55%

The modal split experiment scaled up the use of barges as the choice of transportation for the hinterland. This experiment was performed in Port of Rotterdam simulation conditions where in the demand was raised to 1350 TEU/Day for 45% modality and to 1650 TEU for 55% modality to the hinterland from the existing 1050 TEU/Day[76]. The immediate observations here are that the overall fleet size has been reduced by 18% in both cases from 48 to 39 transporters. While the fleet trade-offs will be delineated in the discussion section, the fleet massively reduces the use of regular barges by replacing them with Super Barges. Both the fleet and congestion therefore see a decrease of 700% in throughput. As will be seen later8.3.1, Amphibious AGVs(fleet of 36) have better productivity with increasing distance and demand compared to trucks. In both tests AAGV transfer time is either better or matches truck transfer but when distance is taken in to account, it is more productive.From a transport time and throughput stand-point, the final chain solution comes on top for the 45% modality but fails for the 55% modality experiment. This is primarily due to the combined time loss experienced in transferring containers from the deep sea terminal to the floating terminal via AAGVs as well as Super Barges to the hinterland. Here, for the same fleet of AAGVs and Super Bargesused, the demand of containers exceeds the transfer time capability for the 55% modality case. The time subsequently has an impact on the possible throughput rate of the experiment. Operators essentially can afford to add more AAGVs to improve productivity and throughput rate. In the case of Super Barges, adding to the existing fleet is not practical since number of berths at floating terminal is limited. Also to note, since these numbers are taken on an average, here 700 TEU capacity barges might be more applicable. Ideally if the floating terminal is closer to the deep sea terminal then consistently better transfer times can be obtained.

7.2.2. Hinterland Share Experiment

Every port has both Containers bound for hinterland and container bound for other terminals. It is anticipated that in the near future, waterways will be used more to boost domestic trade[43]. 2030 projections [81] push the share of Hinterland transport to 70% from the current 60%. This experiment trialed both 70% and 80% scenarios. Similar to other cases, congestion of barges along the Deep Sea-Inland Waterway network is massively reduced. This ranges between a 700% to 800% reduction along the network.Since there isn't a big difference in demand in both tests (1225 TEU vs 1400 TEU), the transfer rates are similar.

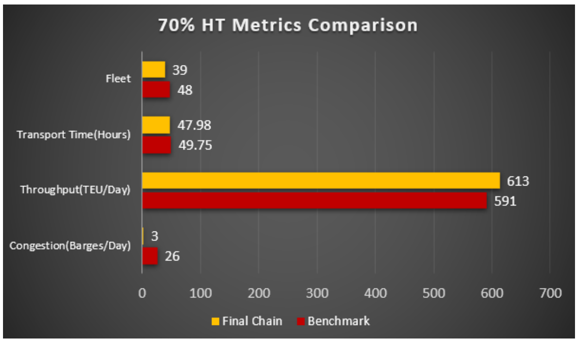


Figure 7.5: hinterland Share Experiment-70%

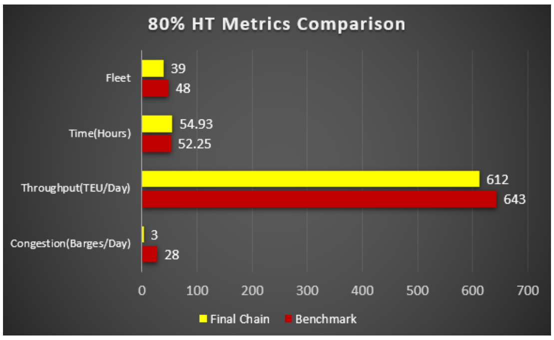


Figure 7.6: Hinterland Share Experiment-80%

Similar to previous experiment, the throughput and time for final-chain solution prevails for the lower demand(70% test) while the benchmark is better for the 80% test. Here the contradiction predominantly arises in the AAGV performance . For the 70% test, the swift deep sea terminal to Floating terminal container transfer is the reason for the faster performance. The same DST-FT transfer is the reason for the slower transfer time in 80% case. This anomaly can be explained by the fact that for the 80% case the ITT(Inter terminal transfer) bound containers from the floating terminal are lower, therefore the utilization of the AAGV itself decreases. Alternatively the number of floating terminal transfers from deep sea terminal also increase adding to Ideathe overall slower AAGV system performance. The tests still show a better distance to containers transferred ratio for AAGVs compared to trucks. The fleet sizes remain the same. The inference here is very similar to previous experiment and recommends upscaling of AAGV and super barge fleet sizes. Furthermore, a closer floating terminal location can be considered like previously mentioned.

7.2.3. Berth/Demand Experiment

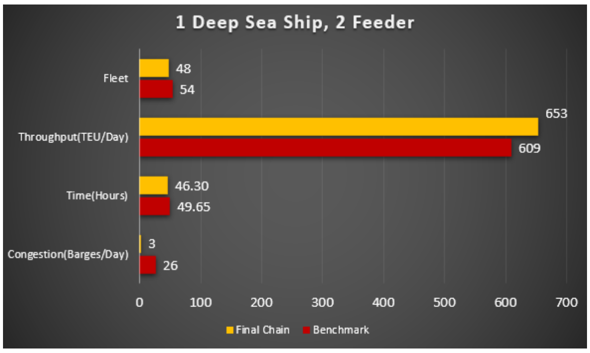


Figure 7.7: Berth Demand Experiment- 1 DSV 2 Feeder

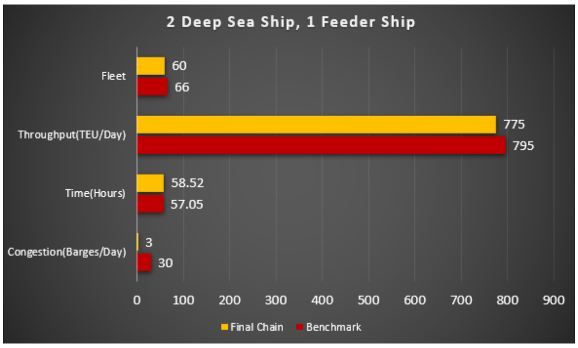


Figure 7.8: Berth Demand Experiment- 2 DSV 1 Feeder

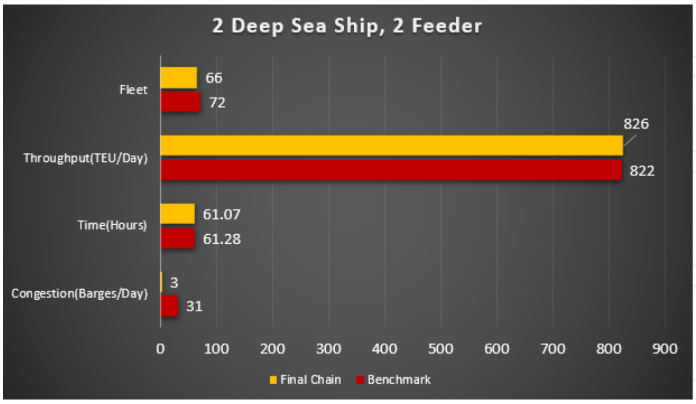


Figure 7.9: Berth Demand Experiment- 2 DSV 2 Feeder

The Berth demand experiment is one that is realistically possible in the near future. Even if hinterland shares or modality do not change, berths and demands will change as terminals undergo expansion. As indicated from earlier sections, this is an experiment on APM Terminals' expanded berth configurations which is set to be in effect by 2026[5]. Therefore demand for the hinterland range from 1260 TEU all the way to 2100 TEU depending on how the berths are used for feeders and deep sea vessels. The previously used barge berths can now be used for deep-sea vessels or feeders. But in this case, to simulate realistic operations, the barge berths are occupied by only one feeder vessel. Congestion still stands at 3 super barges/day, albeit due to higher demand, the super barges would most likely be fully loaded compared to previous low-demand cases. This is still better than the 31 Ships/Day recorded in benchmark. A major consistency observed here is that in all cases, the predominant contributor to lower throughput rate/higher transfer time are the Super barges which take longer than expected transfer times to move containers to the hinterland. This directly implies that AAGVs are the reason for overall competitive times. When the data is looked at, it is clear that AAGVs in some cases have a completion time that is 3 hours faster than trucks. The insight here is that AAGVs can work better than trucks when demands are larger. Coming back to the Super barges, a reason for the slow transfer time could be due to the lack of extra berths at the Floating terminal. An extra berth or extra serving Quay cranes can either accommodate more ships or dispatch existing ships faster. Therefore a recommendation would be to use the large scale floating terminal design3.6 post the expansion in 2026 at APM-Terminals. In terms of fleet size, final chain solution still records lower fleet sizes compared to benchmark cases. Also due to high utilisation rates of Super Barges, 6 Super barges must be inducted into the fleet for the maximum load case(2 DSV 2 Feeder), so one barge is in process while other is loaded.

7.2.4. Special Case

The special case is a maximum demand worse-case scenario where maximum modality(55%), maximum hinterland(80%) share and maximum berth demand are applied in one full case. This is essentially a worse-case scenario simulating worst possible demand.For reference, this special case still uses the small- scale floating terminal, which will be crucial in understanding the limits of the equipment used. Similarly,for the benchmark case, number of berths still remains the same. The results for this experiment are very interesting. In benchmark cases, the deep sea terminal sees a footfall of 36 barges a day which is 12 barges per berth. Theoretically, if you allow 2 hours for a barge to unload,load and depart then 36 barges per day is the absolute limit of what the deep sea terminal can handle. Similarly, upon studying the floating terminal, it can be realised that even tho it sees a congestion of only 4 super barges/day, it is still on the edge in terms of time. Furthermore when the discussion shifts to time and transport rate, then the berth limitations of the floating terminal become more evident. Hence, it can be seen that the transfer times for the proposed final chain solution are almost a day more than the benchmark(90.21 hrs v 111.39 hrs). The takeaway for deep sea terminal operators is that if this demand of 4400 TEU becomes a reality, then it is almost impossible to continue operations with the current transshipment scenario(benchmark). Furthermore in order to realise the full impact of the final chain solution,then one would need to use a large-scale floating terminal(3.6) for this level of demand.

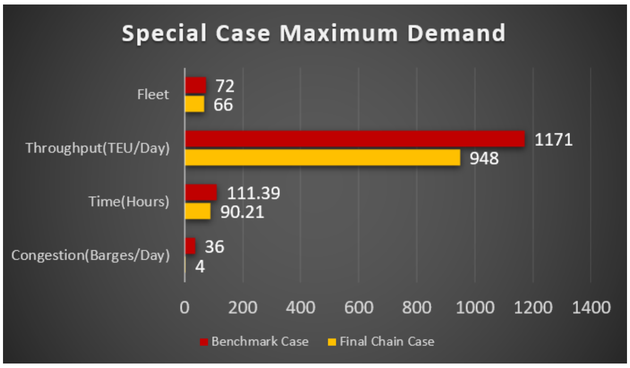


Figure 7.10: Special Case Experiment

7.3. Case Study: Hong Kong- China Pearl River Delta

One of the main objectives of this research was to make solutions that are globally applicable in any context. In order to simulate the performance of the proposed solution, the Hong Kong- China Pearl River Delta will be studied. This network faces 6 times the demand faced in Rotterdam.

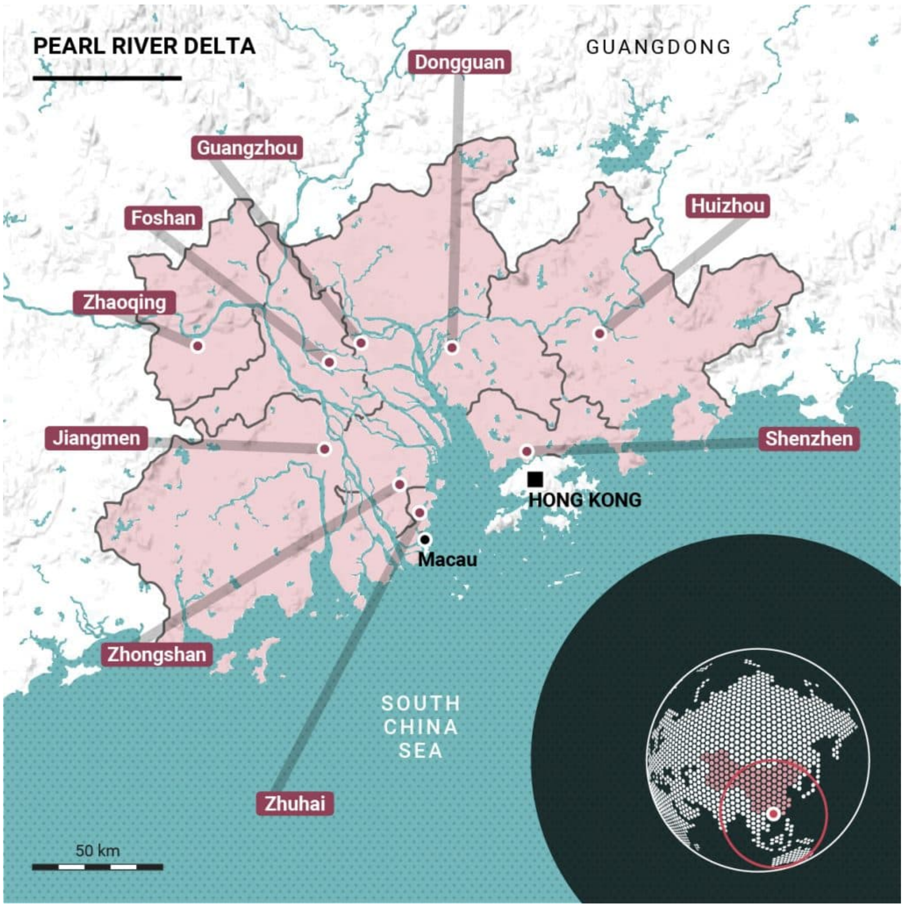
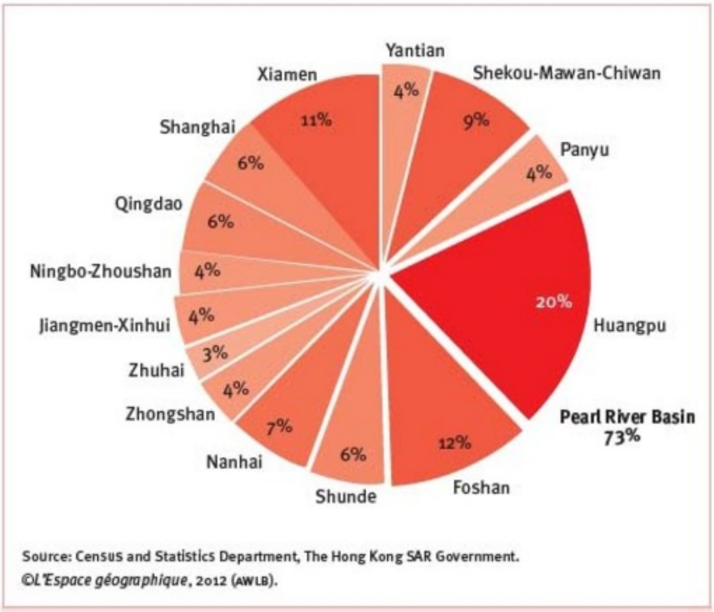


Figure 7.11: Overview of the Hong Kong-Pearl River Delta[95]

The Pearl River Delta is one of the most interesting inland waterway networks in the world. It is so extensive that its area covers a size a footprint comparable to the Netherlands. Of the 14000 Km stretch, 5000km connects the southwest region through the extensive inland waterway network of barges[92]. The main transshipment ports here are Hong Kong, Guangzhou and Shenzhen. From an international transshipment point of view,Hong Kong is a more interesting port owing to the extensive connections it holds to ports further south like Port Klang in Malaysia, Port of Singapore and Up north to Port of

Busan in South Korea and Port of Taiwan.

To expand upon the aforementioned economic significance of the pearl-river Delta, it is made up of 9 major cities in the Guangdong province, namely the cities of Guangzhou,Shenzhen, Foshan, Zhuhai,Jiangmeng, Zhongshan, Huizhou and Zhaoqing.In conjunction with Hong Kong SAR and Macao SAR forms the greater PRD[91],the 57 million population in PRD contribute to 18% of the nation's output.



Source: Census and Statistics Department, The Hong Kong SAR Government.
©L'Espace géographique, 2012 (AWLB).

Figure 7.12: Overview of the Hong Kong-Pearl River Delta[91]

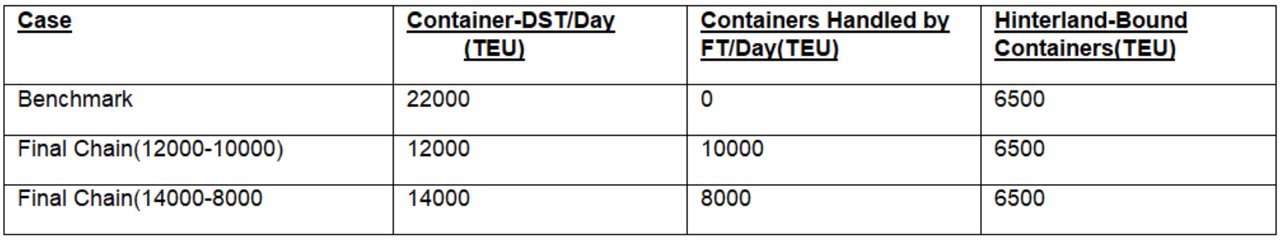
Also for context, the pearl-river basin forms 73% of the total inward transshipment in Hong Kong as depicted in figure 7.12[32]. Post the 1980 Chinese reform, coastal ports gradually became more prevalent in using hub and spoke operation techniques with Port of Hong Kong. Despite this,the lack of funding for Inland Waterway transport led to a major drop in IWT from 26% to 5% from 1980-2000[95]. Post this period, with rising demand and need for sustainability, barge transport is again on the rebound gaining 10% of the transport market. With this new shift in IWT policy, Hong Kong is facing calls for expansion in both barge handling and transshipment services[69]. There is also an added pressure from the local population to dismantle container services of some Container Terminals at the current deep-sea port owing to the raging housing crisis in Hong Kong. While the Government has ruled out such adverse actions in medium term[35],it also calls for a new perspective in transportation strategy for the Hong Kong- Pearl River Delta.

7.3.1. Hong Kong Ports

The Hong Kong port is located in the South China Sea and comprises a river port and a deep water port. The deep water port, commonly known as the Kwai Tsing Terminals receives an average of 36000 TEU Per Day[32] from International Ports like Port Klang, Singapore, Busan in South/Southeast Asia while European ports like Rotterdam,Hamburg and Antwerp also contribute to the Port traffic. There are a total of 9 container terminals which handle up to 24 million TEU annually. These 9 container terminals are operated by 5 major players namely- Hutchinson International Terminals,Modern Terminals, COSCO, DP World and Asia Container Terminals Limited. Owing to the Covid pandemic, traffic at Hong Kong port has declined to 12.869 million TEU in 2022[32]. For this research HIT and COSCO-HIT terminals will be considered. They operate Container Terminal 9S(Left of image, berth in green), Container Terminals 4,6,7 and 8 which are all marked in green in figure 7.13. The barge berths spread across terminals 4 and 6 are shown in red. Terminals 4 and 6 combined house 9 such barge, berths[88]. HIT and COSCO handled a peak of almost 6500 TEU per day in 2016 with 120 barges making footfall on a daily basis[85]. In order to make the process faster, HIT and COSCO use 2 Barge/Quay cranes per barge to load and unload. Looking at current split between transshipment and PRD containers, calculations estimate the overall number of container throughput of HIT/COSO as 22000 TEU per Day. The terminals see 15-18 vessels make footfall per day. These are a mix of feeder/feedermax vessels, panamax and ultra-large container ships(ULCS).

Figure 7.13: Overview of berths and locations[30]

The floating terminal is located in the region marked in yellow. This will use the large scale floating terminal design (3.6), which has a 1km with a theoretical handling capacity of 2.52 million - 4.2 million TEU annually. T**he berth configurations will be exactly used as shown in figure 3.6**. Among the 17 ships that dock at HIT-COSCO for benchmark case, 11 of them are either feeder or feedermax vessels. Going by the methodology of the final chain case, the feeder/feedermax vessel traffic can be shifted to the floating terminal. Three RMG cranes per feedermax vessel will be used to unload and load containers. Owing to the length of these ships, realistically 3 feedermax ships, 3 Super Barges and 5 AAGVs can be accommodated at once in the floating terminal. The other simulation conditions are akin to Rotterdam's environment.Since there is a shift in traffic from deep sea terminal to the floating terminal, the Floating terminal was run in two different contributions.



Case	**Container-DST/Day (TEU)**	**Containers Handled by FT/Day(TEU)**	**Hinterland-Bound Containers(TEU)**
Benchmark	22000	0	6500
Final Chain(12000-10000)	12000	10000	6500
Final Chain(14000-8000	14000	8000	6500

Figure 7.14: Floating Terminal- Deep Sea Terminal- Inland Container Distribution

Evident from the aforementioned figure, two scenarios were tested where the floating terminal handled 10000 TEU and 8000 TEU /day respectively.

7.3.2. Inland Ports in Pearl River Delta

There are a number of inland ports across 9 cities in the Guangdong greater-bay area province. China as a country consists of 34 major ports and 2000 inland ports[26] For the purpose of simulation, 7 such ports have been chosen that have significance in both hinterland penetration and also transshipment capability. They have been represented in figure 7.15. Ports such as Yantian and Shekou are also deep water ports which have connections to Shenzhen and Shanghai. Other ports like Sanshui,Jiangmeng and Foshan are key drivers in the automotive,plastics and transportation industry, therefore play an important role[91].

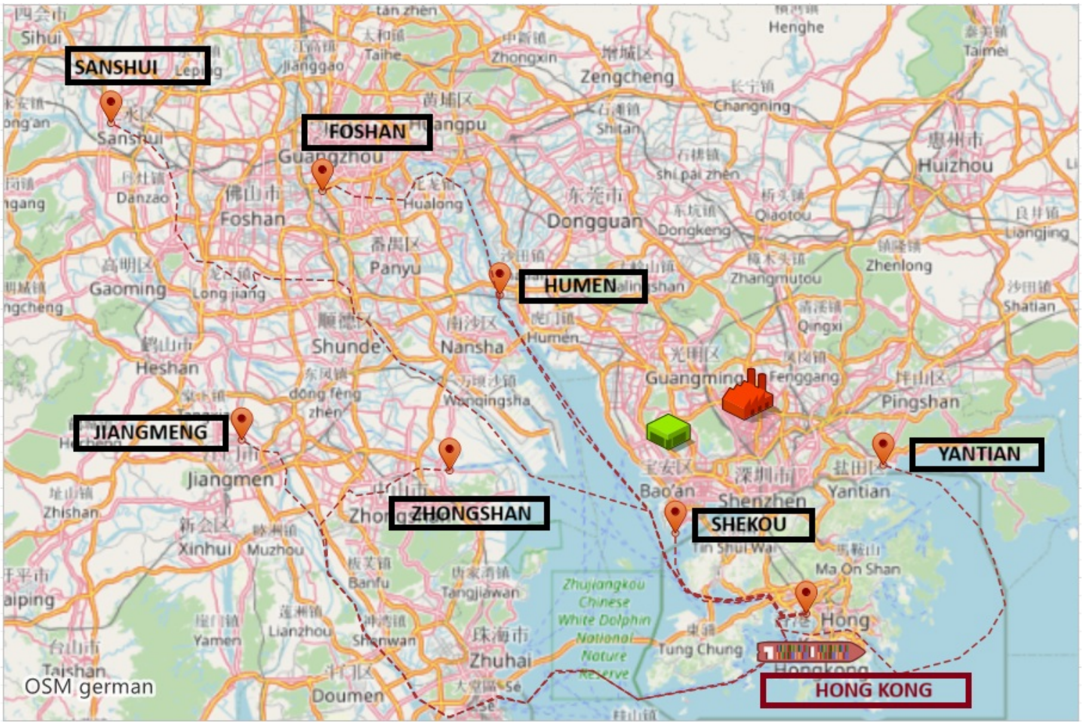


Figure 7.15: Inland Ports and Terminals[2]

7.3.3. Simulation Results and Analysis

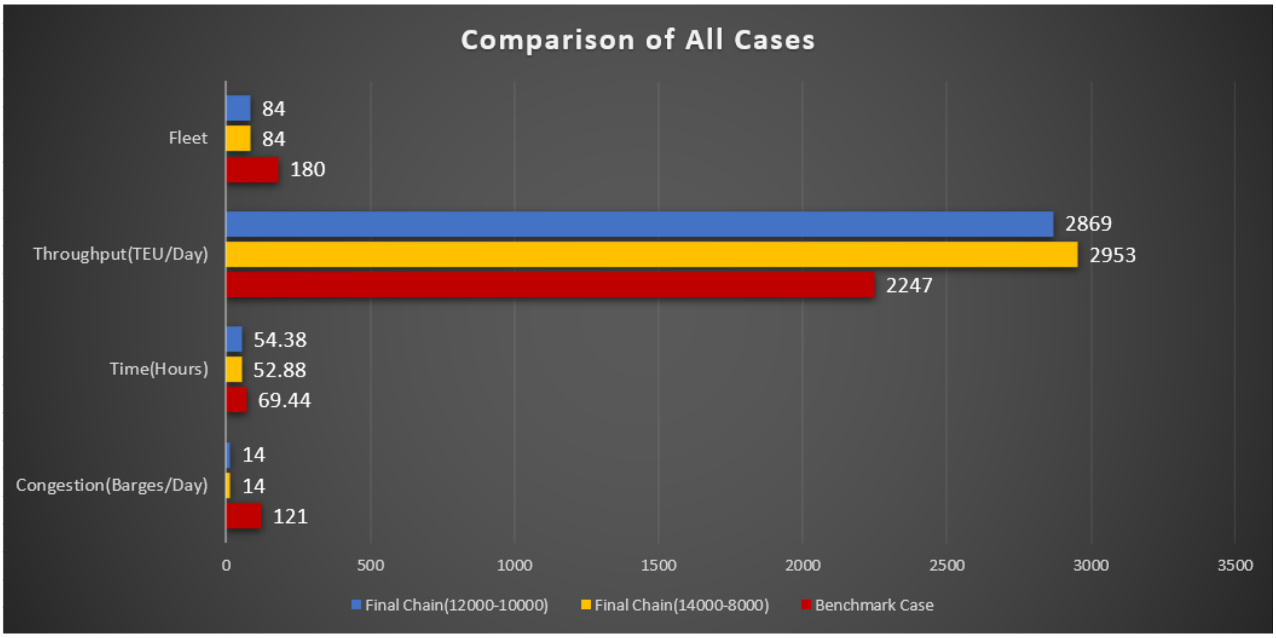


Figure 7.16: Hong Kong- Comparison of all metrics

The Hong Kong -Pearl River Delta represented an interesting array of results for different KPIs. It is quickly clear from the results that when the whole final chain solution is scaled up, the performance amplifies drastically. For context, when we compare this to the Special case experiment, it is evident that the use of a small-scale floating terminal design(3.5) hampered the overall performance. Coming back to this,the benchmark case presents the reader with some crucial insights. The simulation output of 121 barges/day congestion correlates with the terminal established data[85]. In terms of throughput, when truck travel, barge transport and other transportation components are taken into account, a maximum container transfer rate of 2247TEU/Day to the inland ports. Due to varying distances of the inland ports from Hong-Kong, each hinterland terminal receives a different number of ships and containers per day.It has to be kept in mind that also here the call size of each barge is assumed to be 50 TEU. This assumption comes close to the terminal data(6500TEU/120Barges =54 TEU/Barge)[85]. On an average the benchmark takes around 69 hours to transport the entire consignment of 6500TEU to the inland terminals. With more ports in the real world, this transfer process could take much longer. When it comes to the fleet, 126 barges and 54 trucks are required to accomplish this process, adding up to a total transporter size of 180. The deep sea terminal handles 22000 TEU as mentioned before

The final chain solution was implemented with two different configurations in mind. The first case, which handles 8000TEU at the floating terminal(DST-14000) and second case which handles 10000 TEU at the floating terminal(DST-12000). Jumping into the results, it is clear that this solution excels for all KPIs. Employing large call sizes in super barges have reduced the congestion from 121 barges/day to just 14 super barges/day. Unlike Rotterdam, it would make sense to use high call sizes such as 700 TEU in the Hong Kong-Pearl River Delta due to the multiple trips that are made on a daily basis from the Hong-Kong port to the same inland port. The lower congestion has also lead to a substantial decrease in fleet size from 180 transporters to just 84 transporters. These 84 consist of 14 Super Barges and 70 AAGVs, It is also prudent to note that one of the limitations in Rotterdam cases has been solved. The floating terminal is located much closer to the set of deep sea terminals. This contributes to a total transfer time between 52.8 to 54.4 hours which is 23-25% improvement in total transfer times. It was also noticed that the fleet of AAGVs transferred the same set of containers in 31-33 hours while the benchmark took 43 hours to accomplish the same which is a 30% improvement. The productivity of the AAGV is much more pronounced when uncertainties like floating terminal distances are eliminated. In terms of throughput, both the final chain configurations are able to transfer 30% more containers in the same time frame as benchmark case. When we compare both the final chain cases themselves, there are negligible differences, These configurations are demonstrated to show the flexibility and effectiveness of concepts like AAGVs and floating terminals.

Variability in number of Ships/Day to each Inland Destination

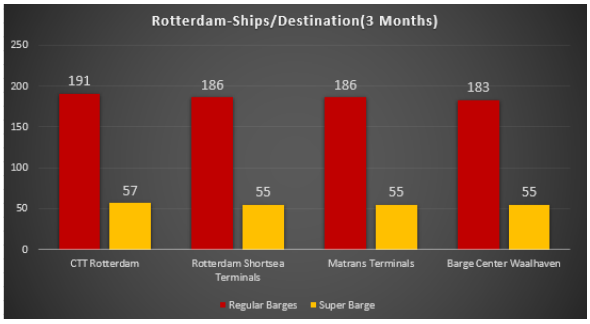


Figure 7.17: Rotterdam Simulation -Barges/Destination(3 Months)

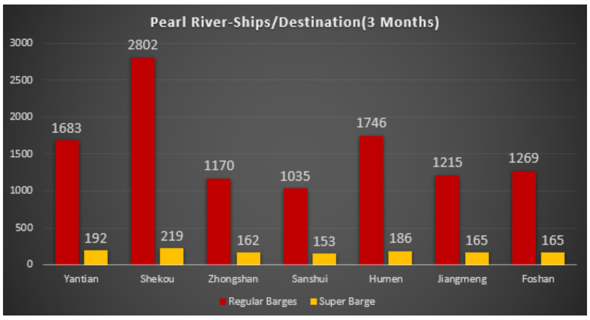


Figure 7.18: Pearl River Delta Simulation-Barges/Destination(3 Months)

A noticeable difference seen between the Rotterdam and Pearl River Delta solutions are the variabilities in barges/destination. It is clear that not all destinations receive the same number of ships or containers per day. In the case of Rotterdam since the hinterland terminals are nearly equidistant from the deep sea terminal, the variabilities in number of ships recorded per destination are minimal regardless of whether it is Super Barge or Regular barge. However when the same is looked at Pearl-River Delta, shorter the distance from Hong Kong, more the number of barges and containers delivered. The Difference is clear when we see the nearest inland port Shekou and the farthest inland port at Sanshui(2800 vs 1000 for regular barges). The substantial variabilities can also be seen for Super barges as well despite the higher call sizes.Therefore it is prudent to realise that this model works based on distance since demand is set constant in the beginning.

8

Discussion

8.1. Fleet Trade-off- Choice of Transshipment Networks

One of the major contributing factors to congestion is the fleet that is available for use.The graphs given below and 7.2 are to be referred for this section.The fleet trade-off is an important comparative analysis to understand how fleets can be arranged in the future. The benchmark and proposed solutions, along with experiments and the Hong Kong case study, are considered here. As mentioned earlier, the benchmark case employed in Rotterdam uses 24 barges and 24 trucks in the process(7.2). This translates to a 50 percent barge share in the system. For solutions that utilized the Super Barge idea, it can be noticed that the overall congestion on a long-distance waterway route was significantly reduced from 24 barges a day to just 3 Super Barges a day. The trade-off here is that some solutions involve multiple handling points in the process, leading to the use of different types of transporters. For instance, the short-medium term scenario uses 3 different types of transporters (truck-super barge-AAGV). This would mean that additional resources would be needed in terms of operations and maintenance. However, this solution ensures a nearly similar fleet size and moves containers 10 hours faster than similar cases, such as the short-term scenario and long-term solutions (42 transporters vs 39 in the short term vs 58 in long term 1). If deep-sea terminal operators are only looking at diverting barge traffic, then the medium-term solution can be considered a candidate. The floating terminal would still employ barges but use AAGVs for deep-sea terminal to floating terminal transfers. This would result in 64 transporters (24 Barges + 40 AAGVs) but essentially would be as fast as benchmark cases. An economic and sustainability analysis would be needed to compare 24 Trucks with 40 AAGVs in the medium-term case, as more fuel and energy will be required for these fleets as well

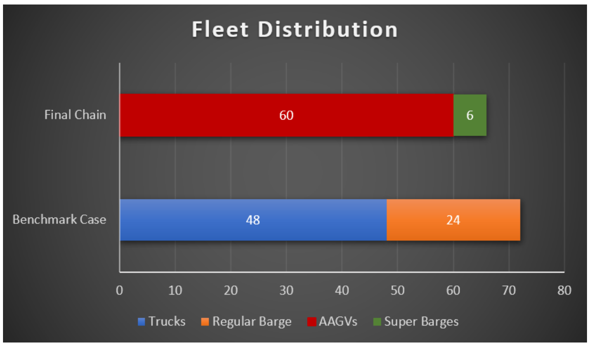


Figure 8.1: Special Case Experiment Fleet

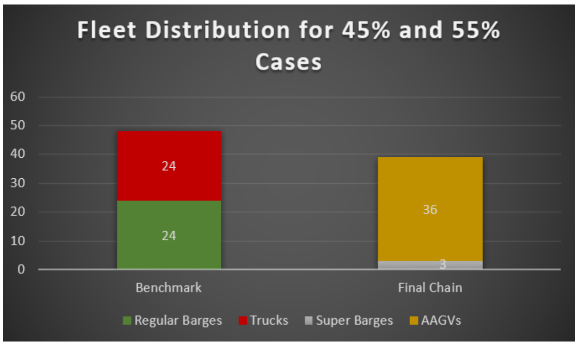


Figure 8.2: Modal Split Experiment Fleet

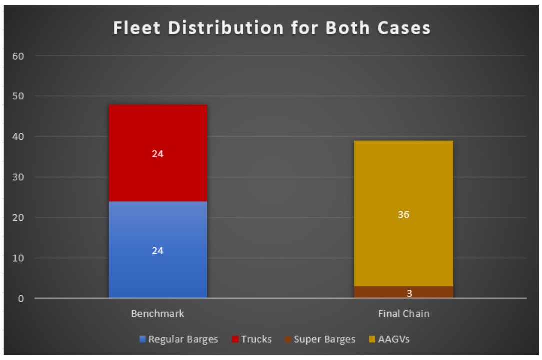


Figure 8.3: Hinterland Share Experiment

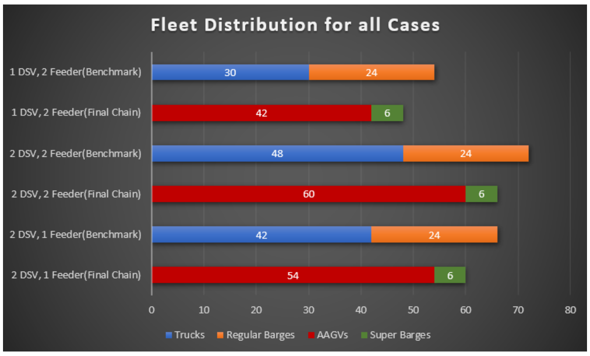


Figure 8.4: Berth Demand Experiment Fleet

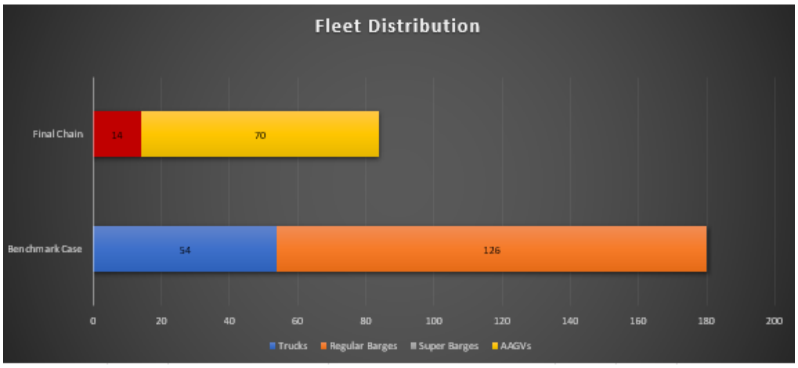


Figure 8.5: Fleet Distribution Hong Kong

The final chain solution also presents a very interesting take. By experimenting with berths for super barges at floating terminals, we can simultaneously increase or decrease berths for AAGVs docking at the floating terminal. This influences the eventual transporter fleets. It is a tradeoff between transporting containers faster on short distances (AAGV berths) versus transporting containers faster on long distances (Super barge berths). Moreover, having more AAGVs would mean faster transport time but more **fuel/energy used in the process, along with higher CAPEX and OPEX**. It is between 39 transporters (3 Super Barge + 36 AAGV) with 3 Super Barge Berths versus 51 transporters (3 Super Barge + 48 AAGV) with 2 Super Barge berths

The case for fleet trade-offs becomes more clear when experiments are looked at in more detail. In the Special case experiment where maximum demand and maximum barge/hinterland share is applied (refer 8.1), fleet size compares between 72 for benchmark versus 66 transporters for the final chain case. The question here is whether it's logical to have 18 extra barges(24 barge vs 6 super barge) or if it is better to have 12 extra AAGVs compared to trucks (48 truck v 60 AAGVs). When we think about utilisation rates, maintenance and fuel needed, then it is definitely economical to have 12 extra AAGVs compared to 18 extra barges. Thats where AAGVs are more efficient and present a better outlook for the long term. As it will be seen later AAGVs are more efficient per km compared to trucks due to their dual land-water mobility. Briefly as we see the Hong Kong case(graph 8.5) it is also clear that the fleets for the benchmark are double that of the final chain. The sheer number of barges (112 v 14 for final chain) highlight the efficiency of both the Super barge and AAGV.

8.2. Congestion v Throughput- Insight for Super Barge Operators

A useful insight for barge operators and ports can be understood by comparing congestion, throughput and container call size of super barges heading to the hinterland. More specifically, the final chain cases are compared here. In the barging industry, there is always a trade-off between the call size of containers heading to a certain terminal, congestion caused on the waterways and terminals, and the throughputs managed by the fleet of barges themselves. These are extremely sensitive metrics due to a few reasons. While higher call sizes are preferable for barges, it must be realized that the uncertainty of fulfillment also increases along with it. A hinterland terminal can never be promised that a barge would bring a high amount of containers every time; this number can be lower as well due to seasonal demands or turbulent events like droughts and pandemics. A lower container call size would essentially ensure more certainty While this is logistically convenient for operators, this comes at a cost of increased fleet sizes,congestion and possibly lesser throughput rates.

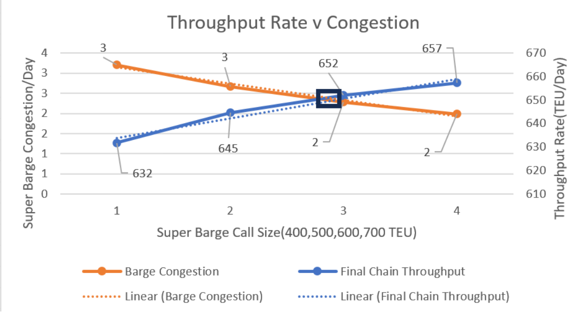


Figure 8.6: Modal Split Experiment - 45% (RTM)

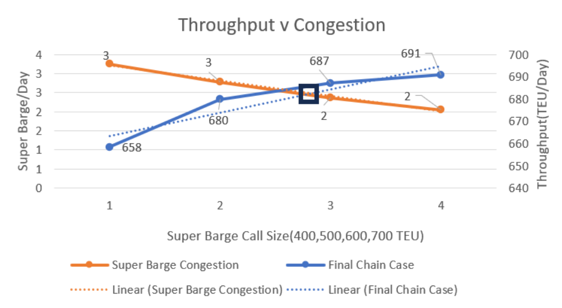


Figure 8.7: Modal Split Experiment - 55% (RTM)

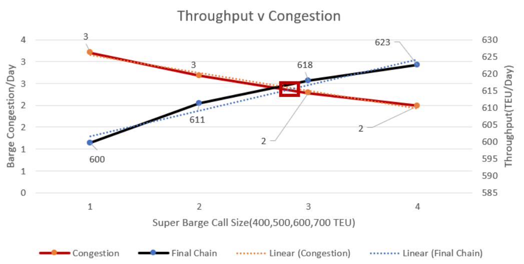


Figure 8.8: Hinterland Share - 70% (RTM)

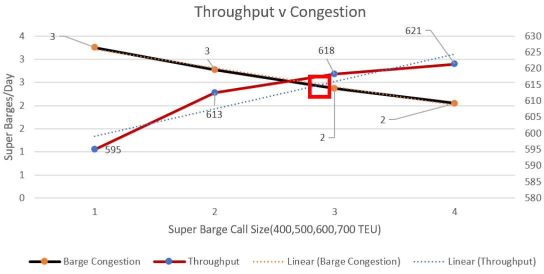


Figure 8.9: Hinterland Share- 80% (RTM)

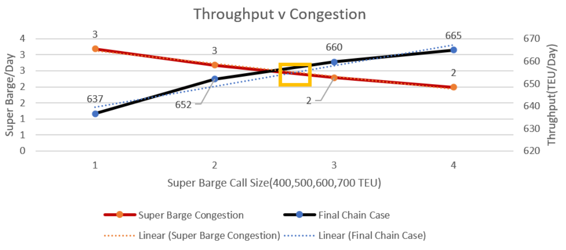


Figure 8.10: Berth Demand- 1 DSV + 2 Feeder(RTM)

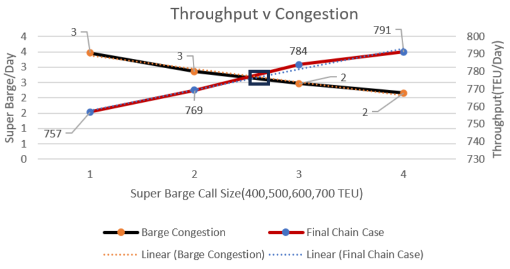


Figure 8.11: Berth Demand- 2 DSV + 1 Feeder(RTM)

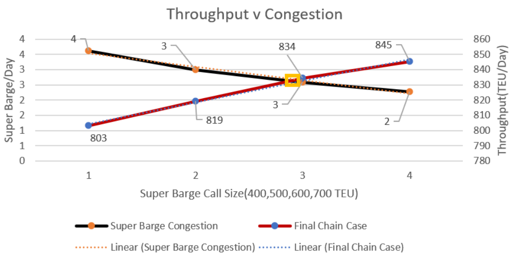


Figure 8.12: Berth Demand- 2 DSV+2 feeder(RTM)

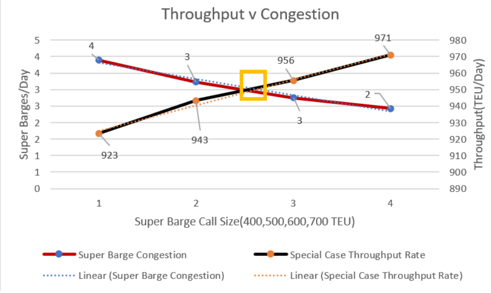


Figure 8.13: Special Case Statistics(RTM)

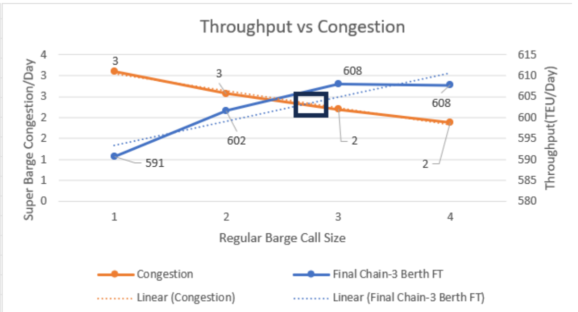


Figure 8.14: Current Demand Results(RTM)

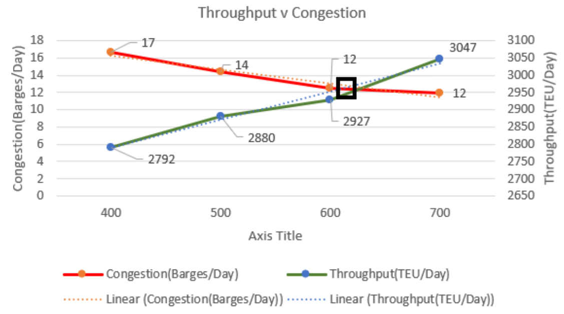


Figure 8.15: Hong Kong Statistics(HKG)

The listed graphs present interesting trade-offs between the aforementioned criteria. It is quickly noticeable that for all cases there exists a sweet spot between throughput, congestion and the preferable call size of the super barge.A point to be noted here is that the sweet spot is found by intersection of the trendlines and not plotted lines. This is indicated by a small black box in all graphs. For all scenarios and cases, super barge call sizes from 400 TEU to 700 TEU(presented as data points 1,2,3,4) were experimented with. Irrespective of the case and experiment, the results of congestion and throughput always gave a call size between 550 and 600 TEU.

With the exception of the current demand graph (8.14), all other cases showed an ascending throughput curve with increasing call sizes. A reason for this anomaly is due to lesser demand. The logic is that in this case there is a requirement of only 1050 TEU a day (for 4 terminals together),here it would not make any sense to send a 700 TEU call size due to the lower demand. Therefore it can be seen here that a 700 TEU and 600 TEU call size barge would practically give us the same throughput results and similar congestion levels as well. Another important point to discuss here is the practicality of these call sizes from a hinterland terminal operator persepctive. While the graph for current demand (8.14) gives a sweet spot of a 580 TEU call size at a congestion rate of around 2-3 Super barges/day, it might be more practical to have a lower call size such as 400 TEU. This is because when the demand itself is only 1050 TEU for 4 terminals, 400 TEU is ideally above the equal division of containers (1050/4 = 262.5). This call size can ensure regular supply of containers to each of the hinterland terminals and ensure reduced.If hinterland terminals are however only concerned about container delivery over a period of time (100 days or more) and not daily, then higher call sizes on these barges can be instrumental in that. It is advantageous in time but risks arise as deep-sea ships are prone to late arrivals at deep-sea terminals and AAGV fleets are also limited for floating terminal transfers. This would possibly bottleneck the whole process. This is however only for low demands

Contrary to this,the biggest impact of an increasing barge call size affecting the overall throughout is in the Hong Kong case(8.15) where throughputs range from 2790 TEU(Barge call size- 400 TEU) to 3050 TEU(Barge Call size-700TEU).There is also a noticeable reduction in congestion from 17 Super Barges/Day to 12 Super Barges/Day. Here the sweet spot of call size is at about 620 TEU. Since the demand for containers on a daily basis is 6500 TEU to 7 different hinterland ports in the pearl river-delta, it is sensible to use maximum call sizes here. Another motivation here also comes from the reduction in barge congestion on a daily basis which prompts networks like the Hong Kong- Pearl river Delta to use larger call-size barges. The idea of super barges in the future can involve a lot of implications on policy and viability and this will be discussed in future section.

8.3. The Case for Amphibious AGVs- Advantages & Opportunities

Amphibious AGVs have been one of the major innovation points in this research. They bring massive versatility through mobility on both water and land. The role of Amphibious AGVs is two-fold. One is to reduce the double handling of containers in the system. The second benefit is to access any location by utilising both land and water modes. In essence AAGVs are instrumental in diverting traffic either from terminals(like deep sea terminals) or reducing rehandling points in the transportation setup. Therefore it is essential to understand how they would fare in a transshipment process. The main concerns here are how the fleet compares with the number of trips recorded and it's correlation with distance covered.

8.3.1. Inventory Angle

From the previous sections, it has been made clear that for the best solutions, the time-consuming aspect is definitely the AAGV transport. This can be visualised by the number of trips,AAGVs can perform compared to a fleet of trucks. For instance when we look at graph 8.16, the benchmark case completes 473 trips per day with a fleet of 24 trucks. The final chain solution which has been seen as an optimum solution gives an output of 452 AAGV trips and 498 Trips per day(for 3 berth and 2 berth Floating terminal configurations. While there is a winner in terms of trips completed, this comes at a cost of reduced berths for super barges and feeders at the floating terminal. Reduced barge/feeder berth would mean that more containers from deep-sea terminals would pile up on the floating terminal and clog the system. The floating terminal aims to have a lean container inventory with less work in process containers. Also fleets of 48(498 trips/day) and 36(452 trips/day) have been recorded. Ideally a 3 berths solution would ensure a lesser fleet of AAGVs and with better transport time prospects given the fact that more ships would transfer containers faster to the hinterland.

AAGV V Truck V Distance

Referring to the same graph 8.16, initially it shows that trucks have the ability to do more container trips a day compared to the AAGV as this pattern is consistent for all experiments and the Hong Kong Case(8.17 and 8.18). The AAGV fleet numbers also do not seem to be competitive. But however when the distance of each trip is considered, it is clear that AAGVs have more distance to cover to floating terminals when compared to trucks that engage in berth to berth transfers. The argument then shifts in favour of AAGVs. For instance when we consider the Berth Demand experiment in graphs (8.17 and 8.18), the trip rates of truck and AAGV are 873 and 813 trips respectively at 48 trucks and 60 AAGV respectively. A round trip for truck and AAGV are 4km and 8km respectively. Twice the distance for AAGVs does not translate into twice the fleet compared to trucks(48 v 60). Similarly, even with a higher speed(40% faster), trucks are only 7% faster in terms of trips completed in a day. This becomes clearer looking at the Hong Kong case where AAGVs perform competitively despite having to cover nearly 5 times the distance a truck has to cover. The number of trips completed in a day is also much higher for AAGVs(2511/day) compared to trucks(1788/Day). Therefore an inference here is that AAGVs perform better when demand is higher. Even in terms of fleet, an AAGV fleet of 70 in the Hong Kong Case against a truck fleet of 54 is advantageous considering the larger distance.

8.3.2. Implications on Floating Terminal

The above insights also suggest that if floating terminals are located closer to deep sea terminals, the fleet rates can be lower than current computations, or conversely, more AAGV trips can be completed within the same fleet size. This would give AAGV better productivity compared to a similar fleet of trucks. Floating terminals however have to be located for the convenience of not only one terminal but all deep-sea terminals in the vicinity without hampering existing operations.

8.3.3. AAGV impact on double/multi-handling procedures

The AAGV was envisaged as a tool for quick transfer as well as preventing double handling of containers. When two of the initial solutions 5.2 and **??** are considered, an immediate difference is the reduction in transport time in the short-medium case by 10 hours compared to the short term case.This is because the last two transfer legs(truck+barge) of the short-term case(5.2) are now replaced by a single AAGV leg. This has therefore seen the replacement of 6 barges and 6 trucks with 18 AAGVs which are faster compared to the double hassle. This is another proof of how AAGVs conserve transport time in the process. While these two specific cases were not efficient in transport time or throughput, it gives this research some valuable insights on how to go about with AAGVs in its implementation for both hinterland and deep-sea terminals.

8.4. Floating Terminals For Transshipment- Growth Potential & Scalability

Among the many transhipment concepts considered in this work, floating terminals are instrumental in diverting the majority of the hinterland traffic away from deep-sea terminals. While it plays a role in achieving a major goal of this work, it also enables greater throughputs at deep-sea container terminals itself

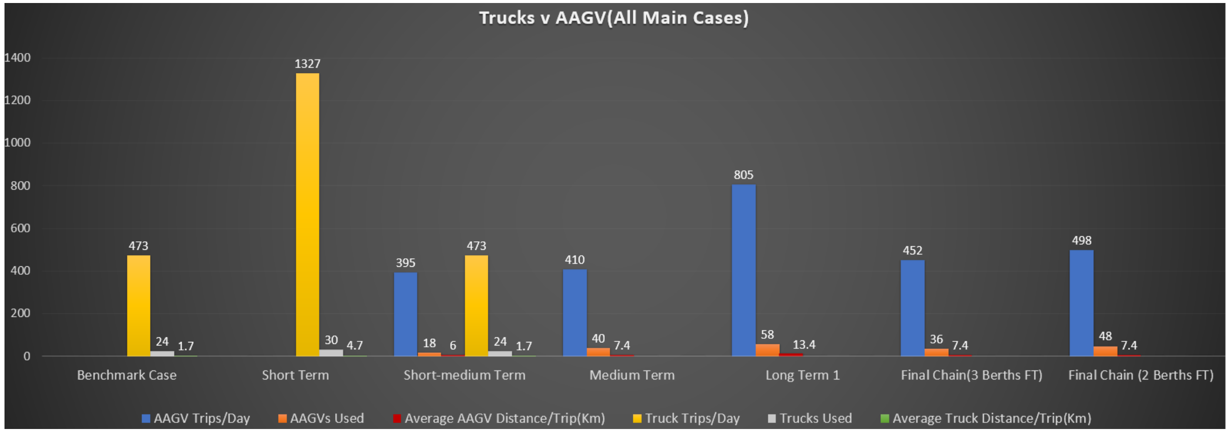


Figure 8.16: Truck Performance with Distance- Experiments and Case Studies

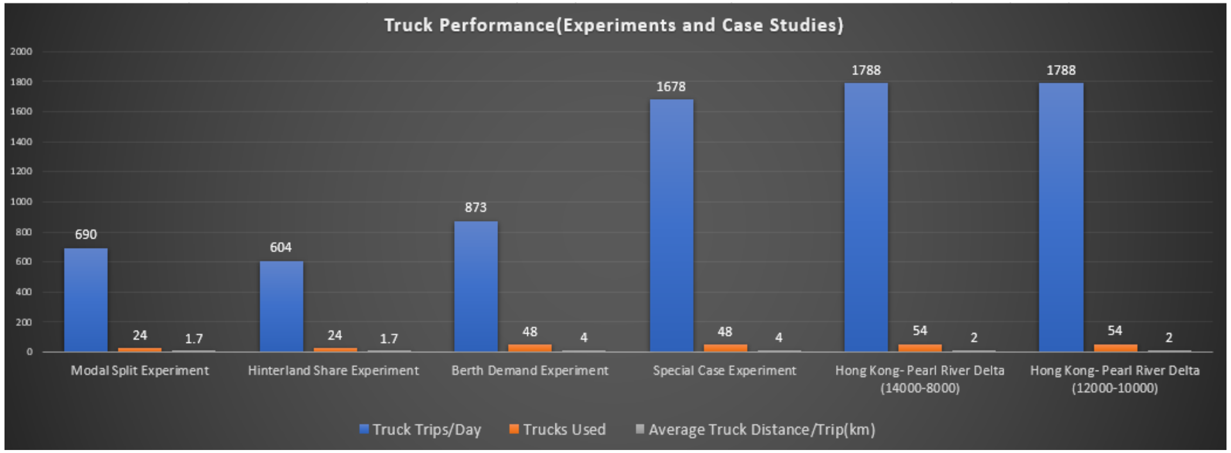


Figure 8.17: Truck Performance with Distance- Experiments and Case Studies

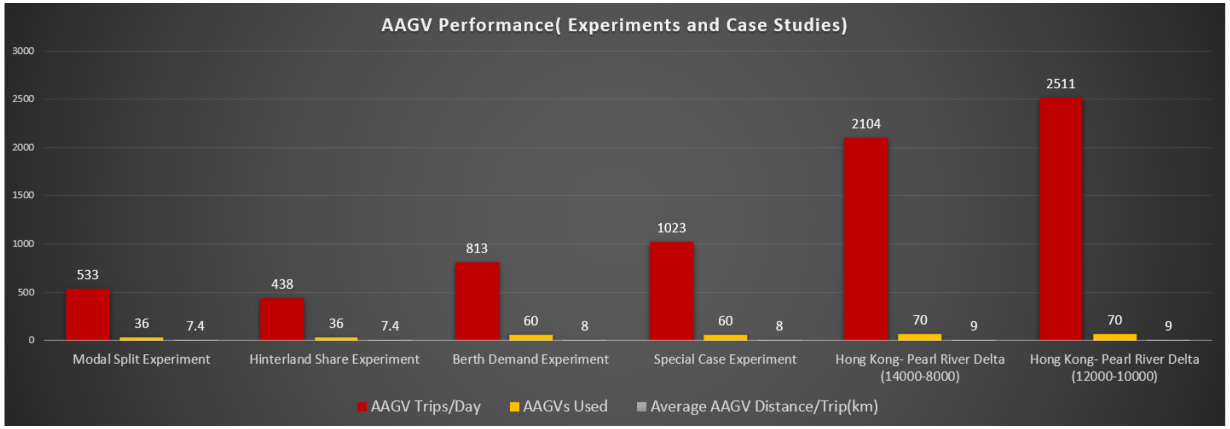


Figure 8.18: AAGV Performance with Distance- Experiments and Case Studies

Floating Terminal Implications on Deep Sea Terminal Growth

Among the many transhipment concepts considered in this work, floating terminals are instrumental in diverting the majority of the hinterland traffic away from deep-sea terminals. While it plays a role in achieving a major goal of this work, it also enables greater throughputs at deep-sea container terminals itself. Due to the diversion of super barges to floating terminals, barge berths at deep sea terminals are now free and in terminals like APM-T Rotterdam, the barge quay alone is 500m. This is enough to occupy either an **Ultra large container ship (ULCS)(18000TEU+,399m**) or allow **2 berths for Feeder Vessels (1000TEU+)**. Furthermore, extra berths at the Floating Terminals help accommodate Feeder/Feedermax vessels.Profound impacts can be seen especially in the case of Rotterdam's APM Terminal throughputs. When the berth demand experiments were performed (7.2.3), it was seen that even with the current non-expanded terminal layout, the new final chain configuration boosts the throughput by 1.2-2 million TEU/Year(1.825 v 2.9/3.6) within the same canvas. When APM terminals is considered with its expanded layout, we can see potential for **2 deep sea ships and 2 feeders** a day with current methods accounting for 10000TEU/Day or 3.65 million TEU/Year. However owing to the floating terminal, the barge berths can occupy a deep sea vessel pushing its maximum container throughput per year to 5.48 million TEU. Depending on the case considered, this is a 30-100% growth potential for APM-T thanks to creating deep sea berths (due to diverting hinterland traffic to Floating Terminal). This traffic diversion creates an opportunity for at least 3 extra feeders or a combination of 2 feeder vessels and a ULCS vessel.

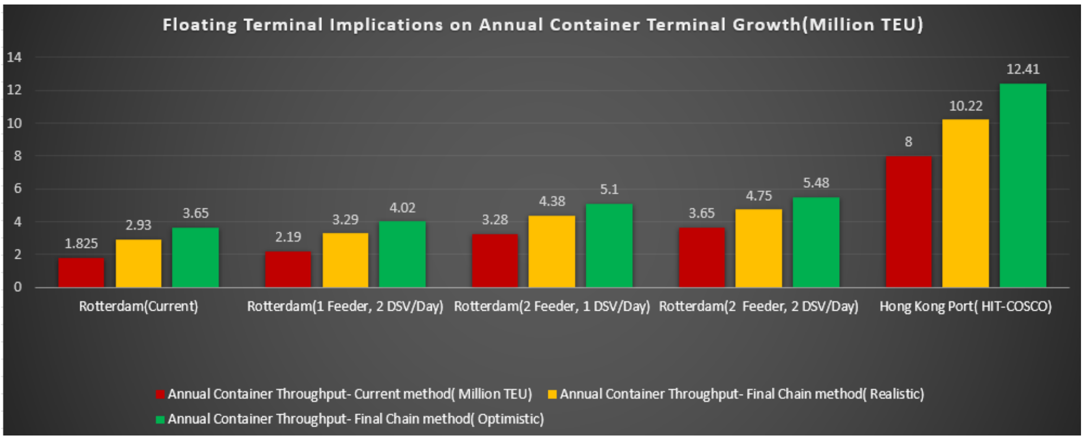


Figure 8.19: Effect of Diverting Barge Traffic on Deep Sea Terminal Growth

A major assumption here is that the Yard-side operations will be able to handle the extra footfall of feeders and deep sea vessels due to the newly created berths. When the same in Hong Kong is considered, the effect of floating terminal is more pronounced due to the large scale of operations. A large-scale floating terminal (refer figure 3.6 would enable the diversion of atleast 6 feedermax vessels from the Kwai Tsing Terminals to floating terminals. This translates to 3 berths for the Ultra-large container ships. This pushes the throughput of the terminal to 12.4 million TEU from the current 8 million TEU.

8.4.1. Floating Terminal Performance and Scalability

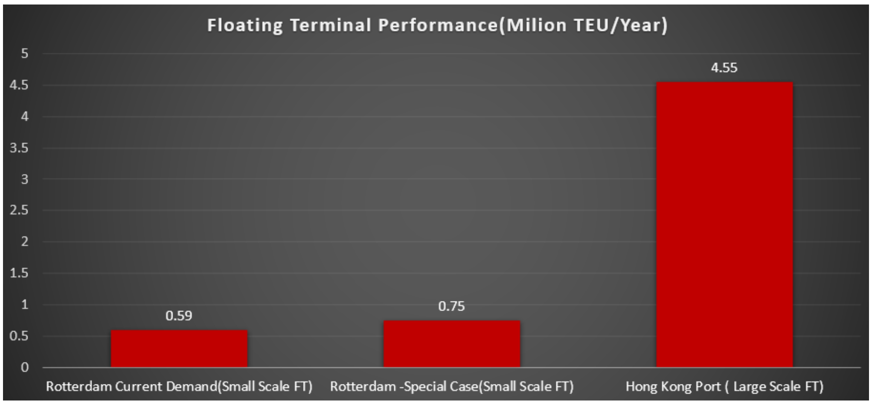


Figure 8.20: Floating Terminal Scalability& Performance

The floating terminal's benefit is more apparent when its capacity and capability are scaled up for larger ports and deep sea terminals. It is apparent that the floating terminal only handles anywhere between 590,000 to 750,000 TEU even during maximum demand scenarios in Rotterdam. This is against a theoretical floating terminal capacity of 2.1 million TEU. This essentially implies that the terminal can potentially handle more containers and ships. In the case of Hong Kong the floating terminal is more productive with an annual throughput of 4.55 million TEU(against a conservative capacity of 4.2 million). A reason for this high floating terminal productivity is the handling of both hinterland-bound containers as well as inter-terminal-bound containers. This is more evident in Hong Kong where 50 percent of containers handled at floating terminals are scheduled for other deep-sea terminals within the same port. This is an advantageous time because of the versatility of floating terminals and also through this mechanism majority of **AAGVs used will travel on full load for to and fro trips**. What is also clear is that floating terminals prove their worth for bigger throughput situations like Hong Kong compared to Rotterdam. The contradictory trade-off here is when compared to figure 8.19, that for smaller terminals like in Rotterdam, a small shift in Hinterland traffic might result in low floating terminal productivity but enables better deep sea terminal growth.

8.4.2. Comparison with Barge Hub

When comparing the floating terminal to a transshipment concept like a barge hub, it is clear that the raw figures show noticeably higher handling capacities. This is predominantly due to two reasons. The first one is that floating terminals have direct over-the-air(3.5) container transfer from super barge to feeder/AAGV while barge hub would need additional transportation equipment like trucks. This reduces vehicles and container handling equipment in terminals and keeps the system lean. The floating terminal handles and sorts both hinterland and inter-terminal bound containers therefore boosting its productivity. The barge hub however provides flexibility in the form of reconfiguring an existing terminal versus creating a new offshore floating terminal which is complex. A tradeoff/ return on investment for the floating terminal can be realised in the form of lesser Operating Expenditure due to the absence of several redundant trucks, straddle carriers and yard cranes.

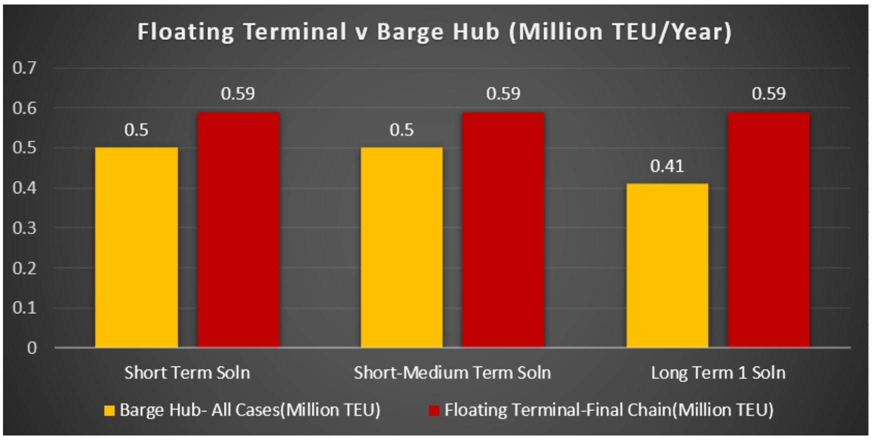


Figure 8.21: Floating Terminal v Barge Hub

8.5. Policy Suggestions- Contract & Business Model Recommendations

This research has been made with the assumption that most of the technologies will have policies in place for their operability and viability. Many technologies in this thesis such as AAGVs would need clearance from governing authorities focusing on autonomous vehicles. Similarly in order to make Deep sea Terminals and Hinterland transportation more attractive, it is also important to have contracts and business models in place that could support super barges and Amphibious AGVs in the near future

8.5.1. Recommendation for Operators of Entities

The operator of entities is important as it dictates the chain of command in a hinterland transportation process.

- **Floating Terminal**- As reiterated before, the floating terminal has been envisioned as an offshore container exchange platform that can accommodate super barges, AAGVs and feeder ships. In both the case of Rotterdam and Hong Kong, floating terminals act as a hub for hinterland traffic. Therefore floating terminals will be operated by Hinterland Terminals themselves. In the case of Rotterdam, the motivation comes from the fact that multiple Hinterland operators have intentions to set up a barge/feeder terminal at the deep sea terminal complex, therefore the obvious operators are the Hinterland terminals themselves. In the case of Hong Kong, since the floating terminal is located far away from the Chinese Pearl River Delta, ideally the floating terminal should be owned by a company based in China. A company with a consortium of barge terminals across this Pearl-river delta should be the owner of the floating terminal.
- **Amphibious AGVs**- The amphibious AGVs will come under an interesting split-operator scheme where both hinterland terminals and deep-sea terminals are involved. This will be delineated in the following section along with its business model
- **Super Barge**- The super barge will be owned by regular barge operators as previously established.

8.5.2. Barge Contracts-Recommendation for Barge Operators

In order to implement this idea of a super barge, it is essential to have barge contracts in place. This is essentially because of the uncertainty posed due to these high call sizes. Furthermore, one of the main arguments at the start of this research was the congestion and lack of coordination at deep sea terminals. For this research multiple types of contracts and models were looked at that could be useful for super barges. Keeping in mind the future implications of Super barge to meet demands, prevent delays and also be financially viable, an account of a barge contract is given below that could be suitable.

1. **Port Agreement**- The barge operator and Deep Sea Terminal should agree with the port operator to transfer the prescribed modal split of containers to the Hinterland. For instance by 2030,

Rotterdam plans to increase share of barge transport to 45%. This implies the barge operator must transport 45% of hinterland-bound containers through its barges on a daily basis or a yearly basis, depending on the timeline agreed upon.

2. **Operating Window and Berth Reservation**- In order to prevent the problems currently faced in deep-sea terminals in terms of congestion and lack of coordination, operating time windows should be firstly agreed upon for super barges at floating terminals. Here, the current protocol of 2 hours can be followed. Since the new system only expects 3 super barges in Port of Rotterdam(earlier 24) and only 14 in the case of Hong Kong(earlier 120), the floating terminals can easily accommodate Super Barges. However, if a super barge is massively delayed due to some problems and if a berth is unavailable at the floating terminal then in that case the super barge can offload containers at a prior agreed deep sea terminal berth. A condition such as a maximum of ”once a week usage of deep-sea berth”s should be applied to prevent any misuse by barge operators.
3. **Minimum Call Size**- Lastly a minimum call size should be agreed upon between the deep sea terminal operator, floating terminal and hinterland operator. In order to maintain these high 400-700 TEU call sizes, a clause must be added that would allow only a maximum of 10% lower call sizes per trip compared to whats agreed upon.

From a business model point of view, super barges should also be profitable for the operators. With uncertainties in global fuel/ energy prices and volatile nature of the container shipping market, bage operators might not be able to own a barge completely by themselves. Instead they would possibly adopt leasing and hedging strategies that have been mentioned below

1. **Lease Type**- In order to make it attractive for super barge operators and owners alike, a specific lease type is crucial in determining how super barges could function in the future. The aviation industry has frequently utilized various models, such as the sales and leaseback model, as well as the concepts of dry/wet/damp leasing.[48]. A sales and leaseback model would require a large fleet to be feasible. This concept will be better understood when the AAGV business model is discussed in subsequent sections. Furthermore, since the Super Barge is a new idea, operators would likely opt for a pilot trial period. However, a long-term option for Super Barge operators would be a damp lease or a dry lease, where the Super Barge is leased out to an operator either with or without maintenance, depending on the lease terms.
2. **Energy/Fuel Hedging**- Since the super barge will be bigger in scale, the energy requirements will also go up. Along with the added uncertainty in call size, the uncertainty in energy prices will also go up. With the volatility in both marine gas prices [71] and electricity prices for EVs [73], a secure energy policy is important for future barge/deep sea vessel owners. That is where fuel hedging comes into play. Pioneered by Southwest Airlines [74] and Emirates Airlines [72], fuel hedging is a form of fuel/energy insurance where the operator pays a higher than normal fuel price to the provider. This price stays constant regardless of the market situation. No matter what happens to the market the price the operator would pay will still remain the same. This protects the barge operator from unpredictability and will allow them to plan their operations without any anxiety.

An overview of a super barge contract and business model implementation can be seen below

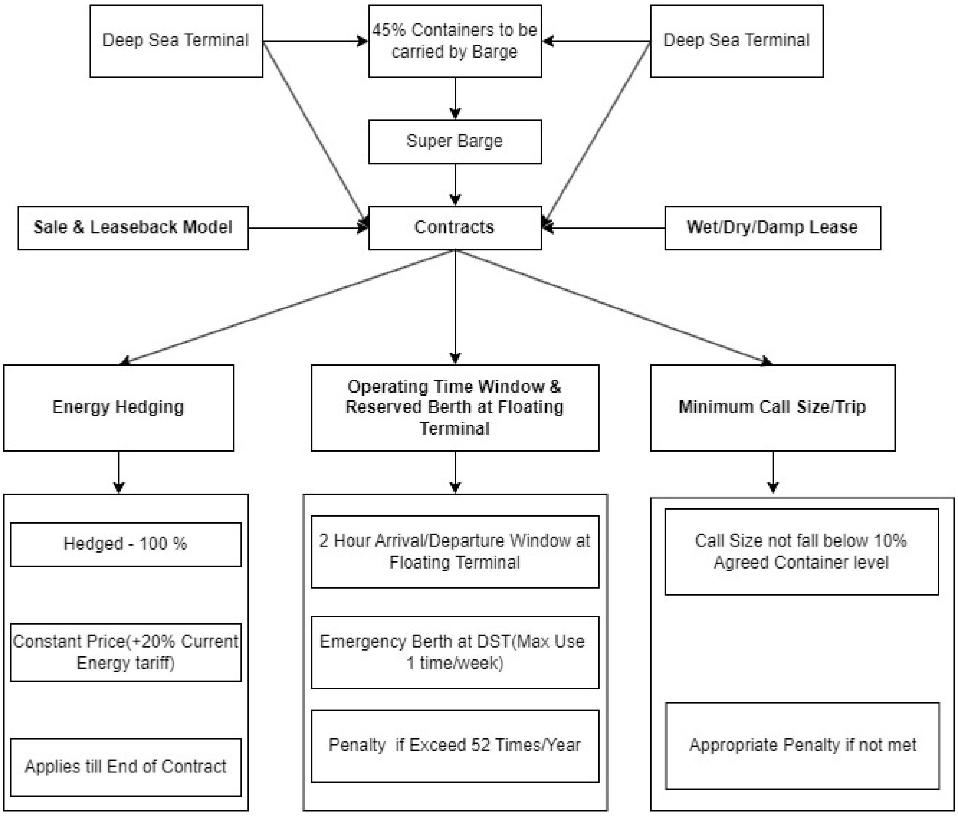


Figure 8.22: Barge Contracts & Business Model

8.5.3. Amphibious AGV Operators & Business Model

The amphibious AGV in essence will be a large fleet of vehicles used across terminals. Taking cues from the aviation industry, the sale and leaseback model can be considered as a possible model for implementing large fleets of AAGVs. This strategy was particularly successful in the case of Indigo Airlines [12] and is a suggestion for AAGV implementation.For ports, a leasing agreement aligns with the typical arrangement, as most terminals lease land for a fixed period before new bids open. A potential framework encompassing all stakeholders and the sales-leaseback model is outlined in Figure 8.23.

The business model formulated for this work,

1. The Amphibious AGV can be bought in bulk by the hinterland terminals. Usually in bulk orders, buyers get heavy discounts up to 50%.
2. Since the AAGV is going to be operated in the deep sea terminal it makes sense to get deep sea terminals involved. Incorporating the sale and leaseback model, the AAGVs are sold to deep sea terminal operators at a profit (thin margin of 10-20%). The advantage here is that deep sea terminals will still be paying lesser than buying it first-hand from the AAGV manufacturer.
3. This provides cash flow to the hinterland terminal operator. From now on the hinterland terminal operator can rent/lease the AAGVs from the deep sea terminal while ensuring that the owner(deep sea terminal) takes care of maintenance and other technicalities. This way the hinterland operator only needs to pay for fuel/energy of the AAGV. The rent will be paid by the hinterland terminal operator who earn operating income from the floating terminal (also owned by Hinterland)
4. Deep sea terminals could be allowed to operate 20% AAGV fleet for their inter-terminal and intra-terminal activities while 80% AAGVs are reserved for the hinterland operator who will employ floating terminal transfers from deep sea terminal via AAGV.

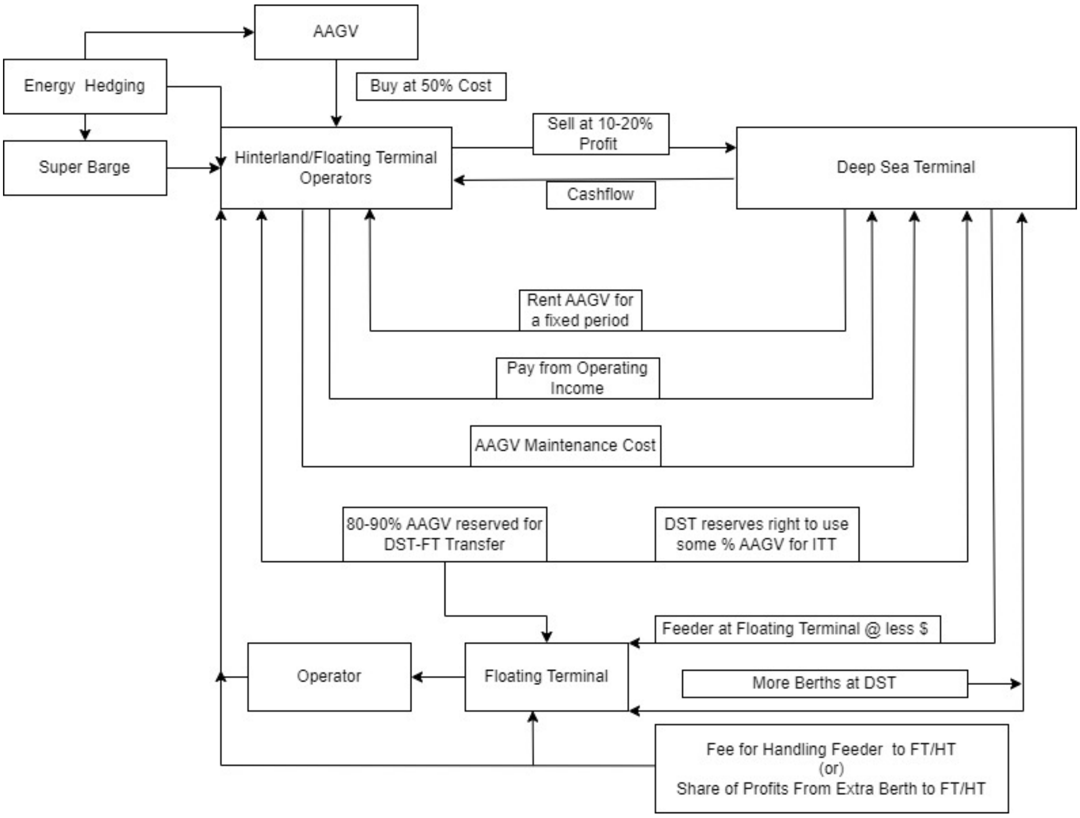


Figure 8.23: AAGV Business Model and Information Flow

5. The fuel for the AAGV fleet can also follow a similar strategy employed previously for super barge, i.e, fuel/energy hedging. Here the AAGVs would involve battery charging and hence electricity prices should be hedged here. The electricity/energy needs for the floating terminal can also be hedged.
6. In turn for being allowed to use some AAGVs for deep sea terminal activities, the operators of these container terminals can consider docking feeder ships at the floating terminal instead. This would free up berth space at the deep sea terminal for more berths. The business model here could go in two ways, the optimistic one is where the profits and revenue of handling the feeder ship are shared between the floating terminal and the deep sea terminal.
7. Alternatively, the floating terminal aka hinterland terminal can independently deal with feeder companies and offer competitive rates. Both scenarios are equally likely as essentially in Rotterdam, the floating terminal will be functioning as a barge feeder terminal. However if the shifting of the feeder from deep sea terminal to floating terminal allows for a docking of an Ultra large container vessel at the Deep sea terminal, then a facilitation fee can be paid to the floating/hinterland terminal.
8. With regard to the AAGVs, they should preferably be both ordered and delivered in batches so hinterland terminals also have the option of cancelling some AAGV orders should they deem it unnecessary.

9

Conclusion & Recommendations

9.1. Conclusion

Deep-sea hinterland transportation forms a significant part of the services sector in the world economy since over 80% of the volume of international trade is carried by the sea. Therefore, any improvements in this area will also impact the prices of our goods and home appliances that we use on a daily basis. Especially since hinterland transportation is about bringing goods into the deeper parts of a region, it is a priority to improve transportation efficiency and penetration in this area. One such barrier, and in many ways an irony, is the issue of congestion in container terminals due to hinterland-bound barges.Knowing the significance of swift delivery of containers and the underlying conflict between deep-sea terminals and barge operators, the maritime industry warrants solutions that solve the problem of congestion while balancing throughput, time, and lower fleet sizes. The extent of problems in the current system was **validated through an agent-based modeling simulation methodology** with the Port of Rotterdam as a test case. It could clearly be inferred from the results that each barge berth was facing a number as high as 8-9 barges/berth/day. Subsequently, new transshipment solutions were realized in the form of short-term, short-medium term, and long-term solutions. The solutions used innovative concepts like Amphibious AGVs, Super-Barges, and floating terminals which showed promise in a variety of circumstances.

Similar agent-based models were again utilized as the simulation strategy for these solutions. Based on simulation of current demand, the final chain solution was found to be the one that produced lower congestion while achieving faster transport time and lower fleets compared to the current transshipment scenario. This solution diverted feeder traffic to the floating terminal while leveraging the amphibious capability of AAGVs to divert hinterland traffic to the floating terminal. Subsequently, the Super barge carried the container consignments to the hinterland. The resulting outcome for the final chain solution was that congestion was reduced by 7 times, while transport time and throughput improved by 10%. The fleet size also improved by 20%.The final chain solution and the current transshipment scenario were subsequently tested with multiple experiments such as modal split, hinterland share, and berth:demand which explored the limits up to which the proposed final chain solution can be successful. However, the absolute extent and advantage of this new transshipment solution could be realized only when it was implemented in the Hong Kong-Pearl River Delta, which covers a footprint the size of the Netherlands. This addressed the **global applicability** of this entire research. Pearl River Delta faces a demand of 6500 TEU/Day and congestion of 120 Barges/Day from Hong Kong, 6 times higher than that of Rotterdam. The final chain solution, when simulated in the Hong Kong environment, showed a 25% improvement in both transport time and throughput. However, the biggest improvement came about in congestion where 126 regular barges could be replaced by 14 super-barges, the fleet employed was just 70 transporters in the final chain case compared to the current transshipment scenario which used 180 transporters. Beyond this, the relevance of this research was also discussed in recommendations and suggestions for future operators as one of the final research questions emphasised the growth potential of proposed networks. From a terminal perspective, it was shown how floating terminals could divert traffic while offering a 25-50% combined growth in container throughput for deep sea terminals. This is particularly relevant for space-constrained areas like Hong-Kong. From a congestion and throughput perspective, the research also showed possible trade-offs in choosing the optimum call size for Super barges in different scenarios. This again plays a part in balancing growth, congestion and overall throughput. One of the most innovative ideas used here is Amphibious AGVs. This research placed an emphasis on using these AAGVs in its right window of demand and distance since they are advantageous on short stints with high demand.These suggestions have also been detailed in the Discussions chapter. From a business and operator perspective, the author has also discussed how concepts like sale and leaseback model and fuel hedging can be instrumental in providing sustainable business model options for operators going forward.

The takeaway from this research is that a solution can indeed be found that reduces congestion while being able to achieve competitive fleet sizes, transport time, and throughput. However, it must be realized that the proposed solution would work as expected only when the demand is as high as the one experienced in Hong Kong. This research also showed possibilities for several other solutions such as the short-medium term set of solutions that prioritized lower investment and could possibly be used in ports of low-income economies. From a societal scale, concepts like AAGVs showed that their versatility could potentially be used to connect small and micro-businesses that are situated along inland waterways. The author encourages researchers to look into such possibilities which could provide economical alternatives to businesses that use the AAGV. From a sustainability point of view, this work has sufficiently shown concepts like floating terminals can prevent unnecessary expansion of ports and land reclamation which is hazardous.The author also believes that in the coming years, this work will be critically looked at to encourage impactful concepts like AAGVs and floating terminals to be introduced for the benefit of hinterland transportation and beyond. Eventually, all these technologies in unison will be instrumental in making our networks more efficient and from an end-user perspective, this could translate into lower prices for the goods that we use on a daily basis.

9.2. Limitations of the Work

While this work gives a good direction for future of deep sea-hinterland transportation, it is not without its flaws.

9.2.1. Lack of Concrete Data

It is important to note that since there was no official agreements with ports/terminal operators, only website information was available to make inferences regarding arrivals, departures and number of barges. Sensitive information like handling capacity, moves per hour and cranes used per vessel were all taken from cited literature sources and not directly from terminals.

9.2.2. Model Limitations

Since the student version of Anylogic was used, the model has a limitation of 10 agents per model. Therefore all cases such as the benchmark had to be split into a series of small models. While this did eventually give results matching literature and terminal data, the author recommends that future work be done with software versions capable of handling a larger number of agents.Some limitations also noticed with Anylogic and corresponding models were that even if a large-scale non-split up model was made, the vehicle flow rates were not consistent and didn't match expectations, therefore a split strategy was beneficial.

9.2.3. Assumptions

This work was accomplished with several assumptions in mind,

1. Many technologies such as floating terminals and amphibious AGVs were given a timeline of 10-15 years. This is considering the R&D done in areas of terminals and waterborne AGVs[101]. However, it does not guarantee that these concepts will be in place by then.
2. It also assumed that regulations are already in place for concepts like Floating terminal to materialise in Rotterdam and Honk Kong. The allocation of space for waterways depends on environmental and geopolitical factors. These are determined by Rijkswaterstraat for Netherlands[47] and Environmental Protection Department for Hong Kong[93].

3. Another assumption is that AAGV and the Floating terminal operate autonomously, therefore expectation is that laws would come into force by the time they are established.
4. Another assumption is that integrated infrastructure linking the yardside,quayside and landside is already in place. This will be crucial for scheduling, container inventory management and so on.
5. It is therefore desired to have all the above assumptions fulfilled in order to realise the industrial application of this work succesfully.

9.3. Future Research and Recommendations

This work on deep-sea- hinterland transportation will have a profound impact on transshipment going forward. But when we look at the micro-scale, it is important to see how concepts can impact the end user. One of those impactful concepts is the Amphibious AGV itself. Today there are multiple small businesses along inland waterways of different regions and most of these businesses transport their goods to main ports by hiring barges. For some less well-off ventures that in itself could be a very expensive process. That is exactly where Amphibious AGVs can come in and help. Companies could possibly save money by owning their own AAGV and using it as and when necessary. A future research direction for AAGVs will be exploring it's effectiveness for small business which in the process could create a sustainable business strategy.

In earlier sections,business models such as sales and leaseback models were proposed but however its feasibility is yet to be established. A future research direction could be evaluating how potential operators could benefit from AAGV fleets by deploying them in Hinterlands. As an extension of the previous idea, small businesses along hinterlands could also be benefited by renting only the fleets they need. This is where ideas like Sales and leaseback models can show its potential

With regard to Amphibious AAGV, their effectiveness has predominantly been along short distances, therefore a recommendation would be to investigate how they can efficiently transport containers for Inter-terminal transport in regions like the Maasvlakte or Kwai-Tsing Terminals in Netherlands and Hong-Kong respectively. They could also use floating terminals to interact with deep-sea terminals. With demand expected to soar in the coming years, AAGVs could be a faster and efficient alternative to current methods and this requires an extensive research comparing its efficiency to current possibilities like barge, AGV and trucks.

An interesting concept discussed with waterborne AGVs was the use of eco-vessel-train formation[14]. Essentially these are platoons of vehicles which travel in a coordinated manner. The author of this thesis also suggests that a similar line of work be done for AAGVs but for different reasons.From a transportability point of view, a lot of AAGVs transporting containers from deep-sea terminals to floating terminals could clutter the system and that's where coordinated platoons can come into play. Ideally, a terminal can send a set of AAGVs at once at a fixed time slot instead of individual AAGVs. This would allow operators to plan barge or deep sea arrivals and can be assured that there will not be a conflict situation between AAGVs and ships on water. From a business angle, these AAGV platoons can also be monetised by operators for companies, since only a fixed set of AAGVs would be allowed at once.

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A

Appendix A- Research Paper

Transshipment for the 21st Century: A Novel Approach to Deep Sea- Hinterland Transportation

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***Abstract*—Globalization's impact on container trade has heightened maritime congestion at terminals worldwide, a trend set to worsen with increasing demand. This research addresses these challenges in deep-sea to hinterland transportation networks, proposing scalable transshipment solutions. Evaluating innovative concepts like amphibious AGVs and floating terminals, the study aims to enhance container transportation efficiency and reduce congestion. Key performance indicators prioritize reduced maritime congestion, maintaining daily throughput, transport time, and minimizing transporter fleet sizes. Utilizing agent-based modelling simulations, the research validates proposed transportation networks and assesses their impact on the Port of Rotterdam. The global applicability is demonstrated in the Hong Kong-Pearl River Delta, showcasing scalability. This work envisions a sustainable and adaptable future for maritime transshipment, introducing versatility through concepts like Amphibious AGVs and floating terminals. While exploring future prospects, the study acknowledges and addresses potential limitations and concerns.**

***Index Terms*—Transshipment, Agent-Based-Modelling, Globalisation, Deep Sea-Inland Waterway Network, Hinterland, Amphibious AGV, Floating Terminals**

I. INTRODUCTION

Globalization has spurred a significant surge in international trade, encouraging unified transport chains and diversified transportation options. The annual growth rate of world trade stands at 2.7% [1], with container shipping experiencing an encouraging 2.5% CAGR [2]. The escalating demand is met by container ship capacities reaching 24,000 TEUs, a notable increase from sub-10,000 TEU capacities two decades ago, accompanied by a 230% rise in container handling since 2000 [3]. This growth extends to hinterland transportation, particularly in intermodal and maritime sectors.Efficiency in transportation is crucial, as it directly impacts the cost of goods and commodities. Inland waterway transport, known for its cost-effectiveness and sustainability, plays a pivotal role. As global maritime platforms aim for net zero carbon emissions by 2030, ports advocate for increased inland waterway transport [6].The surge in inland waterway transport is positive, aligning with sustainability goals and supporting family-owned barge businesses. However, congestion issues are surfacing in major ports like Rotterdam and Antwerp [5], as well as in transshipment hubs like Hong Kong [9].Deep-sea container terminals, such as APM Terminals in Rotterdam, are expanding capacities without addressing barge berth limitations, leading to congestion [8]. Financial and environmental constraints challenge the feasibility of continuous expansion [7]. Barge operators face difficulties due to the inefficient arrivals/departures and meager call sizes absence of contractual relationships with deep-sea terminals [10],worsening congestion issues.This study addresses congestion in the deep-sea terminal-hinterland network, seeking solutions for both terminals and barge operators. Emphasizing future-proofing, innovative concepts like floating terminals, Amphibious AGVs, and Agent-Based Modeling were explored to propose novel transshipment network ideas applicable to all ports and networks. This work aims to contribute to the development of efficient and sustainable deep-sea to hinterland transportation networks.

II. RESEARCH QUESTIONS

How can an **efficient transshipment solution** be developed to mitigate **barge congestion** and enhance Hinterland transport within the **Deep Sea-Inland Waterway Network**, ensuring competitive throughput, transport times, and reduced fleet sizes amidst goals of barge significance and deep-sea terminal growth? Sub-questions:

1) **Current Challenges:** What challenges impact inter-terminal barge networks between inland and deep-sea

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terminals, influencing Barge/Deep Sea Operator performance?

2) **Logistical Adaptations:** Considering land/space constraints, what logistical changes can address these challenges, and what are the short-term, medium-term, and long-term goals for revamped transshipment setups?
3) **Impacts and Trade-offs:** What time-to-throughput impacts can be expected with port condition changes, aiming to reduce barge congestion, and what business/logistical trade-offs might arise between novel transshipment concepts and current operations, influencing terminal growth?
4) **Global Applicability:** To what extent can these transshipment changes be globally applicable across ports and hinterlands worldwide?

III. LITERATURE REVIEW

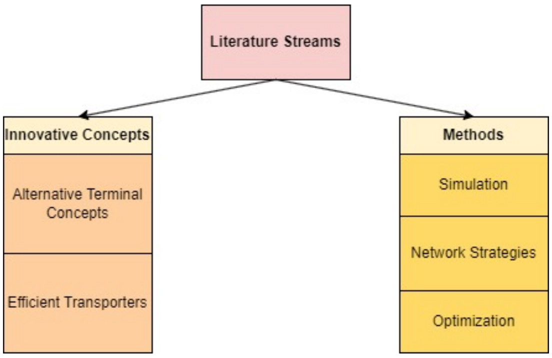

Fig. 1. Literature Streams

A. Innovative Concepts

1) Transshipment Concepts: Investigating ways to meet future demand without extensive port expansion, a promising solution is the concept of a floating terminal. This offshore platform, adaptable and modular in design, mimics a traditional container terminal but at potentially 1/3rd the cost. Designs, like Rother [11] and Baird's, utilize run-down panamax vessels and barges, indicating a swift return on investment. Productivity-focused [13]innovations, such as carrier cranes [12], eliminate the need for extra handling equipment, reducing the reliance on AGVs/straddle carriers. The Space@Sea [14] project proves the time and throughput benefits of floating terminals in network strategy, connecting hinterland traffic with deep-sea terminals. The concept of a barge hub, discussed by Konings [15], offers advantages in handling large call sizes, especially when converted from existing terminals. However, feasibility for small cargo volumes [17] is noted for both floating terminals and barge hubs.

2) Efficient Transporters: In container shipping, addressing efficiency requires innovative concepts like the Amphibious AGV, which combines land and water travel for swift inter-terminal transport, potentially reducing transfer times by 21% compared to trucks for short distances. AAGVs, envisioned by TU Delft's Timo Kleefstra [19] and a subsequent improved version which is used here [18], offer versatility, diverting hinterland congestion from deep-sea terminals.This is shown in figure 2. Another innovation, the waterborne AGV [20], proposed by H. Zheng and Dr. Rudy Negenborn, has shown promise, especially around the Maasvlakte in Rotterdam. However, compared to AAGVs, they still require an additional handling point between water and land. To address the challenge of low call sizes, a concept referred to as ”Super Barge” is introduced, capable of transporting 400-700 TEUs [21], potentially benefiting barge hubs and floating terminal concepts designed for large call sizes.

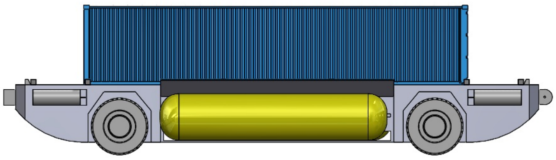

Fig. 2. Amphibious AGV [18]

B. Simulation and Optimization in Marine Transport

Simulation is crucial for understanding maritime transshipment processes, particularly in the context of deep-sea terminals to hinterland transportation. It aids in identifying bottlenecks and assessing a range of solutions, providing insights into optimal and suboptimal scenarios for decision-making. Two predominant methods, discrete event simulation (DES) and agent-based modeling (ABM) [22], are commonly used. DES models systems as sequential processes [23], representing each step as an event in a structured manner, lacking flexibility for simultaneous processes. In contrast, ABM classifies entities as agents, simulating their actions and interactions, offering flexibility and allowing for parallel processing. The autonomy of entities and the potential for simultaneous activities make ABM preferable over DES. Optimization is vital for determining fleet sizes for different models. Mathematical optimization falls into three categories: exact algorithms, which solve problems to optimality but require high computational time; approximation algorithms, which find approximate solutions with a guaranteed closeness to optimality and provide a good trade-off between accuracy and computation time; and heuristics, which prioritize speed over solution quality. Metaheuristics [24], like genetic algorithms, iteratively optimize a set of feasible solutions, making them suitable for large-scale simulations and fleet sizing optimization, striking a balance between speed, accuracy, and precision.

C. Network Strategies

Two predominant network strategies, hub-and-spoke [16] and point-to-point, shape logistics networks. Point-to-point theory involves individual transporters connecting each point directly, requiring numerous unique vehicles for an expansive network. In contrast, hub-and-spoke theory designates a central hub from which transporters originate, reducing the need for unique vehicles. The ideal maritime transshipment system combines both strategies, utilizing point-to-point for short-distance transfers and hub-and-spoke for long-distance ones. Successful companies like Maersk [**?**] and Indigo Airlines [25] have adopted a hybrid approach for efficient goods transit. This literature-driven inference guides the chosen network strategy for this work, ensuring a balanced and effective system.

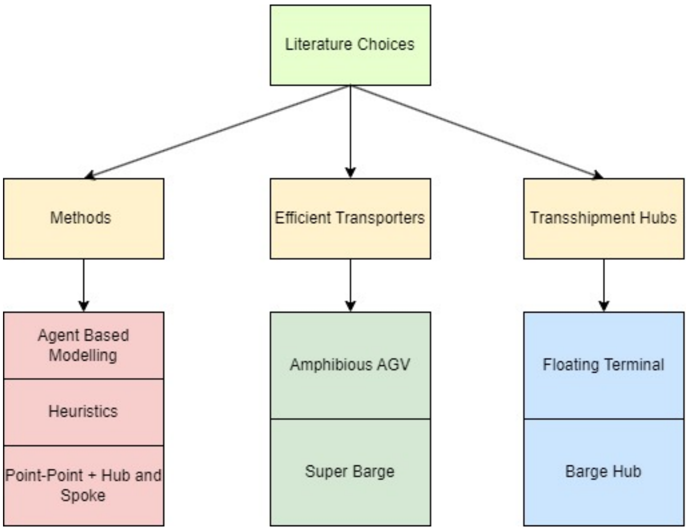

Fig. 3. Final Choices Summarised

IV. METHODOLOGY/METHODS

The methodology of investigating the above research questions is given in the figure

A. *Method- Agent-Based Modelling*

The deep sea terminal to inland waterway network consists of multiple entities which are modelled as agents and hence will follow an agent-based modelling approach due to the reasons stated in literature. The agents are predominantly of three categories namely *Ports and Terminals,Containers and Transporters*. There are multiple tyes under each of these agents and they are presented in figure 4. These agents are linked by a routing and distribution network that determines routes and checks container order fulfillment for the hinterland terminals.The combination of these agents form the transshipment networks which will be seen in the current transshipment scenario(benchmark) and the proposed solutions.

B. *Methodology-Simulation Model*

This agent-based model can be fully realised by implementing it under a simulation platform, which in this case was AnyLogic. In order to accomplish this, a process logic was defined that connects the three category of agents(Terminals, containers and transporters). For example, one of the common process logics used was the loading and unloading of containers to transporters from/to various terminals.This would happen at each container handling point and can be seen in section VI and section VII. The agent-based model and process logic are the major inputs to the model. The model gives us data such as containers and ships traversed and with help of data analysis tools like excel, we can obtain answers to our main parameters such as congestion which must be achieved at similar or better throughput,transport-time rates and fleet trade-off as current operational scenarios. Figure 4 represents an idea of how both the agent-based model and simulation would work together to give us the KPIs

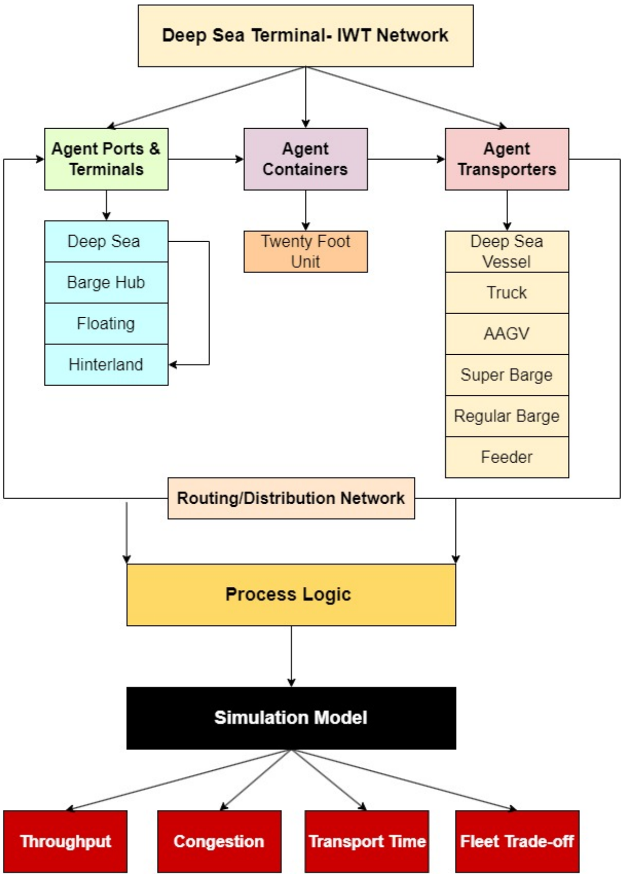

Fig. 4. Agent Based Modelling & Simulation

V. ENVIRONMENT

The chosen environment for comparing and implementing all solutions is the Port of Rotterdam, where terminals experience a daily in-flow of at least 5000 TEU. In the Port of Rotterdam, approximately 35% of hinterland-bound containers are transported to the hinterland by barges, making barge transport the primary focus for comparing the various solutions. Taking into account the container split between hinterland and inter-terminal transport, terminals like APM-II Maasvlakte send around 1050 TEU [26] to the hinterland every day.

VI. BENCHMARK SOLUTION

Deep sea Ships and Feeder Ships carrying 4000 TEU and 1000 TEU respectively reach the APM-II deep sea terminal. Subsequently, the containers from both ships are unloaded

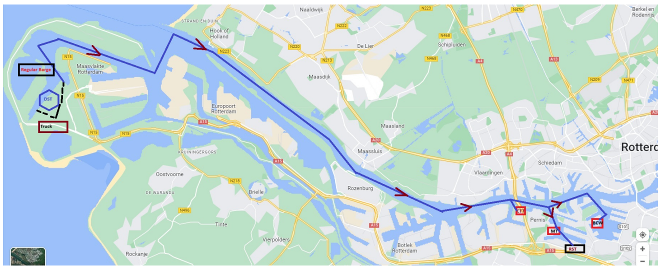

Fig. 5. Port of Rotterdam Layout

to trucks, facilitating the transfer between the deep-sea berth and barge berth within the deep-sea terminal. The final step involves barges with small call sizes transporting consignments of 50 TEU to the hinterland terminals.The layout of this is presented in figure 6

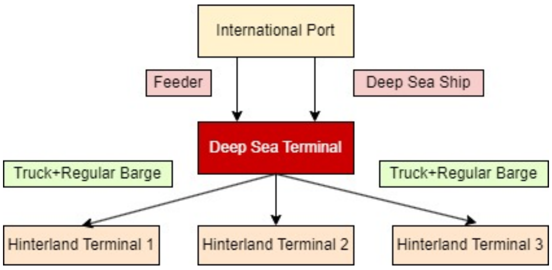

Fig. 6. Benchmark Case

VII. PROPOSED SOLUTIONS

A. *Short Term Solution- Use of Existing Infrastructure*

Strategy- Deep sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke). The short-term solution, designed for the next five years, relies on existing infrastructure for the transshipment network, with an exception for Super Barge, expected to materialize within this timeframe through technology transfer from high-density e-barge concepts in ports like Shanghai. The operational process includes daily arrivals of deep-sea and feeder ships at the APM-II deep-sea terminal, followed by unloading and transfer to a barge berth using a fleet of trucks and AGVs. Containers are then loaded onto a Super Barge at the barge berths, with common containers for all hinterland terminals for cost efficiency. The Super Barge travels to the barge hub, unloading consignments ending at the hub and transferring the remaining containers to the hinterland. Split consignments are further moved from the Super Barge Berth to regular barge berths at the hub using trucks. Finally, smaller call-size barges transport the remaining containers to the three hinterland terminals. The layout of this is shown in figure 7.

B. *Short-Medium Term Solution- Introduction of AAGV*

Strategy- Deep Sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke)

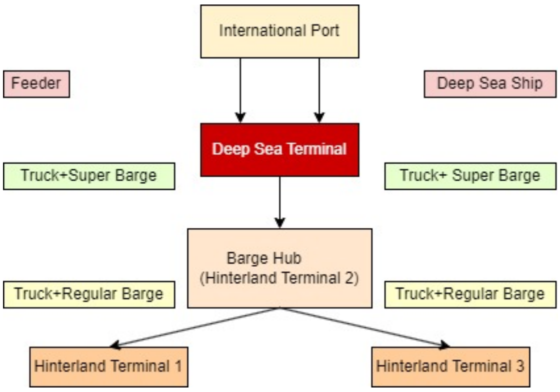

Fig. 7. Short-Term Solution

Projected for implementation in the next 10 years, the short to medium-term solution assumes the development of amphibious AGVs within this timeframe, inferring from existing literature. It is similar to the previous short-term scenario but replaces the final truck+barge leg with unimodal AAGV transport. The process involves daily arrivals of deep-sea and feeder ships from Hamburg and Felixstowe at the APM-II deep-sea terminal. Upon arrival, these ships are unloaded and transferred to barge berths using trucks. Containers are then loaded onto a super barge at the barge berths, following an efficient process similar to the short-term case. The final step entails transferring the remaining 75% of containers to three hinterland terminals via amphibious AGVs stationed near Super Barge Berths. The layout of this solution is shown in figure 8.

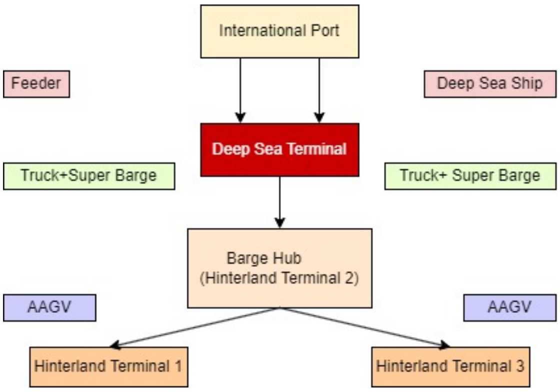

Fig. 8. Short-Medium-Term Goal- Introduction of Amphibious AGVs

C. *Medium Term Solution- Introduction of Floating Terminals and Use of AAGVs*

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke) The medium-term solution, anticipated within the next 10-15 years, envisions the active use of both floating terminals and Amphibious AGVs This used a floating terminal, specifically designed for this research. A small-scale Terminal can handle 1.26-2.1 million TEU (figure10). This approach mirrors the benchmark case, maintaining the same number of handling points. The process involves feeders and deep-sea ships arriving at the deep-sea terminal, where they are unloaded to Amphibious AGVs. Subsequently, these AGVs transfer hinterland-bound containers to the floating terminal. The containers are directly unloaded from deep-sea ships onto the AGVs, which exit the terminal through ramps, traveling by sea to the floating terminal. The final leg entails transporting hinterland-bound containers from the floating terminal to the hinterland via a regular barge system with low on-call sizes, resembling the existing system—a direct transfer from the floating terminal to the hinterland. The layout of this is shown in figure 9.

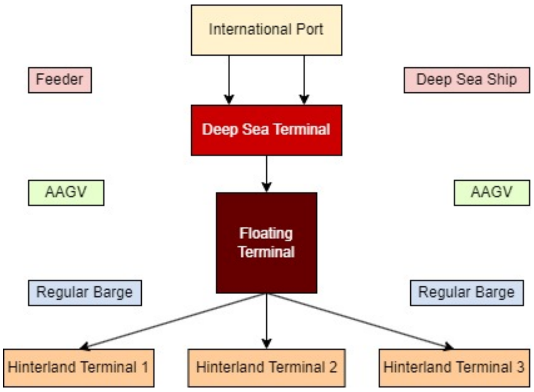

Fig. 9. Medium-Term Solution-Use of Floating Terminals and AAGVs

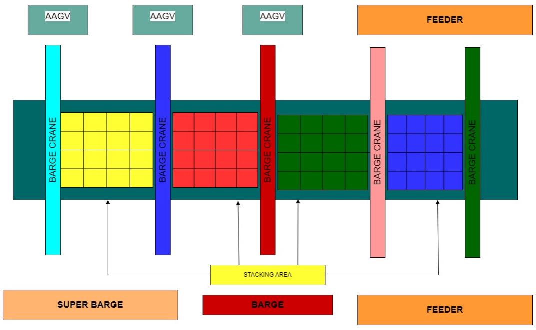

Fig. 10. Small Scale Floating Terminal

D. Long Term Solution 1- Combination of Transshipment Concepts

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland Terminals(Hub and Spoke)

Seen as a long-term project for enhanced operational efficiency spanning 15 years or more, this integrated approach combines barge hub, floating terminal, amphibious AGV, and a 400-700 TEU super barge. Running in parallel with short and short-medium-term strategies, the international port and deep-sea terminal remain unchanged. Hinterland-bound containers are transferred to the floating terminal via amphibious AGVs, and then moved to the barge hub using a super barge. At the barge hub, containers destined for the hub are unloaded, with the remainder taken over by AAGVs. The final step involves transferring 75% of the containers to three hinterland terminals via amphibious AGVs near Super Barge Berths. Notably, containers for all terminals are efficiently loaded onto a super barge, maintaining consistent configurations for deep-sea terminals, barge hubs, and hinterland terminals in this integrated approach. The layout of this is shown in figure 11

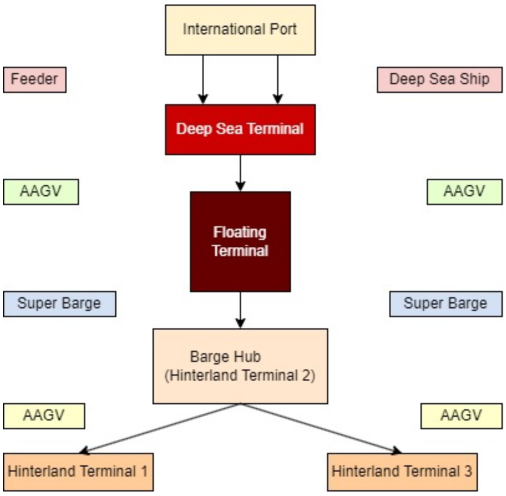

Fig. 11. Long Term Solution-Combination of Transshipment Concepts

E. Long Term- The Final Chain

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke) To reduce congestion issues in floating terminals and barge hubs, a strategic shift in feeder traffic is proposed. Notably, the UK feeder ship would now directly transfer to the floating terminal, freeing up space for an additional deep-sea ship. The deep-sea vessel from Hamburg maintains its usual docking at the deep-sea terminal. Container consignments for the hinterland are moved from the deep-sea to the floating terminal, while those for inter-terminal transport from feeder ships are rerouted to the deep-sea terminal, optimizing AAGV utilization. Super Barges now transport hinterland containers directly from the floating terminal to individual hinterland terminals, minimizing trips. Importantly, the feeder accommodates containers under a modal split of truck and train, necessitating consideration of the entire hinterland consignment in flow rate calculations. The final chain layout is given in figure 13

VIII. VALIDATION OF THE BEST SOLUTION

The five solutions were subsequently compared with base demand and from this, a solution was found that performed best for each of the KPIs. The common best solution was then chosen and tested for different set of experiments as shown

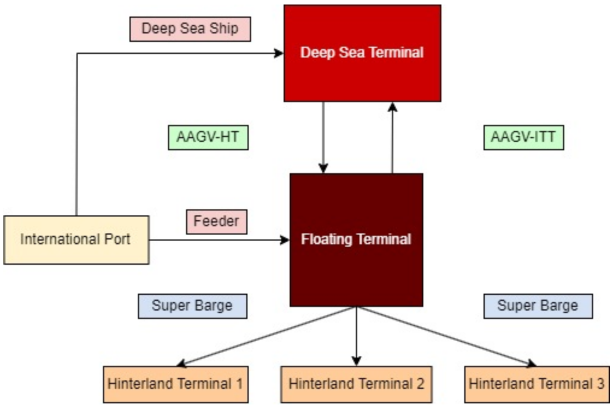

Fig. 12. Long Term- Final Chain

in the figure, as well as a different environment which in this case is Hong-Kong.

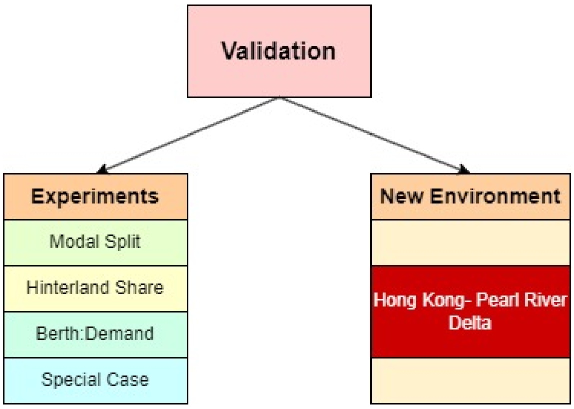

Fig. 13. Validation

A. Modal Split Experiments

Currently in Ports around the world, only 35% of the hinterland traffic is carried by barges. Ports like Rotterdam, Antwerp and Shanghai aim to increase this to 45%. thos experiment will test loads up to 55% as well.

B. Hinterland Share Experiments

Every consignment brought into a port is a mix of both interterminal and hinterland container loads. While this primarily operates at 40-60(ITT:HT), future projections show increased hinterland shares as high as 70 or 80%.

C. Berth:Demand Experiment

With terminals expanding, berths spaces will increase With revised transshipment setups, the increased demand can have swinging effects and has to be investigated through experiments.

D. Special Case Experiment

This is a worse case scenario which takes in a combination of factors shown above(55% modal split + 80% hinterland share + Maximum Demand/Berths)

E. New Environment

The new environment here is the Hong-Kong- Pearl River Delta where the new found solution will be tested against the benchmark.

IX. RESULTS

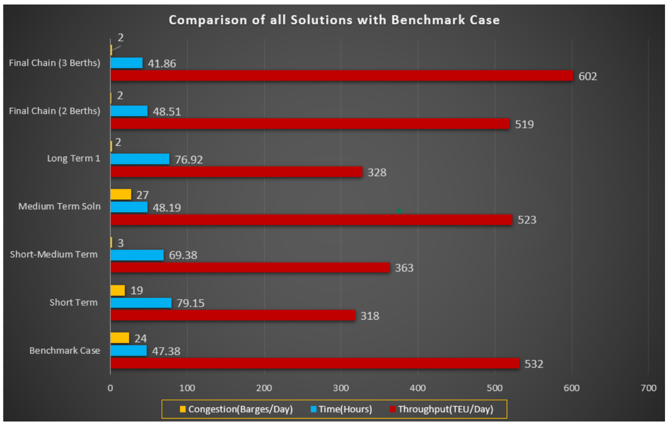

Fig. 14. Comparison of All Cases

A. Congestion

In reviewing the general results, the benchmark records 24 barges/day, aligning with APM-Terminals' data of 22 barges per day. This validates initial research questions on barge congestion, highlighting that low call sizes (50 TEU and under) can cause bottlenecks. Strategies in most solutions focus on diverting the congestion center or using larger call sizes. The comparison with five proposed solutions reveals candidates with reduced congestion: the short-medium term solution, long-term 1, and the final chain solution, all utilizing super barges with higher call sizes (400-700 TEU). These solutions effectively reduce congestion to about 2-3 super barges/day from the current 24 barges. However, the short-term case performs worse, recording 19 barges/day, causing congestion at the barge hub. The short-medium term solution, replacing truck+barge legs with Amphibious AGVs, eliminates berth congestion entirely.

Containers are unloaded onto Amphibious AGVs from super barges, improving sea-going vessel congestion by eliminating double-handling. The long-term solution 1 mimics the short-term scenario but introduces AAGVs and floating terminals, potentially facing congestion at change points. Another promising solution is the final chain solution, employing AAGV, super barge, and floating terminal, with only three handling/change points and 2-3 super barges/day in sea-going congestion. Conversely, the medium-term solution mimics the benchmark but suffers severe congestion at the floating terminal (26 barges/day, 9 barges/berth). However, this solution is competitive in time.

B. Transport Time

The transport time of hinterland container consignments depends on factors like handling points, call sizes, and equipment. The benchmark records a transport time of 47.37 hours, with the final chain solution, using three berths at the floating terminal, achieving a 12% improvement at 41.8 hours. The twin spreader technology and AAGVs contribute to this efficiency. The medium-term solution and final chain solution with 2 floating terminal berths offer close second-best solutions with times of 48.19 and 48.15 hours. Solutions with extra handling points suffer the most in transport time: Short Term Solution, Short-Medium Term Solution, and Long Term-1 record 79, 69, and 76 hours, respectively.

All three solutions focus on the barge hub concept, shifting hinterland traffic to the barge hub while reducing barge traffic using a Super Barge. However, major time losses occur at the barge hub during container transfers. Future prospects may lie in solutions like short-medium term, leveraging Amphibious AGVs in the last leg to reduce overall time by 10 hours. Though amphibious AGVs are limited by speed constraints, this motivates further research for their applications in inland waterways.

C. Throughput

Throughput performance parallels transport time, with the benchmark remaining effective at 532 TEU/Day due to the fast in-fast out concept. The final chain solution with 3 FT berths provides the best performance, recording a 12% improvement. The medium-term solution and final chain-2 FT berth solution are also effective. Solutions with additional handling points lead to significant time losses, although reducing congestion of sea-going vessels. While this research does not advise against their use, solutions like short-medium term might be more useful as a filler until new technology is introduced or for ports with lower traffic.

D. Fleet Size

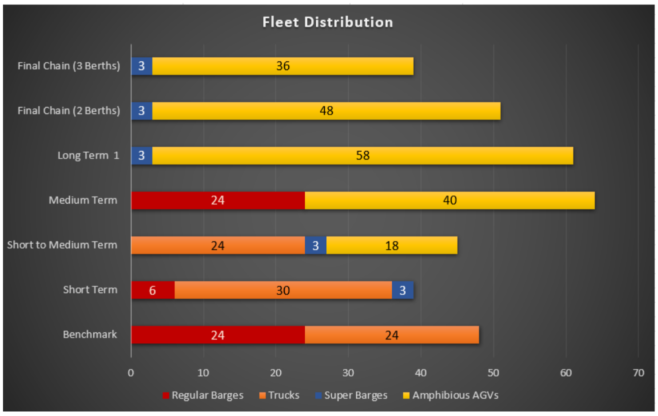

Fig. 15. Fleet Size Distributions

Fleet size control is crucial for the future, and the benchmark case's fleet of 24 regular barges and 24 trucks reveals congestion. The short-term solution reduces the fleet to 39 transporters, 20% better than the benchmark, using multiple transporter types efficiently. The short-medium term case, with a fleet size of 45, proves advantageous, being 10 hours faster overall than the previous short-term scenario. The medium-term solution sees a fleet size of 64 against the benchmark's 48, primarily due to AAGV transfer from the deep-sea terminal to the floating terminal. The long-term solutions, focusing on maximum barge reduction, increase fleet size to 61. The final chain solution with 3 FT berths provides a fleet size of 39, matching earlier solutions and offering competitive figures for transport time and throughput.

E. Inference

Studying all the solutions, it is clear that the final chain solution figures as the common solution among all KPIs that perform best. For experiments and the Hong-Kong Case Study, the final chain solution will be put against the current benchmark. This will also validate the proposed candidate solution in the process.

X. HONG KONG- PEARL RIVER DELTA CASE STUDY

A. Hong Kong- Pearl River Delta Environment

Hong Kong's Kwai Tsing Terminals, receiving 36,000 TEU daily from international ports, including Hutchinson International Terminals and COSCO-operated Container Terminals, handle up to 24 million TEU annually. Despite a pandemic-related drop to 12.869 million TEU in 2022, the HIT and COSCO-HIT terminals, handling 6500 TEU/day [9] with 120 barges in 2016, use 2 Barge/Quay cranes per barge, achieving an estimated throughput of 22,000 TEU/day. The large-scale floating terminal in the yellow-marked region, mirroring Rotterdam's conditions, can shift feeder/feedermax vessel traffic. Realistically, it accommodates 3 feedermax ships, 3 Super Barges, and 5 AAGVs, running with two different contributions. Seven inland ports in Guangdong, including Yantian and Shekou, are chosen for simulation due to their hinterland penetration and transshipment significance

Fig. 16. Hong-Kong Berths

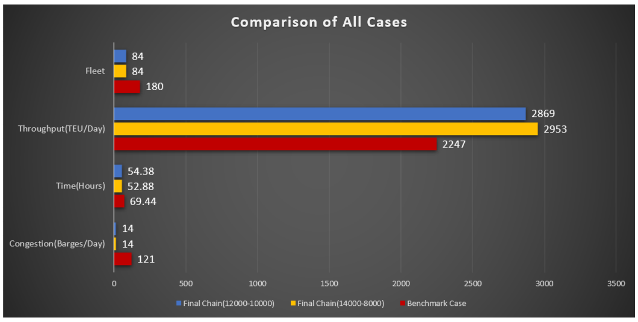

Fig. 17. Hong kong metrics comparison

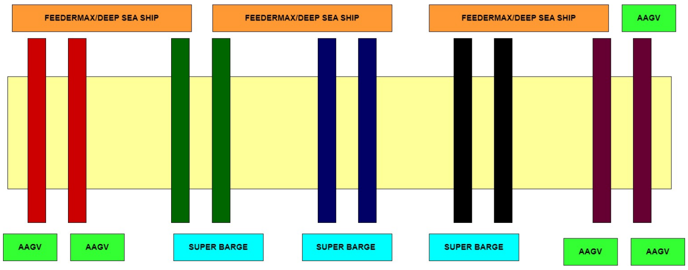

Fig. 18. Large-Scale Floating Terminal

B. Results

The Hong Kong-Pearl River Delta reveals notable results for various KPIs. Scaling up the final chain solution significantly boosts performance, contrasting with the hindrance observed in a small-scale floating terminal design (10) in the Special case experiment. Here a bigger 4.2 million TEU capacity floating terminal is used (18). The benchmark case shows 121 barges/day congestion, aligning with established terminal data [9]. Throughput, factoring in truck travel, barge transport, and other components, reaches a maximum container transfer rate of 2247 TEU/day to inland ports, considering a barge call size of 50 TEU. The benchmark takes around 69 hours for the entire 6500 TEU consignment. With 126 barges and 54 trucks, totaling 180 transporters, the deep-sea terminal handles 22000 TEU, as mentioned earlier.The final chain solution, implemented with two configurations (DST-14000 handling 8000 TEU, DST-12000 handling 10000 TEU at the floating terminal), excels in all KPIs. Large call sizes in super barges reduce congestion from 121 barges/day to just 14 super barges/day and 70 AAGVs. The final chain records a transfer rate of (2869-2953 TEU/day), substantially higher than the benchmark's 2247 TEU/day. High call sizes, like 700 TEU, make sense in this region, given multiple daily trips from the Hong Kong port to the same inland port. Lower congestion results in a significant fleet size reduction from 180 to 84 transporters (14 Super Barges and 70 AAGVs). One limitation in Rotterdam cases is resolved with the floating terminal's closer proximity to deep-sea terminals, contributing to a 23-25% improvement in total transfer times (52.8 to 54.4 hours). AAGVs transfer the same containers in 31-33 hours, a 30% improvement over the benchmark's 43 hours. The productivity of AAGVs is more pronounced when uncertainties like floating terminal distances are eliminated. In terms of throughput, both final chain configurations transfer 30% more containers in the same timeframe as the benchmark case, showcasing the flexibility and effectiveness of concepts like AAGVs and floating terminals.

XI. DISCUSSION

A. The Case for Amphibious AGVs

Amphibious AGVs (AAGVs) are a key innovation, offering dual mobility on water and land. They reduce double handling of containers, divert traffic from terminals, and enhance access. Assessing their performance:

1) AAGV vs. Truck vs. Distance: Examining distance productivity, while trucks initially outperform AAGVs in trips/day, considering the distance covered reveals AAGVs' advantage. Despite covering twice the distance, AAGVs don't require double the fleet compared to trucks. Even with trucks being 40% faster, AAGVs demonstrate competitive performance. In the Hong Kong case, with nearly five times the distance to cover, AAGVs outperform trucks in trips/day, emphasizing AAGVs' efficiency in higher-demand scenarios. This suggests that AAGVs perform better when demand is higher and cover greater distances.

2) Implications on Floating Terminal: Insights suggest that locating floating terminals closer to deep-sea terminals could lower fleet rates or allow for more AAGV trips within the same fleet size, enhancing productivity. However, floating terminals must be strategically located to serve all nearby deep-sea terminals without disrupting existing operations.

3) AAGV Impact on Double/Multi-handling Procedures: AAGVs prove effective in reducing transport time and preventing double handling. In specific cases, replacing truck and barge legs with a single AAGV leg results in a significant time reduction, showcasing the efficiency of AAGVs in certain scenarios.

B. Floating Terminals for International Transshipment

1) Floating Terminal Performance and Scalability:: Floating terminals, when scaled up, show the potential to handle more containers and ships. In Rotterdam, the theoretical capacity is 2.1 million TEU, but during maximum demand, it handles 590,000 to 750,000 TEU. In Hong Kong, the annual throughput is 4.55 million TEU against a capacity of 4.2 million TEU. The versatility of floating terminals is evident, especially when handling both hinterland-bound and inter-terminal-bound containers.

2) Comparison with Barge Hub:: Floating terminals outperform barge hubs in handling capacities due to direct over-the-air container transfers, reducing the need for additional transportation equipment. The floating terminal's ability to handle and sort both hinterland and inter-terminal containers enhances productivity. While a barge hub offers flexibility in reconfiguring existing terminals, the floating terminal's return on investment is realized through reduced Operating Expenditure without redundant equipment.

C. Policy Suggestions and Implications

1) Operators of Entities: :

- **Floating Terminal/Barge Hub**- Since they handle hinterland traffic and sortation, the operator of floating terminal and barge hub will be the hinterland terminals itself.
- **Amphibious AGV**- The amphibious AGVs will come under an interesting split-operator scheme where both hinterland terminals and deep-sea terminals are involved. This will be delineated in the following section along with its business model
- **Super Barge**- The super barge will be owned by regular barge operators as previously established.

2) Barge Contracts& Business Model:

- **Port Agreement**- Define modal split agreements with deep-sea terminals, ensuring a prescribed percentage of containers is transported by super barges to the hinterland.
- **Operating Window and Berth Reservation**- Establish operating time windows and reserve berths at floating terminals to prevent congestion. Allow occasional use of deep-sea berths with conditions to avoid misuse.
- **Minimum Call Size**- Agree on a minimum call size to maintain high-capacity trips, incorporating a clause allowing only a 10% deviation from the agreed-upon size.
- **Lease Type**- Explore leasing models, such as short-term wet leases for trial periods, and damp or dry leases for long-term arrangements, depending on the operator's needs.
- **Energy/Fuel Hedging**-Implement fuel hedging strategies similar to Emirates/Southwest Airlines [27] to mitigate uncertainties in energy prices.

3) Amphibious AGV Business Model: AAGVs could follow a sales and leaseback model akin to Indigo Airlines [25]

- **Bulk Purchase**-Hinterland terminals buy AAGVs in bulk, securing discounts.
- **Sale and Leaseback**- AAGVs sold to deep sea terminals; leasing generates cash flow for hinterland terminals.
- **Fleet Operation**-80% of AAGV fleet leased to hinterland terminals; deep sea terminals handle maintenance.
- **Fuel Hedging**-AAGV fuel costs follow a hedging strategy to mitigate uncertainty.
- **Berth Optimization**-Encouraging feeder ship use at floating terminals frees up deep sea berths; possible facilitation fee for redirection

XII. CONCLUSION

Deep-sea hinterland transportation forms a significant part of the services sector in the world economy since over 80% of the volume of international trade is carried by the sea. Therefore, any improvements in this area will also impact the prices of our goods and home appliances that we use on a daily basis. Especially since hinterland transportation is about bringing goods into the deeper parts of a region, it is a priority to improve transportation efficiency and penetration in this area. One such barrier, and in many ways an irony, is the issue of congestion in container terminals due to hinterland-bound barges.Knowing the significance of swift delivery of containers and the underlying conflict between deep-sea terminals and barge operators, the maritime industry warrants solutions that solve the problem of congestion while balancing throughput, time, and lower fleet sizes. The extent of problems in the current system was validated through an agent-based modeling simulation methodology with the Port of Rotterdam as a test case. It could clearly be inferred from the results that each barge berth was facing a number as high as 8-9 barges/berth/day. Subsequently, new transshipment solutions were realized in the form of short-term, short-medium term, and long-term solutions. The solutions used innovative concepts like Amphibious AGVs, Super-Barges, and floating terminals which showed promise in a variety of circumstances.

Similar agent-based models were again utilized as the simulation strategy for these solutions. Based on simulation of current demand, the final chain solution was found to be the one that produced lower congestion while achieving faster transport time and lower fleets compared to the current transshipment scenario. This solution diverted feeder traffic to the floating terminal while leveraging the amphibious capability of AAGVs to divert hinterland traffic to the floating terminal. Subsequently, the Super barge carried the container consignments to the hinterland. The resulting outcome for the final chain solution was that congestion was reduced by 7 times, while transport time and throughput improved by 10%. The fleet size also improved by 20%.The final chain solution and the current transshipment scenario were subsequently tested with multiple experiments such as modal split, hinterland share, and berth:demand which explored the limits up to which the proposed final chain solution can be successful. However, the absolute extent and advantage of the final chain solution could be realized only when it was implemented in the Hong Kong-Pearl River Delta, which covers a footprint the size of the Netherlands. Pearl River Delta faces a demand of 6500 TEU/Day and congestion of 120 Barges/Day from Hong Kong, 6 times higher than that of Rotterdam. The final chain solution, when simulated in the Hong Kong environment, showed a 25% improvement in both transport time and throughput. However, the biggest improvement came about in congestion where 126 regular barges could be replaced by 14 super-barges, the fleet employed was just 70 transporters in the final chain case compared to the current transshipment scenario which used 180 transporters.

The takeaway from this research is that a solution can indeed be found that reduces congestion while being able to achieve competitive fleet sizes, transport time, and throughput. However, it must be realized that the proposed solution would work as expected only when the demand is as high as the one experienced in Hong Kong. This research also showed possibilities for several other solutions such as the short-medium term set of solutions that prioritized lower investment and could possibly be used in ports of low-income economies. From a societal scale, concepts like AAGVs showed that their versatility could potentially be used to connect small and micro-businesses that are situated along inland waterways. The author encourages researchers to look into such possibilities which could provide economical alternatives to businesses that use the AAGV. From a sustainability point of view, this work has sufficiently shown concepts like floating terminals can prevent unnecessary expansion of ports and land reclamation which is hazardous. The author also believes that in the coming years, this work will be critically looked at to encourage impactful concepts like AAGVs and floating terminals to be introduced for the benefit of hinterland transportation that could eventually lower prices of commodities that we use every day.

XIII. FUTURE WORK

A. *AAGV For Hinterland Businesses*

This research on deep-sea hinterland transportation has profound implications. The Amphibious AGV is a key concept, offering potential cost savings for small businesses in regions with inland waterways. Future research should explore its effectiveness for small businesses and assess business models like sales and leaseback.

B. *AAGV for Coordinated Transportation*

Amphibious AAGVs, investigating efficiency in inter-terminal transport is recommended. A coordinated platoon approach, inspired by eco-vessel-train formations, can prevent system clutter and offer efficient container transport from deep-sea to floating terminals. This approach benefits operators and allows monetization.

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B

Appendix B

B.1. General Results

The link to the general results can be found by clicking this link the general results mainly consist of the comparison between the benchmark cases and proposed cases. It consists of data pertaining to the following **by clicking this**

- Benchmark Case
- Short-Term Scenario
- Short-Medium Term Scenario
- Medium Term Scenario
- Long Term Solution 1
- Final Chain Solution

B.2. Experiments

Multiple Experiments were performed under Modal split, special case, hinterland share and berth demand experiment. The links for all experiments can be found below in corresponding section.

- Modal Split- The link to entire data set can be found **by clicking this**
- Hinterland Share- The link to entire dataset and analysis can be found **by clicking this**
- Berth:Demand Experiment- The link to the entire dataset and analysis can be found by **by clicking this**
- The Special case experiment data- The link to the entire dataset and analysis can be found by **by clicking this**

B.3. Hong Kong Pearl River Delta

The Hong-Kong Pearl River Delta represented the global applicability of the whole transshipment setup. It can be accessed by **by clicking this**

B.4. Simulation Files

The AnyLogic simulation files here are as follows

- Benchmark- Mix of the following files
  ”Scenario1” + ”SceenarioEverythingDSTberthtoBargeBerth” +”All Cases Scenario 1” +”Scenario ALL Felixstowe to Rotterdam DST”

- Short Term Cases- Mix of following files
  ”All Cases Scenario 1” +”Scenario Felixstowe ALL Rotterdam DST” +”SceenarioEverythingDSTberthtoBargeBerth” + ”Scenario2.2DSTBH”

+ ”Scenario2HubBerthtoBargeBerth” + ”Scenario2BHHT”

- Short-Medium Term Scenario- Mix of following files
  ”All Cases Scenario 1” +”Scenario ALL Felixstowe Rotterdam DST”+”SceenarioEverythingDSTberthtoBargeBerth” + ”Scenario2.2DSTBH” + ”Scenario4.3BHHT”

- Medium Term Scenario- Mix of following cases
  ”All Cases Scenario 1” +”Scenario ALL Felixstowe Rotterdam DST” + ”Scenario 3.2AAGVFT”+”Scenario 3.3FTHT”

- Long Term Solution 1- Combination of Transshipment Concepts
  ”All Cases Scenario 1” +”Scenario ALL Felixstowe Rotterdam DST” + ”Scenario 3.2AAGVFT” +Scenario4.2FTBH + Scenario4.3BHHT

- Final Chain Solution- Mix of following files
  ”All Cases Scenario 1” +”Scenario 6. UK to Floating Terminal” +ScenarioFTDST +ScenarioDSTFT + Scenario3.3FTHT

The links for all these files can be found by **by clicking this**

B.5. Container Orders/Transporter

Table B.1: Orders to Containers Conversion

Type of Transporter	Order to TEU
Regular Barge	1 Order –(50,100) TEU
Super Barge	1 Order – (400,500,600,700)
AAGV	1 Order –2 TEU
Container Truck	1 Order- 2 TEU
Deep Sea Ship	1 Order- 4000 TEU
Feeder	1 Order- 1000 TEU

B.6. Terminal Specifications

B.6.1. APM Terminals

Table B.2: APM Terminal Specifications

APM-T Components	Numeric Value
Barge Berths	3
Deep Sea Berth(Panamax, ULCV)	1
Feeder Berths	2
Quay Cranes	10
Barge Cranes	3
Deep Sea Quay Length(Current)	1000m
Quay Cranes/Deep Sea Vessel	6
Barge Cranes/Regular Barge	1
Quay Cranes/Feeder Barge	2
Crane Moves Per Hour	30-50(Triangular Distribution)

B.6.2. Rotterdam Hinterland Terminals

Table B.3: Important Specifications of Hinterland Terminals[79]

Category	Rotterdam Short Sea Terminals	CTT,Matrans,BCW Terminal
Barge Berths	10 (1 berth taken)	1
Barge Cranes/Terminal	14	2
Barge Cranes/Barge	1. 1/Regular Barge 2. 2/Super Barge	1. 1/Regular Barge 2. 2/Super Barge
Crane Moves/hour	30-50	30-50

Transshipment for the 21st Century: A Novel Approach to Deep Sea- Hinterland Transportation

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***Abstract*—Globalization's impact on container trade has heightened maritime congestion at terminals worldwide, a trend set to worsen with increasing demand. This research addresses these challenges in deep-sea to hinterland transportation networks, proposing scalable transshipment solutions. Evaluating innovative concepts like amphibious AGVs and floating terminals, the study aims to enhance container transportation efficiency and reduce congestion. Key performance indicators prioritize reduced maritime congestion, maintaining daily throughput, transport time, and minimizing transporter fleet sizes. Utilizing agent-based modelling simulations, the research validates proposed transportation networks and assesses their impact on the Port of Rotterdam. The global applicability is demonstrated in the Hong Kong-Pearl River Delta, showcasing scalability. This work envisions a sustainable and adaptable future for maritime transshipment, introducing versatility through concepts like Amphibious AGVs and floating terminals. While exploring future prospects, the study acknowledges and addresses potential limitations and concerns.**

***Index Terms*—Transshipment, Agent-Based-Modelling, Globalisation, Deep Sea-Inland Waterway Network, Hinterland, Amphibious AGV, Floating Terminals**

I. INTRODUCTION

Globalization has spurred a significant surge in international trade, encouraging unified transport chains and diversified transportation options. The annual growth rate of world trade stands at 2.7% [1], with container shipping experiencing an encouraging 2.5% CAGR [2]. The escalating demand is met by container ship capacities reaching 24,000 TEUs, a notable increase from sub-10,000 TEU capacities two decades ago, accompanied by a 230% rise in container handling since 2000 [3]. This growth extends to hinterland transportation, particularly in intermodal and maritime sectors.Efficiency in transportation is crucial, as it directly impacts the cost of goods and commodities. Inland waterway transport, known for its cost-effectiveness and sustainability, plays a pivotal role. As global maritime platforms aim for net zero carbon emissions by 2030, ports advocate for increased inland waterway transport [6].The surge in inland waterway transport is positive, aligning with sustainability goals and supporting family-owned barge businesses. However, congestion issues are surfacing in major ports like Rotterdam and Antwerp [5], as well as in transshipment hubs like Hong Kong [9].Deep-sea container terminals, such as APM Terminals in Rotterdam, are expanding capacities without addressing barge berth limitations, leading to congestion [8]. Financial and environmental constraints challenge the feasibility of continuous expansion [7]. Barge operators face difficulties due to the inefficient arrivals/departures and meager call sizes absence of contractual relationships with deep-sea terminals [10],worsening congestion issues.This study addresses congestion in the deep-sea terminal-hinterland network, seeking solutions for both terminals and barge operators. Emphasizing future-proofing, innovative concepts like floating terminals, Amphibious AGVs, and Agent-Based Modeling were explored to propose novel transshipment network ideas applicable to all ports and networks. This work aims to contribute to the development of efficient and sustainable deep-sea to hinterland transportation networks.

II. RESEARCH QUESTIONS

How can an **efficient transshipment solution** be developed to mitigate **barge congestion** and enhance Hinterland transport within the **Deep Sea-Inland Waterway Network**, ensuring competitive throughput, transport times, and reduced fleet sizes amidst goals of barge significance and deep-sea terminal growth? Sub-questions:

1) **Current Challenges:** What challenges impact inter-terminal barge networks between inland and deep-sea

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terminals, influencing Barge/Deep Sea Operator performance?

2) **Logistical Adaptations:** Considering land/space constraints, what logistical changes can address these challenges, and what are the short-term, medium-term, and long-term goals for revamped transshipment setups?
3) **Impacts and Trade-offs:** What time-to-throughput impacts can be expected with port condition changes, aiming to reduce barge congestion, and what business/logistical trade-offs might arise between novel transshipment concepts and current operations, influencing terminal growth?
4) **Global Applicability:** To what extent can these transshipment changes be globally applicable across ports and hinterlands worldwide?

III. LITERATURE REVIEW

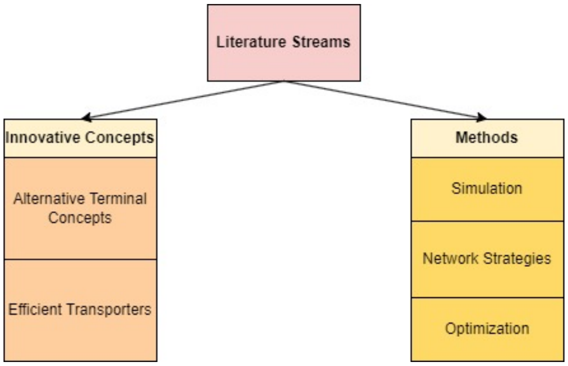

Fig. 1. Literature Streams

A. Innovative Concepts

1) Transshipment Concepts: Investigating ways to meet future demand without extensive port expansion, a promising solution is the concept of a floating terminal. This offshore platform, adaptable and modular in design, mimics a traditional container terminal but at potentially 1/3rd the cost. Designs, like Rother [11] and Baird's, utilize run-down panamax vessels and barges, indicating a swift return on investment. Productivity-focused [13]innovations, such as carrier cranes [12], eliminate the need for extra handling equipment, reducing the reliance on AGVs/straddle carriers. The Space@Sea [14] project proves the time and throughput benefits of floating terminals in network strategy, connecting hinterland traffic with deep-sea terminals. The concept of a barge hub, discussed by Konings [15], offers advantages in handling large call sizes, especially when converted from existing terminals. However, feasibility for small cargo volumes [17] is noted for both floating terminals and barge hubs.

2) Efficient Transporters: In container shipping, addressing efficiency requires innovative concepts like the Amphibious AGV, which combines land and water travel for swift inter-terminal transport, potentially reducing transfer times by 21% compared to trucks for short distances. AAGVs, envisioned by TU Delft's Timo Kleefstra [19] and a subsequent improved version which is used here [18], offer versatility, diverting hinterland congestion from deep-sea terminals.This is shown in figure 2. Another innovation, the waterborne AGV [20], proposed by H. Zheng and Dr. Rudy Negenborn, has shown promise, especially around the Maasvlakte in Rotterdam. However, compared to AAGVs, they still require an additional handling point between water and land. To address the challenge of low call sizes, a concept referred to as ”Super Barge” is introduced, capable of transporting 400-700 TEUs [21], potentially benefiting barge hubs and floating terminal concepts designed for large call sizes.

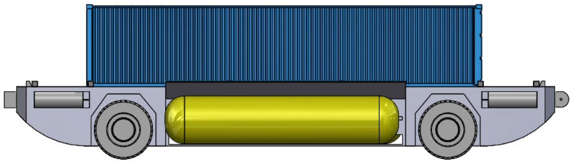

Fig. 2. Amphibious AGV [18]

B. Simulation and Optimization in Marine Transport

Simulation is crucial for understanding maritime transshipment processes, particularly in the context of deep-sea terminals to hinterland transportation. It aids in identifying bottlenecks and assessing a range of solutions, providing insights into optimal and suboptimal scenarios for decision-making. Two predominant methods, discrete event simulation (DES) and agent-based modeling (ABM) [22], are commonly used. DES models systems as sequential processes [23], representing each step as an event in a structured manner, lacking flexibility for simultaneous processes. In contrast, ABM classifies entities as agents, simulating their actions and interactions, offering flexibility and allowing for parallel processing. The autonomy of entities and the potential for simultaneous activities make ABM preferable over DES. Optimization is vital for determining fleet sizes for different models. Mathematical optimization falls into three categories: exact algorithms, which solve problems to optimality but require high computational time; approximation algorithms, which find approximate solutions with a guaranteed closeness to optimality and provide a good trade-off between accuracy and computation time; and heuristics, which prioritize speed over solution quality. Metaheuristics [24], like genetic algorithms, iteratively optimize a set of feasible solutions, making them suitable for large-scale simulations and fleet sizing optimization, striking a balance between speed, accuracy, and precision.

C. Network Strategies

Two predominant network strategies, hub-and-spoke [16] and point-to-point, shape logistics networks. Point-to-point theory involves individual transporters connecting each point directly, requiring numerous unique vehicles for an expansive network. In contrast, hub-and-spoke theory designates a central hub from which transporters originate, reducing the need for unique vehicles. The ideal maritime transshipment system combines both strategies, utilizing point-to-point for short-distance transfers and hub-and-spoke for long-distance ones. Successful companies like Maersk [**?**] and Indigo Airlines [25] have adopted a hybrid approach for efficient goods transit. This literature-driven inference guides the chosen network strategy for this work, ensuring a balanced and effective system.

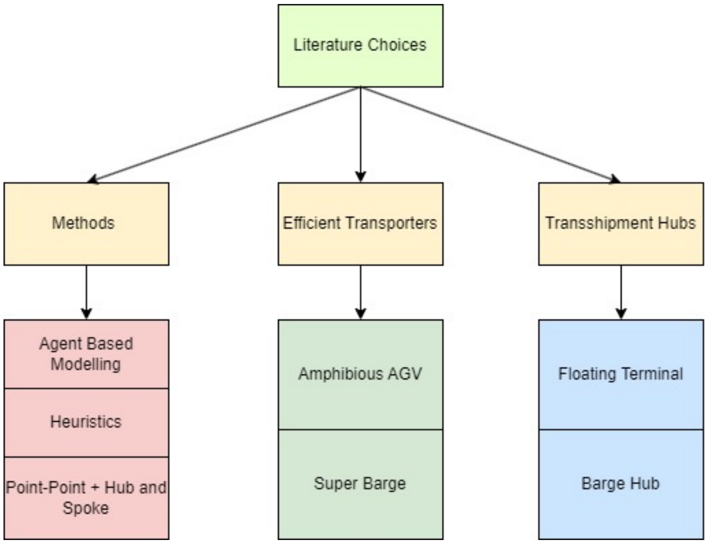

Fig. 3. Final Choices Summarised

IV. Methodology/Methods

The methodology of investigating the above research questions is given in the figure

A. Method- Agent-Based Modelling

The deep sea terminal to inland waterway network consists of multiple entities which are modelled as agents and hence will follow an agent-based modelling approach due to the reasons stated in literature. The agents are predominantly of three categories namely *Ports and Terminals,Containers and Transporters*. There are multiple tyes under each of these agents and they are presented in figure 4. These agents are linked by a routing and distribution network that determines routes and checks container order fulfillment for the hinterland terminals.The combination of these agents form the transshipment networks which will be seen in the current transshipment scenario(benchmark) and the proposed solutions.

B. Methodology-Simulation Model

This agent-based model can be fully realised by implementing it under a simulation platform, which in this case was AnyLogic. In order to accomplish this, a process logic was defined that connects the three category of agents(Terminals, containers and transporters). For example, one of the common process logics used was the loading and unloading of containers to transporters from/to various terminals.This would happen at each container handling point and can be seen in section VI and section VII. The agent-based model and process logic are the major inputs to the model. The model gives us data such as containers and ships traversed and with help of data analysis tools like excel, we can obtain answers to our main parameters such as congestion which must be achieved at similar or better throughput,transport-time rates and fleet trade-off as current operational scenarios. Figure 4 represents an idea of how both the agent-based model and simulation would work together to give us the KPIs

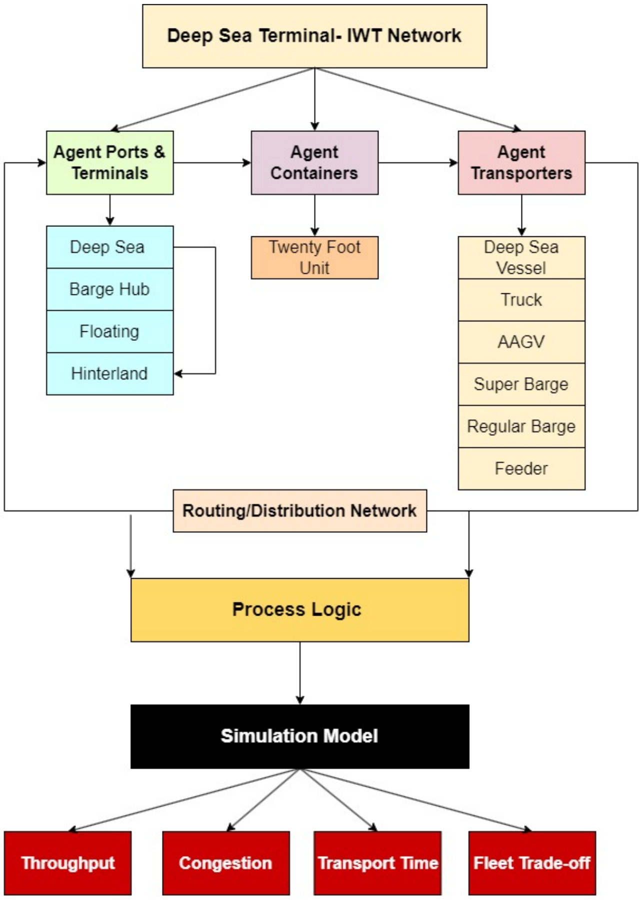

Fig. 4. Agent Based Modelling & Simulation

V. Environment

The chosen environment for comparing and implementing all solutions is the Port of Rotterdam, where terminals experience a daily in-flow of at least 5000 TEU. In the Port of Rotterdam, approximately 35% of hinterland-bound containers are transported to the hinterland by barges, making barge transport the primary focus for comparing the various solutions. Taking into account the container split between hinterland and inter-terminal transport, terminals like APM-II Maasvlakte send around 1050 TEU [26] to the hinterland every day.

VI. Benchmark Solution

Deep sea Ships and Feeder Ships carrying 4000 TEU and 1000 TEU respectively reach the APM-II deep sea terminal. Subsequently, the containers from both ships are unloaded

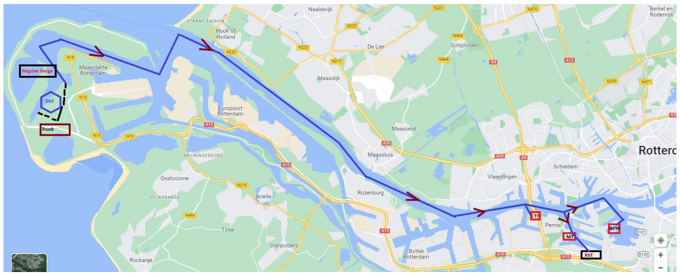

Fig. 5. Port of Rotterdam Layout

to trucks, facilitating the transfer between the deep-sea berth and barge berth within the deep-sea terminal. The final step involves barges with small call sizes transporting consignments of 50 TEU to the hinterland terminals.The layout of this is presented in figure 6

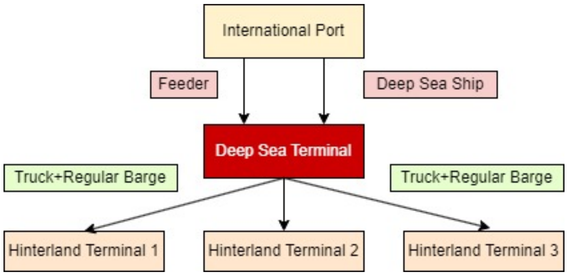

Fig. 6. Benchmark Case

VII. PROPOSED SOLUTIONS

A. Short Term Solution- Use of Existing Infrastructure

Strategy- Deep sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke). The short-term solution, designed for the next five years, relies on existing infrastructure for the transshipment network, with an exception for Super Barge, expected to materialize within this timeframe through technology transfer from high-density e-barge concepts in ports like Shanghai. The operational process includes daily arrivals of deep-sea and feeder ships at the APM-II deep-sea terminal, followed by unloading and transfer to a barge berth using a fleet of trucks and AGVs. Containers are then loaded onto a Super Barge at the barge berths, with common containers for all hinterland terminals for cost efficiency. The Super Barge travels to the barge hub, unloading consignments ending at the hub and transferring the remaining containers to the hinterland. Split consignments are further moved from the Super Barge Berth to regular barge berths at the hub using trucks. Finally, smaller call-size barges transport the remaining containers to the three hinterland terminals. The layout of this is shown in figure 7.

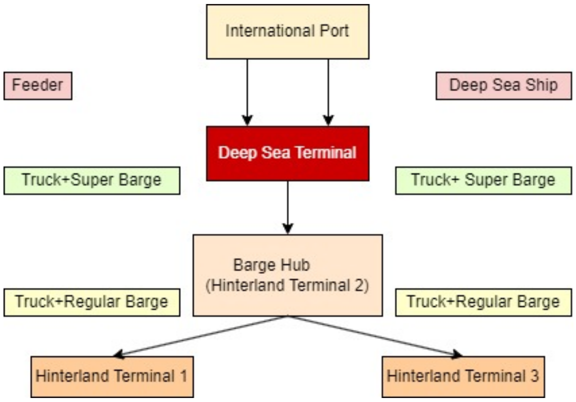

Fig. 7. Short-Term Solution

B. Short-Medium Term Solution- Introduction of AAGV

Strategy- Deep Sea Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland(Hub and Spoke)

Projected for implementation in the next 10 years, the short to medium-term solution assumes the development of amphibious AGVs within this timeframe, inferring from existing literature. It is similar to the previous short-term scenario but replaces the final truck+barge leg with unimodal AAGV transport. The process involves daily arrivals of deep-sea and feeder ships from Hamburg and Felixstowe at the APM-II deep-sea terminal. Upon arrival, these ships are unloaded and transferred to barge berths using trucks. Containers are then loaded onto a super barge at the barge berths, following an efficient process similar to the short-term case. The final step entails transferring the remaining 75% of containers to three hinterland terminals via amphibious AGVs stationed near Super Barge Berths. The layout of this solution is shown in figure 8.

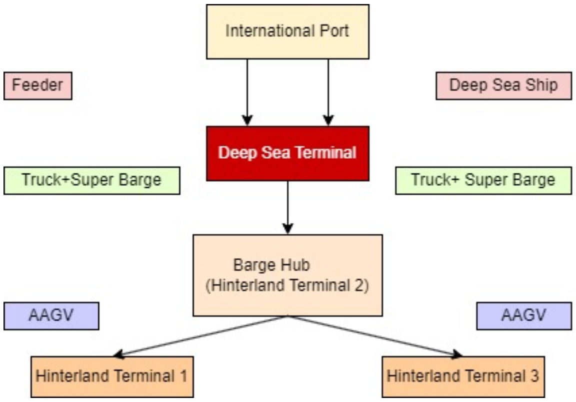

Fig. 8. Short-Medium-Term Goal- Introduction of Amphibious AGVs

C. Medium Term Solution- Introduction of Floating Terminals and Use of AAGVs

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke) The medium-term solution, anticipated within the next 10-15 years, envisions the active use of both floating terminals and Amphibious AGVs This used a floating terminal, specifically designed for this research. A small-scale Terminal can handle 1.26-2.1 million TEU (figure10). This approach mirrors the benchmark case, maintaining the same number of handling points. The process involves feeders and deep-sea ships arriving at the deep-sea terminal, where they are unloaded to Amphibious AGVs. Subsequently, these AGVs transfer hinterland-bound containers to the floating terminal. The containers are directly unloaded from deep-sea ships onto the AGVs, which exit the terminal through ramps, traveling by sea to the floating terminal. The final leg entails transporting hinterland-bound containers from the floating terminal to the hinterland via a regular barge system with low on-call sizes, resembling the existing system—a direct transfer from the floating terminal to the hinterland. The layout of this is shown in figure 9.

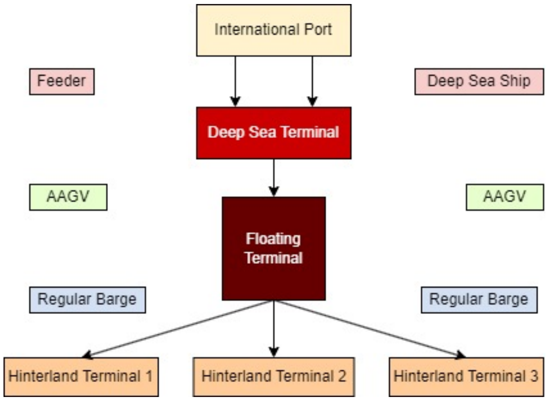

Fig. 9. Medium-Term Solution-Use of Floating Terminals and AAGVs

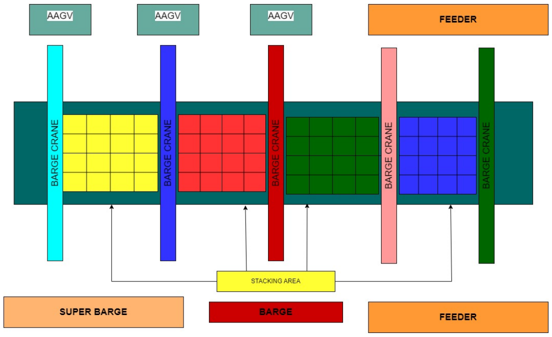

Fig. 10. Small Scale Floating Terminal

D. Long Term Solution 1- Combination of Transshipment Concepts

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Barge Hub(Point to Point) + Barge Hub to Hinterland Terminals(Hub and Spoke)

Seen as a long-term project for enhanced operational efficiency spanning 15 years or more, this integrated approach combines barge hub, floating terminal, amphibious AGV, and a 400-700 TEU super barge. Running in parallel with short and short-medium-term strategies, the international port and deep-sea terminal remain unchanged. Hinterland-bound containers are transferred to the floating terminal via amphibious AGVs, and then moved to the barge hub using a super barge. At the barge hub, containers destined for the hub are unloaded, with the remainder taken over by AAGVs. The final step involves transferring 75% of the containers to three hinterland terminals via amphibious AGVs near Super Barge Berths. Notably, containers for all terminals are efficiently loaded onto a super barge, maintaining consistent configurations for deep-sea terminals, barge hubs, and hinterland terminals in this integrated approach. The layout of this is shown in figure 11

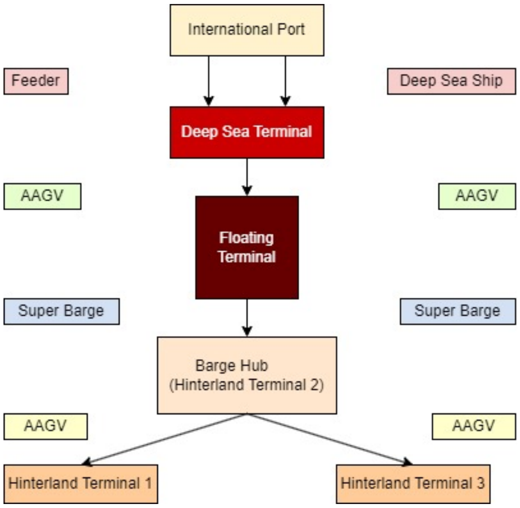

Fig. 11. Long Term Solution-Combination of Transshipment Concepts

E. Long Term- The Final Chain

Strategy- Deep Sea Terminal to Floating Terminal(Point to Point) + Floating Terminal to Hinterland(Hub and Spoke) To reduce congestion issues in floating terminals and barge hubs, a strategic shift in feeder traffic is proposed. Notably, the UK feeder ship would now directly transfer to the floating terminal, freeing up space for an additional deep-sea ship. The deep-sea vessel from Hamburg maintains its usual docking at the deep-sea terminal. Container consignments for the hinterland are moved from the deep-sea to the floating terminal, while those for inter-terminal transport from feeder ships are rerouted to the deep-sea terminal, optimizing AAGV utilization. Super Barges now transport hinterland containers directly from the floating terminal to individual hinterland terminals, minimizing trips. Importantly, the feeder accommodates containers under a modal split of truck and train, necessitating consideration of the entire hinterland consignment in flow rate calculations. The final chain layout is given in figure 13

VIII. VALIDATION OF THE BEST SOLUTION

The five solutions were subsequently compared with base demand and from this, a solution was found that performed best for each of the KPIs. The common best solution was then chosen and tested for different set of experiments as shown

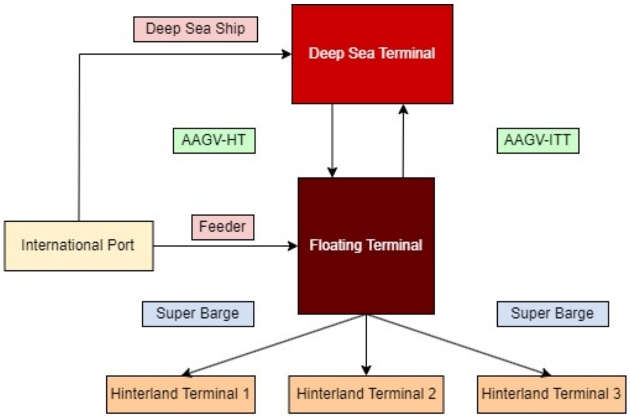

Fig. 12. Long Term- Final Chain

in the figure, as well as a different environment which in this case is Hong-Kong.

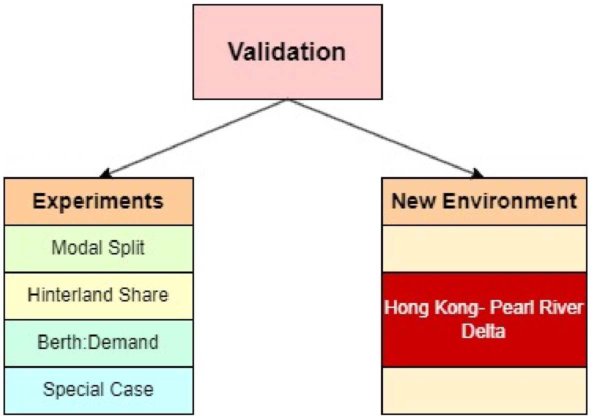

Fig. 13. Validation

A. Modal Split Experiments

Currently in Ports around the world, only 35% of the hinterland traffic is carried by barges. Ports like Rotterdam, Antwerp and Shanghai aim to increase this to 45%. thos experiment will test loads up to 55% as well.

B. Hinterland Share Experiments

Every consignment brought into a port is a mix of both inter-terminal and hinterland container loads. While this primarily operates at 40-60(ITT:HT), future projections show increased hinterland shares as high as 70 or 80%.

C. Berth:Demand Experiment

With terminals expanding, berths spaces will increase With revised transshipment setups, the increased demand can have swinging effects and has to be investigated through experiments.

D. Special Case Experiment

This is a worse case scenario which takes in a combination of factors shown above(55% modal split + 80% hinterland share + Maximum Demand/Berths)

E. New Environment

The new environment here is the Hong-Kong- Pearl River Delta where the new found solution will be tested against the benchmark.

IX. RESULTS

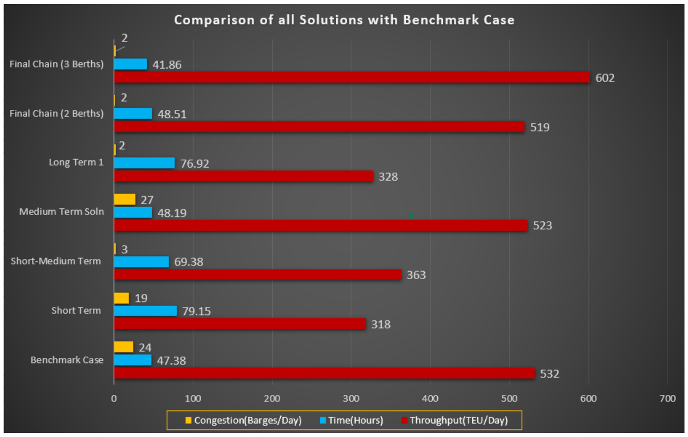

Fig. 14. Comparison of All Cases

A. Congestion

In reviewing the general results, the benchmark records 24 barges/day, aligning with APM-Terminals' data of 22 barges per day. This validates initial research questions on barge congestion, highlighting that low call sizes (50 TEU and under) can cause bottlenecks. Strategies in most solutions focus on diverting the congestion center or using larger call sizes. The comparison with five proposed solutions reveals candidates with reduced congestion: the short-medium term solution, long-term 1, and the final chain solution, all utilizing super barges with higher call sizes (400-700 TEU). These solutions effectively reduce congestion to about 2-3 super barges/day from the current 24 barges. However, the short-term case performs worse, recording 19 barges/day, causing congestion at the barge hub. The short-medium term solution, replacing truck+barge legs with Amphibious AGVs, eliminates berth congestion entirely.

Containers are unloaded onto Amphibious AGVs from super barges, improving sea-going vessel congestion by eliminating double-handling. The long-term solution 1 mimics the short-term scenario but introduces AAGVs and floating terminals, potentially facing congestion at change points. Another promising solution is the final chain solution, employing AAGV, super barge, and floating terminal, with only three handling/change points and 2-3 super barges/day in sea-going congestion. Conversely, the medium-term solution mimics the benchmark but suffers severe congestion at the floating terminal (26 barges/day, 9 barges/berth). However, this solution is competitive in time.

B. Transport Time

The transport time of hinterland container consignments depends on factors like handling points, call sizes, and equipment. The benchmark records a transport time of 47.37 hours, with the final chain solution, using three berths at the floating terminal, achieving a 12% improvement at 41.8 hours. The twin spreader technology and AAGVs contribute to this efficiency. The medium-term solution and final chain solution with 2 floating terminal berths offer close second-best solutions with times of 48.19 and 48.15 hours. Solutions with extra handling points suffer the most in transport time: Short Term Solution, Short-Medium Term Solution, and Long Term-1 record 79, 69, and 76 hours, respectively.

All three solutions focus on the barge hub concept, shifting hinterland traffic to the barge hub while reducing barge traffic using a Super Barge. However, major time losses occur at the barge hub during container transfers. Future prospects may lie in solutions like short-medium term, leveraging Amphibious AGVs in the last leg to reduce overall time by 10 hours. Though amphibious AGVs are limited by speed constraints, this motivates further research for their applications in inland waterways.

C. Throughput

Throughput performance parallels transport time, with the benchmark remaining effective at 532 TEU/Day due to the fast in-fast out concept. The final chain solution with 3 FT berths provides the best performance, recording a 12% improvement. The medium-term solution and final chain-2 FT berth solution are also effective. Solutions with additional handling points lead to significant time losses, although reducing congestion of sea-going vessels. While this research does not advise against their use, solutions like short-medium term might be more useful as a filler until new technology is introduced or for ports with lower traffic.

D. Fleet Size

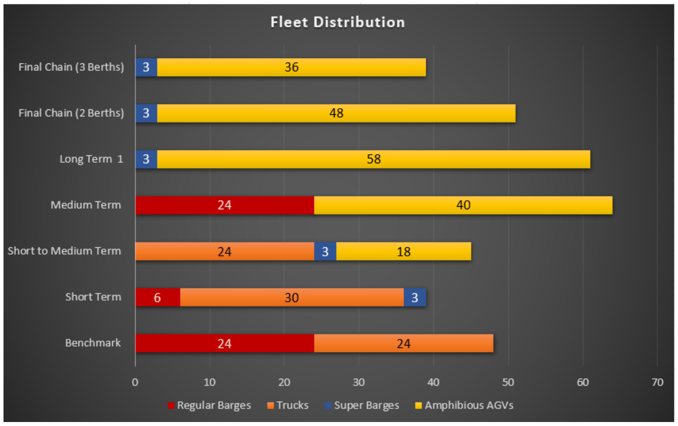

Fig. 15. Fleet Size Distributions

Fleet size control is crucial for the future, and the benchmark case's fleet of 24 regular barges and 24 trucks reveals congestion. The short-term solution reduces the fleet to 39 transporters, 20% better than the benchmark, using multiple transporter types efficiently. The short-medium term case, with a fleet size of 45, proves advantageous, being 10 hours faster overall than the previous short-term scenario. The medium-term solution sees a fleet size of 64 against the benchmark's 48, primarily due to AAGV transfer from the deep-sea terminal to the floating terminal. The long-term solutions, focusing on maximum barge reduction, increase fleet size to 61. The final chain solution with 3 FT berths provides a fleet size of 39, matching earlier solutions and offering competitive figures for transport time and throughput.

E. Inference

Studying all the solutions, it is clear that the final chain solution figures as the common solution among all KPIs that perform best. For experiments and the Hong-Kong Case Study, the final chain solution will be put against the current benchmark. This will also validate the proposed candidate solution in the process.

X. HONG KONG- PEARL RIVER DELTA CASE STUDY

A. Hong Kong- Pearl River Delta Environment

Hong Kong's Kwai Tsing Terminals, receiving 36,000 TEU daily from international ports, including Hutchinson International Terminals and COSCO-operated Container Terminals, handle up to 24 million TEU annually. Despite a pandemic-related drop to 12.869 million TEU in 2022, the HIT and COSCO-HIT terminals, handling 6500 TEU/day [9] with 120 barges in 2016, use 2 Barge/Quay cranes per barge, achieving an estimated throughput of 22,000 TEU/day. The large-scale floating terminal in the yellow-marked region, mirroring Rotterdam's conditions, can shift feeder/feedermax vessel traffic. Realistically, it accommodates 3 feedermax ships, 3 Super Barges, and 5 AAGVs, running with two different contributions. Seven inland ports in Guangdong, including Yantian and Shekou, are chosen for simulation due to their hinterland penetration and transshipment significance

Fig. 16. Hong-Kong Berths

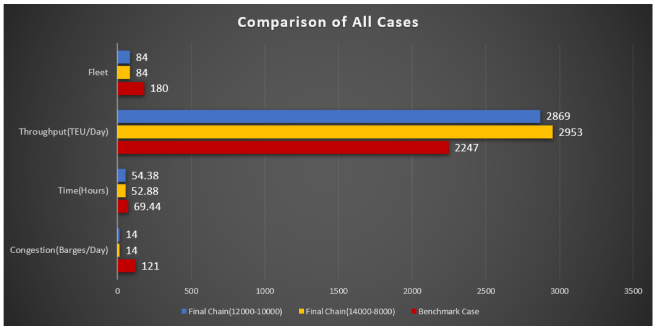

Fig. 17. Hong kong metrics comparison

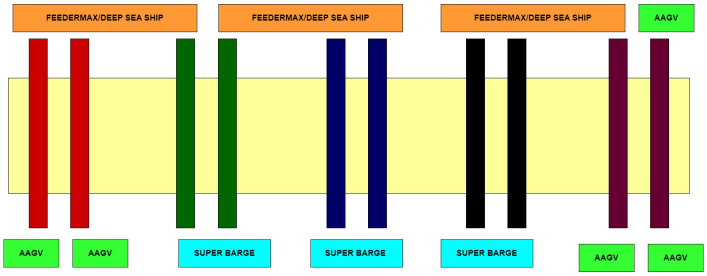

Fig. 18. Large-Scale Floating Terminal

B. Results

The Hong Kong-Pearl River Delta reveals notable results for various KPIs. Scaling up the final chain solution significantly boosts performance, contrasting with the hindrance observed in a small-scale floating terminal design (10) in the Special case experiment. Here a bigger 4.2 million TEU capacity floating terminal is used (18). The benchmark case shows 121 barges/day congestion, aligning with established terminal data [9]. Throughput, factoring in truck travel, barge transport, and other components, reaches a maximum container transfer rate of 2247 TEU/day to inland ports, considering a barge call size of 50 TEU. The benchmark takes around 69 hours for the entire 6500 TEU consignment. With 126 barges and 54 trucks, totaling 180 transporters, the deep-sea terminal handles 22000 TEU, as mentioned earlier.The final chain solution, implemented with two configurations (DST-14000 handling 8000 TEU, DST-12000 handling 10000 TEU at the floating terminal), excels in all KPIs. Large call sizes in super barges reduce congestion from 121 barges/day to just 14 super barges/day and 70 AAGVs. The final chain records a transfer rate of (2869-2953 TEU/day), substantially higher than the benchmark's 2247 TEU/day. High call sizes, like 700 TEU, make sense in this region, given multiple daily trips from the Hong Kong port to the same inland port. Lower congestion results in a significant fleet size reduction from 180 to 84 transporters (14 Super Barges and 70 AAGVs). One limitation in Rotterdam cases is resolved with the floating terminal's closer proximity to deep-sea terminals, contributing to a 23-25% improvement in total transfer times (52.8 to 54.4 hours). AAGVs transfer the same containers in 31-33 hours, a 30% improvement over the benchmark's 43 hours. The productivity of AAGVs is more pronounced when uncertainties like floating terminal distances are eliminated. In terms of throughput, both final chain configurations transfer 30% more containers in the same timeframe as the benchmark case, showcasing the flexibility and effectiveness of concepts like AAGVs and floating terminals.

XI. Discussion

A. The Case for Amphibious AGVs

Amphibious AGVs (AAGVs) are a key innovation, offering dual mobility on water and land. They reduce double handling of containers, divert traffic from terminals, and enhance access. Assessing their performance:

1) AAGV vs. Truck vs. Distance: Examining distance productivity, while trucks initially outperform AAGVs in trips/day, considering the distance covered reveals AAGVs' advantage. Despite covering twice the distance, AAGVs don't require double the fleet compared to trucks. Even with trucks being 40% faster, AAGVs demonstrate competitive performance. In the Hong Kong case, with nearly five times the distance to cover, AAGVs outperform trucks in trips/day, emphasizing AAGVs' efficiency in higher-demand scenarios. This suggests that AAGVs perform better when demand is higher and cover greater distances.

2) Implications on Floating Terminal: Insights suggest that locating floating terminals closer to deep-sea terminals could lower fleet rates or allow for more AAGV trips within the same fleet size, enhancing productivity. However, floating terminals must be strategically located to serve all nearby deep-sea terminals without disrupting existing operations.

3) AAGV Impact on Double/Multi-handling Procedures: AAGVs prove effective in reducing transport time and preventing double handling. In specific cases, replacing truck and barge legs with a single AAGV leg results in a significant time reduction, showcasing the efficiency of AAGVs in certain scenarios.

B. Floating Terminals for International Transshipment

1) Floating Terminal Performance and Scalability:: Floating terminals, when scaled up, show the potential to handle more containers and ships. In Rotterdam, the theoretical capacity is 2.1 million TEU, but during maximum demand, it handles 590,000 to 750,000 TEU. In Hong Kong, the annual throughput is 4.55 million TEU against a capacity of 4.2 million TEU. The versatility of floating terminals is evident, especially when handling both hinterland-bound and inter-terminal-bound containers.

2) Comparison with Barge Hub:: Floating terminals outperform barge hubs in handling capacities due to direct over-the-air container transfers, reducing the need for additional transportation equipment. The floating terminal's ability to handle and sort both hinterland and inter-terminal containers enhances productivity. While a barge hub offers flexibility in reconfiguring existing terminals, the floating terminal's return on investment is realized through reduced Operating Expenditure without redundant equipment.

C. Policy Suggestions and Implications

1) Operators of Entities: :

- **Floating Terminal/Barge Hub**- Since they handle hinterland traffic and sortation, the operator of floating terminal and barge hub will be the hinterland terminals itself.
- **Amphibious AGV**- The amphibious AGVs will come under an interesting split-operator scheme where both hinterland terminals and deep-sea terminals are involved. This will be delineated in the following section along with its business model
- **Super Barge**- The super barge will be owned by regular barge operators as previously established.

2) Barge Contracts& Business Model:

- **Port Agreement**- Define modal split agreements with deep-sea terminals, ensuring a prescribed percentage of containers is transported by super barges to the hinterland.
- **Operating Window and Berth Reservation**- Establish operating time windows and reserve berths at floating terminals to prevent congestion. Allow occasional use of deep-sea berths with conditions to avoid misuse.
- **Minimum Call Size**- Agree on a minimum call size to maintain high-capacity trips, incorporating a clause allowing only a 10% deviation from the agreed-upon size.
- **Lease Type**- Explore leasing models, such as short-term wet leases for trial periods, and damp or dry leases for long-term arrangements, depending on the operator's needs.
- **Energy/Fuel Hedging**-Implement fuel hedging strategies similar to Emirates/Southwest Airlines [27] to mitigate uncertainties in energy prices.

3) Amphibious AGV Business Model: AAGVs could follow a sales and leaseback model akin to Indigo Airlines [25]

- **Bulk Purchase**-Hinterland terminals buy AAGVs in bulk, securing discounts.
- **Sale and Leaseback**- AAGVs sold to deep sea terminals; leasing generates cash flow for hinterland terminals.
- **Fleet Operation**-80% of AAGV fleet leased to hinterland terminals; deep sea terminals handle maintenance.
- **Fuel Hedging**-AAGV fuel costs follow a hedging strategy to mitigate uncertainty.
- **Berth Optimization**-Encouraging feeder ship use at floating terminals frees up deep sea berths; possible facilitation fee for redirection

XII. CONCLUSION

Deep-sea hinterland transportation forms a significant part of the services sector in the world economy since over 80% of the volume of international trade is carried by the sea. Therefore, any improvements in this area will also impact the prices of our goods and home appliances that we use on a daily basis. Especially since hinterland transportation is about bringing goods into the deeper parts of a region, it is a priority to improve transportation efficiency and penetration in this area. One such barrier, and in many ways an irony, is the issue of congestion in container terminals due to hinterland-bound barges.Knowing the significance of swift delivery of containers and the underlying conflict between deep-sea terminals and barge operators, the maritime industry warrants solutions that solve the problem of congestion while balancing throughput, time, and lower fleet sizes. The extent of problems in the current system was validated through an agent-based modeling simulation methodology with the Port of Rotterdam as a test case. It could clearly be inferred from the results that each barge berth was facing a number as high as 8-9 barges/berth/day. Subsequently, new transshipment solutions were realized in the form of short-term, short-medium term, and long-term solutions. The solutions used innovative concepts like Amphibious AGVs, Super-Barges, and floating terminals which showed promise in a variety of circumstances.

Similar agent-based models were again utilized as the simulation strategy for these solutions. Based on simulation of current demand, the final chain solution was found to be the one that produced lower congestion while achieving faster transport time and lower fleets compared to the current transshipment scenario. This solution diverted feeder traffic to the floating terminal while leveraging the amphibious capability of AAGVs to divert hinterland traffic to the floating terminal. Subsequently, the Super barge carried the container consignments to the hinterland. The resulting outcome for the final chain solution was that congestion was reduced by 7 times, while transport time and throughput improved by 10%. The fleet size also improved by 20%.The final chain solution and the current transshipment scenario were subsequently tested with multiple experiments such as modal split, hinterland share, and berth:demand which explored the limits up to which the proposed final chain solution can be successful. However, the absolute extent and advantage of the final chain solution could be realized only when it was implemented in the Hong Kong-Pearl River Delta, which covers a footprint the size of the Netherlands. Pearl River Delta faces a demand of 6500 TEU/Day and congestion of 120 Barges/Day from Hong Kong, 6 times higher than that of Rotterdam. The final chain solution, when simulated in the Hong Kong environment, showed a 25% improvement in both transport time and throughput. However, the biggest improvement came about in congestion where 126 regular barges could be replaced by 14 super-barges, the fleet employed was just 70 transporters in the final chain case compared to the current transshipment scenario which used 180 transporters.

The takeaway from this research is that a solution can indeed be found that reduces congestion while being able to achieve competitive fleet sizes, transport time, and throughput. However, it must be realized that the proposed solution would work as expected only when the demand is as high as the one experienced in Hong Kong. This research also showed possibilities for several other solutions such as the short-medium term set of solutions that prioritized lower investment and could possibly be used in ports of low-income economies. From a societal scale, concepts like AAGVs showed that their versatility could potentially be used to connect small and micro-businesses that are situated along inland waterways. The author encourages researchers to look into such possibilities which could provide economical alternatives to businesses that use the AAGV. From a sustainability point of view, this work has sufficiently shown concepts like floating terminals can prevent unnecessary expansion of ports and land reclamation which is hazardous. The author also believes that in the coming years, this work will be critically looked at to encourage impactful concepts like AAGVs and floating terminals to be introduced for the benefit of hinterland transportation that could eventually lower prices of commodities that we use every day.

XIII. FUTURE WORK

A. AAGV For Hinterland Businesses

This research on deep-sea hinterland transportation has profound implications. The Amphibious AGV is a key concept, offering potential cost savings for small businesses in regions with inland waterways. Future research should explore its effectiveness for small businesses and assess business models like sales and leaseback.

B. AAGV for Coordinated Transportation

Amphibious AAGVs, investigating efficiency in inter-terminal transport is recommended. A coordinated platoon approach, inspired by eco-vessel-train formations, can prevent system clutter and offer efficient container transport from deep-sea to floating terminals. This approach benefits operators and allows monetization.

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