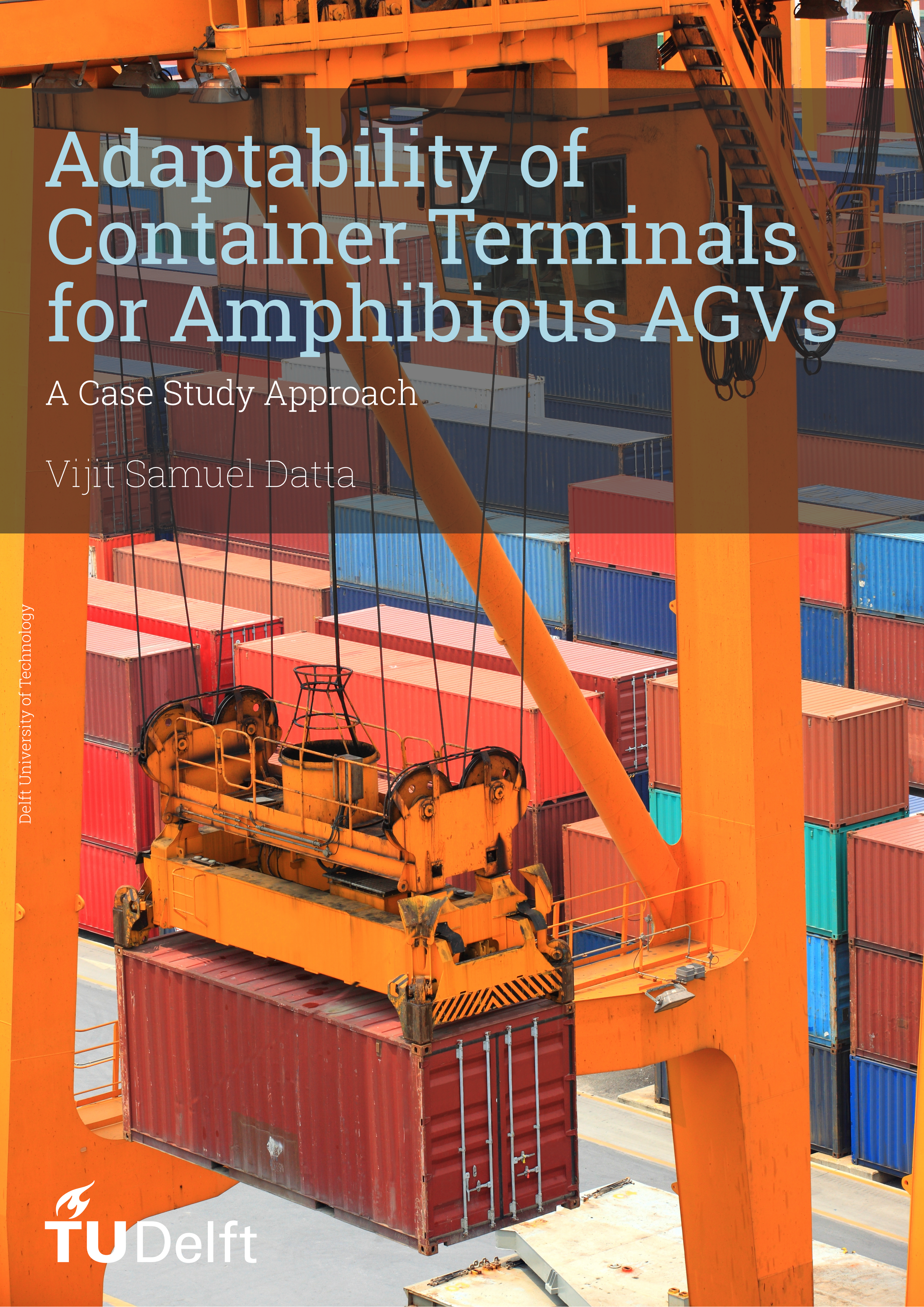
Adaptability of Container Terminals for Amphibious AGVs

A Case Study Approach

Vijit Samuel Datta



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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday, 31st May, 2024 at 1400hrs.

M.Sc. Track:	Multi-Machine Engineering
Student Number:	5491622
Report Number:	2024.MME.8933

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Preface

The exponential growth in maritime trade during the 21st century has posed notable challenges for container terminals, resulting in congestion and operational inefficiencies. This study delves into the efficacy of Amphibious Automated Guided Vehicles (AGVs) as an innovative remedy to tackle these issues and facilitate the shift towards autonomous operations at container terminals.

Motivated by the need to optimize spatial utilization and reduce reliance on conventional material handling equipment in port areas, this study employs an agent-based modeling approach. Subsequently, the formulated model is applied in a case study focusing on major Ports of the World.

This study undertakes a critical examination of the potential of Amphibious AGVs in alleviating congestion and operational challenges faced by container terminals in the context of an increasingly interconnected global trade setting. By conducting a thorough examination of existing literature and creating a generalised simulation model, this study aims to offer valuable insights that can influence the evolution of container terminal operations.

Keywords: Container, Transshipment, Amphibious AGV, Inter Terminal Transportation, Agent Based Modelling, Ramps, Power Consumption, Sustainability

Acknowledgments

This dissertation signifies the culmination of my academic endeavor for the Master's program in Mechanical Engineering with a focus on Multi-Machine Engineering at Delft University of Technology. It denotes the conclusive segment of my exploration into container inter-terminal transport (ITT) employing the Amphibious AGV (AAGV) and the essential adjustments needed within container terminals to enable its deployment.

I wish to convey my sincere appreciation to my supervisors, *Dr. Lavanya Meherishi* and *Dr. Alessia Napoleone*, for their priceless guidance, assistance, and expertise during this project. I am equally thankful to *Dr. Jovana Jovanova*, the chair of my graduation committee, for her commitment and guidance until the completion. Their profound insights and motivation played a crucial role in shaping this study and propelling me towards its conclusion. A consistent pillar of support throughout this dissertation; their collective proficiency in reconfigurability, optimization, and integration made a lasting impression on me and my research. They consistently went the extra mile to prevent me from feeling overwhelmed by the workload, despite having limited leisure time.

A heartfelt acknowledgment is extended to my teammates in Integration Project Group 7: *Abhishek, Benjamin, Casper, Jouke, Quincy, Surya, and Vijay*. The fundamental idea for the AAGV, which laid the groundwork for this thesis, was the result of our collaborative endeavours.

I am also grateful to the contributors from the EU MAGPIE Project and the Port of Rotterdam for their participation and input. Their steadfast dedication to promoting sustainability in the maritime sector is truly commendable.

My appreciation also goes to *all the faculty members in the Multi-Machine Engineering track* of the Mechanical Engineering Department at Delft University of Technology for imparting the knowledge and creating an environment that enabled me to excel in this domain.

I express my deepest gratitude to *my parents* for their unwavering love and encouragement throughout my academic pursuit, and for never giving up on me.

In the end, I thank the Almighty for his blessings that have guided and sustained me on this academic journey towards graduation, and without whom I believe this report would not have been possible.

Vijit Samuel Datta
Delft, May 2024

Summary

In this thesis, we delve into the adaptations necessary for the incorporation of Amphibious Automated Guided Vehicles (AAGVs) into container terminals. We look into integration of ramps, elimination of quay cranes and barges, battery replacement stations through stakeholder analysis and simulations of a generic container terminal yard.

AAGVs can operate both on land and in water, which would allow them to move containers between terminals within a port via water rather than taking a longer route via land. They can reduce or eliminate the need for Ship to Shore cranes and other equipment dedicated to barge operations, since instead of being unloaded by cranes they can directly climb onto land in the container terminal to be directly unloaded in the container yards. Since they operate autonomously and would not need cranes, the human limitations of human operated barges are removed, giving virtually continuous autonomous operations to Container Terminals. In addition, it should also be noted that since the AAGVs are battery powered, they would not generate any operational carbon dioxide emissions in contrast to fossil fuel powered barges or trucks.

Agent-based modeling has been employed to replicate and analyze the operation of container terminals. This approach involves creating computer simulations where individual agents, representing the various entities involved in the terminal's operations, interact and make decisions based on their programmed behavior. These agents include a combination of multiple AGVs, AAGVs, Reach Stackers, Quay Cranes and Gantry Cranes, as well as the containers themselves. By simulating the movement and interactions of these agents, insights are gained into the overall efficiency of the terminal, identifying bottlenecks, and evaluating the impact of various factors such as equipment levels and equipment configurations allowing optimization of the terminal's operations and improvement of its overall performance.

The simulations encompass two scenarios: a base scenario where containers are stacked using a combination of barge, quay cranes, land-based AGVs, and RS or RTG, and a scenario where AAGVs transport the containers between a terminal approximately 5 kilometers away and the home terminal with the containers being stacked by RS or RTG without ever utilizing any quay cranes or barges. These scenarios are all juxtaposed under varying throughputs and varying numbers of reach stackers and AGVs and AAGVs. The model takes into account factors such as travel, unloading and waiting times for the AAGV.

The simulation results show that the AAGV scenario is more effective than the combined scenario of the AGV and Barge for container transportation at any given throughput. This is because the AAGV scenario eliminates the need to unload containers from a barge onto AGVs, which saves time. It must however be noted that a higher number of AAGVs can lead to congestion, which can increase the average container transport time by a small margin.

The key findings of this research demonstrate that the AAGV scenario consistently outperforms the combined scenario of the AGV and Barge for container transportation at any given throughput level, proving that the AAGV approach is more efficient, for both RS and RTG scenarios. Moreover, increasing the number of reach stackers (RS) to an optimal range favorably impacts the average container transport time for both scenarios, indicating that more RS contributes to overall efficiency. While a higher number of AAGVs can initially enhance transportation speed, excessive congestion can occur, particularly if the same container yard is simulated, leading to a gradual increase in average container transport time. This highlights the need for optimizing AAGV deployment to strike a balance between speed and congestion management. In summary, the AAGV approach emerges as the most effective container transportation method.

The report concludes with recommendations for estimating the optimal number of AAGVs for different throughput requirements while also discussing the implications of the findings for the design and operation of container terminals.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
EU	European Union
IMO	International Maritime Organisation
AGV	Automated Guided Vehicle
AGV	Automated Guided Vehicle
AAGV	Amphibious Automated Guided Vehicle
RS	Reach Stacker
ASC	Automated Straddle Carrier
ARMG	Automated Rail Mounted Gantry Cranes
STS	Ship to Shore (Cranes)
TEU	Twenty-foot equivalent unit
ECT	Europe Container Terminals
MHL	Materials Handling Library (AnyLogic)
H&S	Hub and Spoke
COVID-19	Corona Virus Disease of 2019
ITT	Inter-Terminal Transportation
IWT	Inland Waterway Transportation
ABM	Agent Based Modelling
RTG	Rubber Tyred Gantry Crane

Symbols

Symbol	Definition	Unit
g	Acceleration due to gravity	[m/s^2]
L	Length of ramp	[m]
h	Height of ramp	[m]
$mass$	Weight of AAGV	[kg]
$length$	Length of AAGV	[m]
$h_{submerged}$	Height of AAGV which is submerged	[m]
h_{loaded}	Height of AAGV when loaded	[m]
$Dist_{water}$	Distance travelled by AAGV on water in single trip	[km]
$Dist_{land,aagv}$	Distance travelled by AAGV on land in single terminal in single trip	[km]
$ramp$	Distance travelled by AAGV on single ramp in single trip	[km]
$width$	Width of AAGV on land	[m]
$width_{submerged}$	Width of AAGV submerged	[m]
v_{water}	Maximum permitted speed on water	[m/s]
v_{land}	Maximum permitted speed on land	[m/s]
$A_{underwater}$	Frontal Cross Sectional Area of AAGV submerged	[m^2]
$A_{overwater}$	Frontal Cross Sectional Area of AAGV exposed over water	[m^2]
A_{land}	Frontal Cross Sectional Area of AAGV when on land	[m^2]
P_{water}	Power needed by AAGV on water	[kW]

Symbol	Definition	Unit
P_{land}	Power needed by AAGV on land	[kW]
$P_{incline}$	Power needed by AAGV on incline	[kW]
E_{aagv}	Total Energy consumed by an AAGV in a single trip	[kWh]
$C_{battery,aagv}$	Capacity of AAGV Battery	[kWh]
C_d	Drag coefficient	[no unit]
f_r	Coefficient of Rolling friction	[no unit]
θ	Angle of inclination of ramp	[°]
ρ	Density of Air	[kg/m^3]
ρ_{water}	Density of Water	[kg/m^3]

1 Introduction

Automation is transforming port operations, with increasing digitization and automation in the logistics industry. Currently, approximately 60 container terminals across the globe are in various stages of automation, with an additional 100 projects planned for implementation by 2030 [39][38]. Asia has the highest number of such terminals, but Europe is not far behind, with ports like Rotterdam and Hamburg already having automated terminals. In Spain, the ports of Barcelona, Algeciras, and Valencia are semi-automated or set to become semi-automated in the near future.

One example of a highly automated port is the Qingdao port in China [48]. It boasts two fully automated berths spanning 660 meters of its quay and capable of handling 5.2 million TEUs [48]. It also has seven ship-to-shore cranes, 38 automated stacking cranes, and 38 Autonomous Guided Vehicles (AGV) [48]. The automation has taken over the work from the berth to the container yard, enabling human operators to monitor the machines from control rooms [48]. This terminal commenced operations in May 2017 and, in its first year, serviced over 660 vessels and handled close to 800,000 TEUs [48]. Initially, the average loading efficiency was 26.1 containers per crane per hour, which has increased to 33.1, representing a 50% improvement over the global average [48]. Moreover, the terminal has reduced the number of port workers required to unload a shipment from 60 to only nine [48].

The Port of Rotterdam is the largest port in Europe and one of the busiest container ports in the world. In 2022, the port handled over 14 million TEUs (twenty-foot equivalent units) [63]. Container operations in the Port of Rotterdam are highly efficient and automated. The port has a number of state-of-the-art container terminals that are equipped with the latest technology. The port also has a well-developed infrastructure that supports the efficient movement of containers [63].

Figure 1.1: Qingdao Container Terminal operated by APM Terminals [46].

The impact of automation on port efficiency, which is defined as the ratio of inputs to outputs at ports, is not entirely clear despite numerous studies on the topic [39][62]. Additionally, [39] finds that automation has a limited effect on productivity, while size and specialization of a container terminal are crucial factors in enhancing efficiency. This suggests that automation cannot be regarded as the sole determinant of port terminal performance, but rather should be integrated with the general port context to achieve actual benefits. Factors such as port organization, specialization, geographical location, and size play a more significant role in determining the performance of ports than technology alone [39][38].

A prime example of automation's limitations comes from the 2017 cyberattack on the Rotterdam Port. This attack targeted, among many, APM Terminals, a major global container terminal operator with highly automated facilities at Rotterdam [41]. The malware disrupted operations, causing delays and demonstrating the vulnerability of automated systems to cyber threats [41]. This incident highlighted the need for robust cybersecurity measures alongside automation to ensure smooth port operations.

Figure 1.2: APM Terminals Bahrain operating within the Khalifa Bin Salman Port of Manama, Bahrain [46].

The Port of Rotterdam is also a major hub for transshipment. Transshipment is the process of transferring cargo from one ship to another within the same port. The Port of Rotterdam handles over 10 million TEUs of transshipment cargo each year [63]. Transshipment is an important part of the container shipping industry, as it allows shipping lines to transport cargo more efficiently and cost-effectively. Transshipment also helps to reduce congestion at major ports [37].

Containers are transported within the terminal yard using a variety of vehicles, including straddle carriers, reach stackers, and forklifts. The port also has a number of automated guided vehicles (AGVs) that are used to transport containers within the terminal yard [5] which are then loaded onto Barges. The current method of transporting containers between terminals using barges is inefficient and environmentally unfriendly. Barges are slow, consume a lot of fuel, and require additional infrastructure, such as quay cranes, to load and unload containers [40]. This can lead to congestion and delays at ports, and it also contributes to air pollution and greenhouse gas emissions [40].

Figure 1.3: An aerial view of the Container Exchange Route within the MaasVlakte II [6]

Trucks are a common mode of transport used to transport containers to and from the Container

Terminals on the MaasVlakte II to inland destinations having dedicated truck terminals that can handle a large volume of truck traffic [7]. However for ITT, they take the Container Exchange Route (CER) which is much longer than simply travelling between the terminals via the water.

Trains are also used to transport containers to and from the MaasVlakte II, however they are not preferred for Inter-Terminal Transportation since the travel times and the utilization levels needed to make it a feasible option render it unattractive to stakeholders due to the fact that trucks are cheaper and flexible [7].

Figure 1.4: A train being loaded with containers in the Port of Rotterdam [8]

Optimizing Container terminal operations requires a seamless interaction of multiple stakeholders, each playing a crucial role in ensuring efficient cargo movement and overall success [44]. Shipping lines, the carriers that transport containers between ports, rely on terminals for rapid vessel loading and unloading. They collaborate with terminal operators to optimize schedules, minimize delays, and influence pricing [44].

Terminal operators, responsible for day-to-day operations, handle cargo, load and unload vessels, maintain equipment, and manage the workforce[54]. They coordinate with shipping lines, freight forwarders, and other stakeholders to ensure smooth cargo flow and optimize terminal performance [54]. Port authorities are government agencies overseeing ports, manage infrastructure, enforce regulations, and ensure compliance with safety and environmental standards. They attract investment, promote competitiveness, and foster collaboration [54].

Additionally, there are Labor unions which advocate for fair wages, safe working conditions, and equitable labor practices, safeguarding the workforce that drives the terminal [70][61]. Harmonious relationships between unions and operators are essential for terminal stability and productivity. Lastly, Governments regulate and support the container terminal industry, establishing regulations on cargo handling, safety, environmental protection, and labor practices [68]. They fund infrastructure and invest in port expansion projects, contributing to port efficiency and global trade growth [58].

Since we have ruled out trucks and trains, we are left with Barges, which are used to transport containers within the MaasVlakte II as well as from the MaasVlakte II to other terminals inland. Every terminal has dedicated barge berthing facilities that can handle a large volume of barge traffic [7]. The increase in containerization has resulted in an increase in the international trade of manufactured goods and has prompted competition among ports, thereby exerting pressure on the infrastructure of the surrounding areas [47]. In the current landscape of port competition, the efficiency of transport related to ports is of utmost importance, with the of utilization Inland Waterway Transportation (IWT) being viewed as crucial for sustainable development [47].

Despite the existence of policy objectives and the favorable environmental impact of IWT, the percentage of container barging in Rotterdam has experienced minimal growth, and its performance has been observed to be inefficient [47]. A unique solution of transportation via water but not utilising precious Quay Length and Quay Cranes like Barges is required because IWT Barges between deep sea ports and inland ports lead to congestion and prioritisation issues with Barges that are being used for ITT. These inefficiencies can be attributed to coordination issues between deep-sea terminal operators and hinterland transportation companies [47].

ITT efficiency is however not limited to barges. Container handling equipment plays a crucial role in

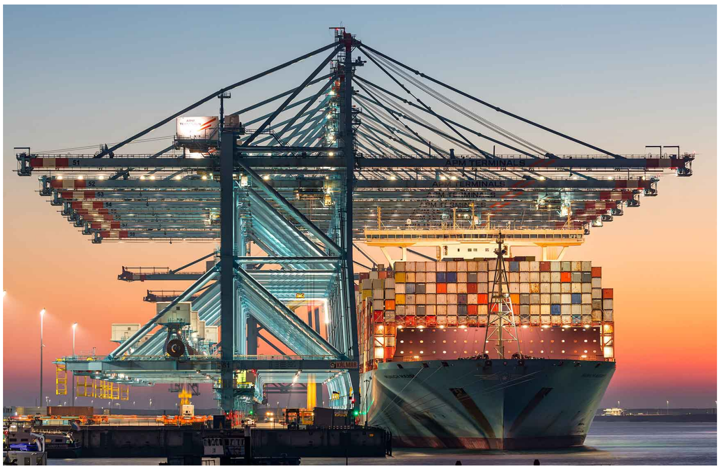


Figure 1.5: Maasvlakte-2 terminal operated by APM Terminals in the Port of Rotterdam [46].

the smooth operation of container terminals, enabling the efficient movement and storage of containers [69]. These specialized machines are designed to handle various tasks, from lifting containers from ships to stacking them in the terminal yard. Three key pieces of container handling equipment are Quay cranes, straddle carriers, and reach stackers [69].

The Quay cranes, also known as ship-to-shore (STS) cranes, are the workhorses of container terminals. They are responsible for loading and unloading containers from ships, a critical step in the container shipping process [69][5]. These massive cranes are mounted on rails along the quayside, enabling them to reach ships at berth. Their powerful hoisting mechanisms lift containers from the ship's hold and stack them on trucks or rails for transport to the terminal yard [69][5]. Automation in STS Cranes enhances precision and speed. The utilize advanced positioning systems and anti-sway technologies to ensure smooth and accurate container handling, minimizing the risk of damage and improving overall turnaround times for docked vessels [74]. Automated cranes can integrate with terminal management systems, receiving real-time data on container locations and optimizing the loading and unloading sequence. This reduces idle time and unnecessary crane movements, leading to significant throughput gains [62].

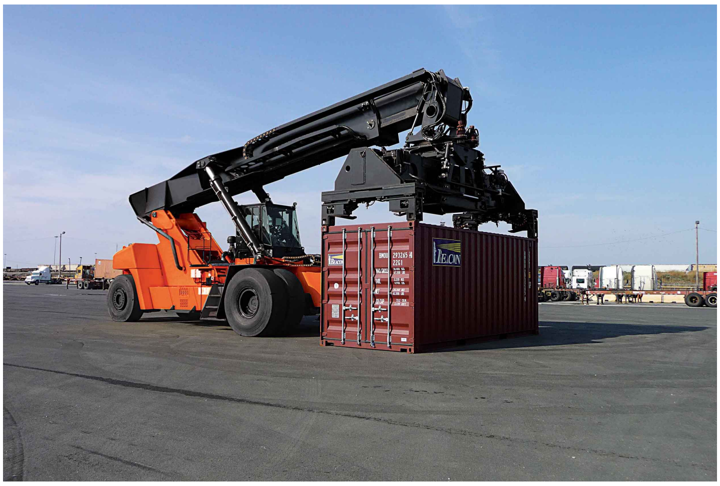


Figure 1.6: Reach Stacker [60]

Straddle carriers are specialized vehicles used to transport containers within the terminal yard. They can lift containers from the ground, move them to their designated location, and stack them on top of each other [69]. Straddle carriers are commonly used to move containers between the quayside and container storage areas. ASCs are essentially straddle carriers equipped with advanced automation technology, allowing them to operate without a human driver [69][5]. They utilize a combination of sensors, cameras, and onboard computers to navigate precisely, identify obstacles, and handle containers autonomously. By removing human error from the equation, ASCs significantly reduce the risk of accidents involving personnel and equipment. Additionally, ASCs operate with greater precision, ensuring smooth and efficient container handling, which further minimizes the potential for damage to cargo[69][5]. They can operate 24/7 without fatigue or breaks, leading to increased throughput and overall shorter times for vessels. ASCs can integrate seamlessly with other automated systems like automated stacking cranes, creating a fully automated workflow that streamlines container movement.

Reach stackers are smaller, more maneuverable vehicles that operate within the container yard. They are used to handle containers within the stacks, loading and unloading trucks, and repositioning containers within the yard. Reach stackers are typically powered by diesel engines or electric motors, and their articulated booms allow them to reach containers stacked high in the yard. They are particularly useful for handling smaller containers and moving containers within the yard. Reach Stackers are generally not automated and almost always use a human operator.

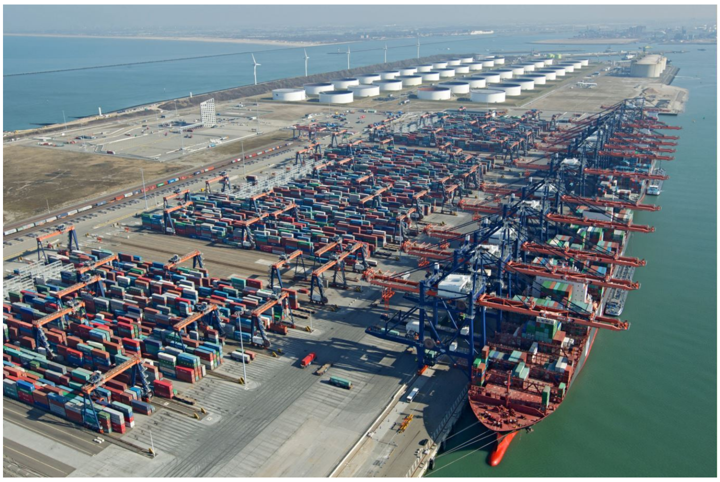


Figure 1.7: Aerial view of the Euromax Terminal [57]

AGVs are unmanned vehicles that operate within the confines of a container terminal, transporting containers between designated points. They are guided by a myriad of sensors, enabling them to navigate the terminal efficiently and safely. Powered by electric motors, modern container AGVs are environmentally friendly and significantly reduce emissions compared to their diesel-powered counterparts [9].

Inefficiencies in container handling equipment can significantly impact Intermodal Transportation Time (ITT). Human decision-making in scheduling cranes and coordinating with AGVs can lead to delays, while maintenance downtime for complex equipment disrupts container flow [59]. Furthermore, integrating automated and human-operated systems requires robust communication to avoid information delays and inefficient equipment utilization. Finally, even implementing automation introduces initial inefficiencies as operators learn the new systems [59].

While automation has taken over many operations on the port side, there is still a huge scope for automation on the water side [39]. Barges that are used for transporting containers over water are at present not automated, and are operated on the commands of human operators that are present in the vessel, which is in contrast to AGVs, which are used to transport containers over land within container terminals, and which are automated. The perceived disadvantages of barge non-automation include potential for human error in navigation, increased reliance on manual labor, and slower reaction times compared to automated systems [66]. This leads to inefficiencies, safety risks, and higher operational costs. [10][75].

In the dynamic realm of container terminals, automated guided vehicles (AGVs) silently navigate the bustling corridors, their movements guided by precise sensors and intelligent algorithms. These robotic workhorses are revolutionizing container handling operations, introducing unprecedented efficiency, accuracy, and safety [1].

AGVs resemble driver less flat trucks, equipped with a variety of sensors, including laser scanners, magnetic encoders, and infrared beacons. These sensors enable the AGV to precisely follow predetermined paths, ensuring seamless navigation within the terminal [73]. The AGV's power source varies depending on the application, with electric AGVs being increasingly prevalent due to their environmental sustainability [1] while the older generation tend to be hybrids [56].

AGVs are highly versatile machines, capable of performing a wide range of container handling tasks. They are frequently used to transport containers between ships, trucks, and rail cars, ensuring seamless movement of cargo between different modes of transportation [11]. Their ability to navigate the terminal efficiently also makes them ideal for repositioning containers within the yard, optimizing storage and retrieval operations [73].

So what if we use Amphibious AGVs as an alternative to barges for ITT? AAGVs can travel on both land and water [65], eliminating the need for barges and quay cranes. They are also more fuel-efficient than barges and can operate on renewable energy sources, such as solar and wind power [32]. Barges are not automated, whereas AAGVs are. This will eliminate the need for a human to be physically present to control each vehicle [38].

In addition to the environmental benefits, AAGVs also offer a number of operational advantages. They can be programmed to follow specific routes over water and schedules, which can help to improve the efficiency of Inter-Terminal container transportation [53]. AAGVs can also be used to transport containers to and from remote locations that are not accessible by barge. This can help to make it easier to transport goods to and from different terminals within a port complex. This could help to reduce congestion and delays at the port [73]. Compared to trucks, AAGVs can potentially reduce traffic congestion and road wear, especially in densely populated areas. Their zero-emission operation aligns with environmental sustainability goals [12]. Additionally, AAGVs can navigate waterways inaccessible to trucks, offering greater flexibility in reaching remote locations. While trains provide efficient long-haul transport, AAGVs can excel in shorter regional deliveries, offering potentially faster point-to-point commutes without the limitations of fixed railway tracks. Their automated nature should further enhance efficiency and safety by eliminating human error in route selection and operation [62].

In addition to the benefits mentioned above, AAGVs could also help to reduce the cost of container transportation. AAGVs run on electric power as compared to barges and do not require the same level of infrastructure [64]. This could lead to lower transportation costs for businesses and consumers [64].

AAGVs are a relatively new technology, but they have the potential to revolutionize the way that containers are transported. As the technology continues to develop and become more cost-effective, it is likely that AAGVs will play an increasingly important role in the global logistics industry [64].

In this thesis, the idea of implementing an AAGV in container terminal operations is looked into along with observation of the changes experienced when an AAGV is deployed for container handling operations. The thesis answers whether it would really be beneficial to implement AAGVs into container terminals and would it really make an impact on the efficiency of ITT within a port. The changes that would be introduced to a container terminal due to the implementation of the AAGV are also looked into so that their effect on efficiency on overall container terminal operations can be observed along with their impact on other container handling equipment. To understand the effects, this thesis utilises container transportation time and container throughput between two container terminals within a port as Key Performance Indicators.

This thesis involves an extensive literature review, an explanation of the methodology that is used in the research, an overview of the data that has been gathered upon which the simulations are built and the final findings that were observed. The conclusions drawn from these observations finally conclude this thesis.

2 Literature Review

The literature review process was conducted to identify relevant academic papers and industry reports that address the feasibility of implementing amphibious Automated Guided Vehicles (AAGVs) in container terminals. The keywords used for the search included ”amphibious AGVs,” ”container terminal,” ”inter-terminal transportation,” ”efficiency,” and ”environmental impact”. The search engines utilised in the search include Google Scholar, ResearchGate, Mendeley and Scispace.

It is carried out in order to understand the possibilities discussed in Chapter 1 so as to explore the challenges that would be faced which can include the congestion within container terminals, the delays caused and experienced by barges, the inefficiency of current equipment, and the environmental impact of the current scenarios of ITT. Amphibious AGVs can offer a potential solution to all these challenges, as they can travel on both land and water, eliminating the need for barges. They are also more fuel-efficient than barges and can operate on renewable energy sources.

The literature review also reveals that there is still a need for more research on the specific challenges of implementing amphibious AGVs in container terminals, such as the modifications that need to be made to port infrastructure and the operational procedures that need to be changed. It provides a valuable foundation for the research presented in this thesis, identifying the key challenges and opportunities associated with amphibious AGVs, and it provides a framework for the research questions that will be answered by the subsequent chapters.

2.1. Congestion in Container Terminals

The ongoing growth of the sizes of container ships leads to situations of high peak in landside container handling at logistic nodes in the port, resulting in congestion. These situations occur due to the continuous increase in the dimensions of container ships, which in turn necessitates the handling of larger quantities of containers at the logistic nodes within the port [50]. As a consequence, the capacity of the landside container handling infrastructure is strained, leading to congestion[50]. This congestion arises from the inability of the infrastructure to cope with the increased demand for container handling services. It is important to note that congestion is a significant issue in the context of container handling, as it hampers the efficiency and effectiveness of the port's operations. This is because congestion not only results in delays and increased waiting times for containers, but it also impacts the overall flow and movement of goods within the port. Consequently, it is crucial to address the issue of congestion in landside container handling at logistic nodes in the port in order to ensure smooth and efficient operations[50].

Congestion in terminals on the seaside has also been increasing over the past years due to Barge Congestion in addition to inefficient terminal operations, inadequate infrastructure, and environmental regulations [66]. There are a number of strategies that can be used to mitigate barge congestion, including enhancing terminal operations, expanding infrastructure and more importantly promoting alternative modes of transport [66].

The flows of containers, which are facilitated and supported by quay cranes, yard cranes, and automated guided vehicles, have a significant and noteworthy impact on the overall capacity of container terminals [59]. These container flows play a crucial role in determining the effectiveness and efficiency of the terminal operations. The estimation of terminal performance also incorporates the concept of unbalanced task assignment, which is an essential aspect to consider in order to accurately gauge the terminal's efficiency and productivity [59]. Previous research has accounted for the allocation of tasks in an unbalanced manner, which led to a more realistic and practical assessment of terminal performance [59]. Additionally, the impact of container batch arrival, in terms of its effect on the terminal's overall performance, has also been researched [59]. This factor is of utmost importance as it directly influences the efficiency and effectiveness of the terminal's operations. It must also be noted that different berth and yard layouts lead to different levels of congestions for different scenarios [59]. Furthermore, in order to improve the overall performance of the terminal, various aspects such as the number of vehicles, berth and yard layouts, and task assignment strategies need to be meticulously optimized. By optimizing these factors, the terminal can achieve higher levels of productivity and efficiency, thereby enhancing its operational capacity [59].

The increasing demands to improve the port's ecological footprint necessitate the port and its companies to adapt, which can lead to congestion as they implement changes [50]. These increasing demands arise from the growing awareness and concern regarding the environmental impact of port operations. As a result, there is a need for ports and their companies to implement measures and initiatives to reduce their ecological footprint [50]. However, the implementation of these changes can lead to congestion, as it requires modifications and adjustments to the existing infrastructure and operational processes. These modifications and adjustments may disrupt the smooth flow and movement of goods within the port, resulting in congestion [50]. Therefore, it is essential to carefully plan and manage the implementation of changes aimed at improving the port's ecological footprint in order to minimize the potential for congestion[50].

2.2. Barges and their Disadvantages

Figure 2.1: A Container carrying barge [47]

It has been found through previous research that the number of barges waiting increases as the barge handling rate drops when the focus of terminal operators shifts to sea vessels [66]. When the number of barges waiting goes up, the focus of terminal operators is re-shifted to barge operations [66]. This has led to recommendations of dedicated barge berthing facilities, since the number of sea going vessels is only bound to increase, thereby leading to a corresponding increase in barge activity [66]. Barge planning is challenging due to the need for appointments, slow speed, and inflexibility in visiting terminals [75]. An inland terminal has contracts with barge and trucking companies for container transportation [75] and naturally does not have as high barge traffic as deep-sea terminals [75].

It has been found that the primary constraint in the planning process for barges is not the capacity of the barges themselves but shortages in handling equipment, since on average, the utilization rates were approximately 70% or less [43]. Container Barges are become a commonly utilised option because the unit costs are significantly lower compared to trucking [43]. It is also known that Barge capacity is much greater than trucking of containers for an equivalent energy consumption [43].

According to APM Terminals, the Maasvlakte II terminal has 500 meters of dedicated barge berthing with a maximum depth of 9.65 meters [13]. The terminal is equipped with three dedicated barge cranes that are fully automated, offering speed, reliability, and efficiency [13]. The majority of operations involving barge cranes are fully automated, including the discharging and loading of containers at the stack [13].

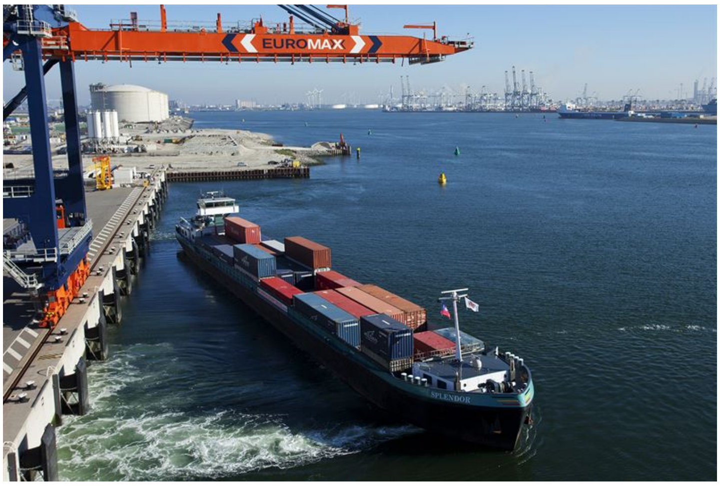


Figure 2.2: Most Major Container Terminals have dedicated Barge Berths [66][14]

APM Terminals also offers a Fixed Windows concept for barge handling, which has proven to be beneficial for both parties: the barge operator is certain about barge handling, and the deep-sea terminal is able to improve quay utilization [13]. Barges that have stable volumes and arrive on time get fixed windows in the week [13].

However, the problems arise if a barge gets delayed beyond the window. Significant coordination problems between terminal operators and barge operators in the container barging sector in the port of Rotterdam exist. It has been emphasized that there exists a need for improved contractual relations in the transport chain to address these coordination problems [47].

Prior research findings suggest that there is a paradox in the container barging sector, with many interdependent actors undertaking institutional arrangements to improve coordination, but a lack of urgency and unwillingness to cooperate among the main stakeholders weakening the sector's market share [47]. This implies that addressing the non-existing sense of urgency and fostering cooperation among stakeholders are crucial for improving the performance of container barging in Rotterdam [47].

It should also be noted that diesel engines on container barges release carbon dioxide (CO2), along with nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) [33]. These pollutants can cause respiratory problems, cardiovascular diseases, and cancer. They can spill oil and other hazardous substances, which can pollute water bodies and harm aquatic life [33].

2.3. Current AGV Operations

AGVs currently deployed in Cotnainer Terminals within the Port of Rotterdam by ECT, which controls both the Euromax and Delta Terminals, are diesel-electric hybrid vehicles, utilizing a combination of diesel engines and electric batteries for power [15]. In contrast, the Port of Singapore utilizes purely electric AGVs. These AGVs are powered by batteries that are charged using a combination of regenerative braking and grid electricity [1]. Konecranes also produces wholly electric powered AGVs for container terminal operations [9].

The choice of power source for AGVs depends on a number of factors, such as the type of application, the operating environment, and the desired level of emissions [56]. Diesel-electric hybrid AGVs offer the advantage of being able to operate for extended periods of time without needing to be recharged [56]. However, they also produce emissions, which can be a concern in environmentally sensitive areas [56].

Purely electric AGVs do not produce emissions, making them a more environmentally friendly option [64]. However, they have a shorter operating range than diesel-electric hybrid AGVs and need to be recharged more frequently [64]. One thing we can also learn is that Battery-powered AGVs have economic, environmental, and technical advantages compared to conventional transport fleets in container

Figure 2.3: AGV produced by Konecranes Gottwald [9]

Figure 2.4: A conceptual AGV developed for Container Terminal Operations by Gaussin [29]

terminals [64].

Shifting charging processes to off-peak hours can yield lower energy procurement costs, resulting in savings of more than 10% compared to a diesel-powered transport fleet [64]. The charging and maintenance costs of a B-AGV fleet are significantly lower than the higher investment costs of procuring charging infrastructure and spare batteries, making electric mobility economically beneficial in container terminals [64].

Simulation studies have been used [64] to determine the minimum battery-to-vehicle ratio sufficient for daily logistic tasks, reducing costs without restricting the AGV fleet's performance. Controlled charging processes with additional spare batteries can significantly reduce energy procurement costs, making it the most promising strategy from an economic perspective [64].

AGVs are typically used to transport shipping containers between the quayside and the yard. They can also be used to transport other types of cargo, such as palletized goods and vehicles [11]. They can run for about 6 to 8 hours on a single charge and have a power-saving mode when they're not in use [2]. Most port AGVs charge their batteries by swapping them with a charged set, while the uncharged set is recharged. This way, the AGVs can keep working without having to wait for their batteries to charge [2].

Battery swapping is a unique method of recharging an AGV, which involves a process of exchanging a depleted battery for a fully charged one in a short amount of time. This is done automatically using a battery swapping station [31]. Battery swapping is a suitable technology for port AGVs because it allows them to operate continuously without having to stop for long periods of time to charge their batteries [45].

Battery swapping stations as seen in Figure 2.5 are typically located in strategic locations throughout a port, such as near loading and unloading areas [45]. When an AGV needs to swap its battery, it simply drives into the station and the process is initiated automatically [45]. The AGV's depleted battery is removed and replaced with a fully charged one in a matter of minutes [45]. The AGV can then continue operating without any interruption.

Figure 2.5: Electric AGVs can be charged by swapping out their depleted batteries in battery swapping stations[9]

There are a number of benefits to using battery swapping for port AGVs. First, battery swapping allows AGVs to operate for longer periods of time without any downtime needed to charge [45]. This can lead to increased productivity and efficiency in the port. Second, battery swapping can reduce the overall cost of operating AGVs [45]. This is because battery swapping stations are cheaper to build and maintain than traditional charging stations [31]. This is because for charging stations, one needs multiple parking bays for the AGV's to park while charging whereas a single battery swapping bay can suffice for all AGVs in the fleet. Third, battery swapping can help to reduce the environmental impact of port operations [45]. This is because battery swapping stations can use renewable energy sources, such as solar and wind power, to charge their batteries [31].

2.4. Amphibious AGV

An Amphibious AGV is an AGV concept that is capable of traversing land and water while transporting a fully loaded 40 foot container. The AAGV model being used for this research is derived from previous research as provided in Appendix A, with data being refined to a greater extent through this research.

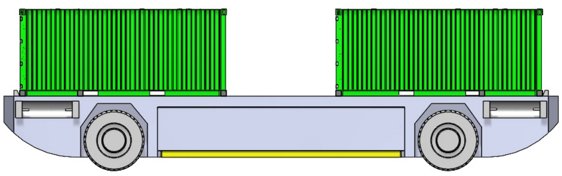


Figure 2.6: Amphibious AGVs in land configuration and carrying 2 twenty foot containers

Barge transshipments are often time-consuming and costly, as containers need to be unloaded from AGVs to barges and vice-versa [40]. Amphibious AGVs can carry containers directly between terminals which can significantly reduce the overall transit time and cost of shipping goods. In addition to this, since they do not need barge berthing spaces to be unloaded by Quay Cranes, they can free up cranes for other purposes, while themselves utilising smaller land-based container handing equipment like RSs and ASCs. This reduces the number of trucks and cranes needed at ports, which can help to alleviate congestion and improve overall efficiency. Amphibious AGVs can also operate more flexibly than trucks, as they are not limited by road networks. This can be especially beneficial in areas with limited road infrastructure, such as island ports.

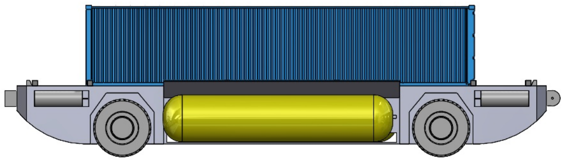


Figure 2.7: Amphibious AGVs in waterborne configuration and carrying 1 forty foot container

As visible in Figure 2.6, while on land the AAGV possess the characteristics of and operates like a normal AGV. When transitioning into water, it utilises inflatable sidepods to operate amphibiously. These are stored in containers on each side of the AAGV, and inflate or deflate, as shown inflated in Figure 2.7, while on the ramp entering the water. It possess water pumpjets for propulsion purposes to power it while on water. Upon reaching its destination, it uses a combination of its traction and pumpjet power to climb the ramp. While it is in water the pumpjet pushes it onto the ramp and the wheels activate upon detecting the ramp with the pump aiding the wheels to climb as far as the water level is, with the wheels fully taking over at the end. The sidepods then deflate and retract into their storage units as the AAGV returns to its land travelling characteristics.

2.5. Benefits of Agent Based Modelling

Agent-based modeling is used to simulate and analyze the container handling processes in a container terminal by creating a virtual environment where individual agents, representing different entities such as containers, equipment, and transportation modes, can interact and make decisions based on predefined rules and behaviors [55]. This approach helps to capture the complexity and dynamics of the system, taking into account various factors and their interactions. By using agent-based modeling, investigating the impact of having information about further transportation modes on container outflow and overall equipment effectiveness in the container terminal is made easier [55]. This method provides a theoretical framework to understand the effects of different scenarios and can be used to inform decision-making and optimize terminal operations [55].

It has been used in prior research to simulate the operations in an automatic container terminal (ACT) with quayside container cranes (QCs), automatic guided vehicles (AGVs), and automatic rail mounted gantry cranes (ARMGs) [30]. Agent-based modeling is chosen because conventional modeling methods such as mathematical models are unable to accurately represent the complex interactions between QC/AGV/ARMG operations and the traffic flow in the port [30]. Agent-based simulation allows for the modeling of individual agents, such as container ships, AGVs, and ARMGs, and their interactions with each other and the environment [30].

The simulation model developed using agent-based simulation provides a realistic representation of the discharging and loading operations in the ACT, allowing for decision support in the design and management of Automated Container Terminals with QCs, AGVs, and ARMGs [30]. Balancing theory and data is crucial in agent-based modeling to explore the implications of change and model dynamic complex systems [36]. The role of theory should not be reduced in agent-based modeling, even as models become more data-driven [36]. Maintaining a balance between theory and data is necessary for agent-based models to serve as useful decision support tools for policymakers [36].

Research has utilized multi-agent systems (MAS) approach to model container terminal operations in a distributed and changing environment of seaports [34]. The MAS-based dynamical model has commonly been used to depict the interactions and processes among eight different agents, including ship, port captain, terminal manager, stevedore, quay crane, straddle carrier, customs, and truck. The agents in previous models interact in various processes such as ship arrival sequencing, determination of ship's service time, and container picking [34]. The simulation results are used to evaluate the effectiveness of the proposed methods in increasing terminal operations efficiency, also providing a proof that consensus will be attained by all the agents in the model [34].

Figure 2.8: An aerial view of the ECT Delta Terminal (mid and mid-left) with Delta II visible (top-center). Euromax is barely visible (top-right). [16]

In accordance with these inputs, the objective of this study is to contribute to the implementation of AAGVs in order to explore the feasibility of alleviating the issue of congestion experienced by barges in large seaports as well as reduction of Inter-Terminal Transportation times for shipping containers. In this context, the study aims to explore the feasibility of AAGVs in decreasing the amount of time that containers take in Inter-Terminal Transportation between deep-sea terminals and improve the adaptability of container terminals to these AAGVs. In the pursuit of these goals, the study endeavors to offer solutions to the research questions that have been identified:

1. What benefits do implementing the AAGVs provide; in the context of efficiency of container transportation within and around a container terminal?
2. What would be the modifications and additional infrastructure needed in container terminals to implement AAGVs?

In answering the research questions, the report is structured as follows: section 2 presented above focuses on the literature review, section 3 deals with the methodology used in the research, while section 4 describes the data used and section 5 presents the results of the research. Finally, in section 6, the conclusion of the research is drawn.

3 Methodology

This chapter is essential for establishing the validity and credibility of the research findings and provides a transparent explanation of the research process, enabling understanding of the methods and data sources used. This transparency fosters trust in the research outcomes and demonstrates the rigor of the research approach.

The research employs a case study methodology to gain an in-depth and nuanced understanding of AAGV operations. This approach allows the exploration of the subject matter within its real-world context, examining various facets and perspectives in detail.[42]. This will also provide us with a general map of the modifications that have to be made in a container terminal for adaptation of an AAGV. Even though modifications will be standard between different terminals, the placements will be different at different terminals. For example, the ramp placement will be at different locations in the container terminal, with the charging station closer to the ramp to make sure that an AAGV can swap its depleted battery before it proceeds to move on water [71].

The Material Handling Library of AnyLogic offers a comprehensive suite of tools for simulating container terminals, leveraging agent-based modeling (ABM) principles to model the dynamic interactions of various entities within the terminal's operations. ABM enables the simulation of individual agents representing AGVs, AAGVs, cranes, reach stackers, container yard blocks, and other components, allowing for detailed modeling of their movement, interactions, and decision-making processes. This granular representation of the terminal's operations enables the simulation to capture complex behaviors and identify potential bottlenecks or inefficiencies. The simulation is used to evaluate different equipment configurations and levels, traffic patterns, and to gain insights into their impact on the overall efficiency and performance of the container terminal. By refining the simulation and implementing optimization strategies, AnyLogic and ABM provide a powerful tool for improving the operations and throughput of container terminals.

There will be two main Scenarios to be looked at, the base case scenario consisting of a land based AGV and barge combination, and the other being the AAGV Scenario. All data utilised in the simulations can be found in Chapter 4. The scenarios were formulated on the basis of a thorough literature review and analysis of existing container terminal operations. The base scenario reflects the current standard practice, while the AAGV scenario introduces the proposed use of amphibious AGVs. The scenarios are designed to be realistic representations of container terminal operations, taking into account factors such as container handling, vehicle movement, and energy consumption.

The comparison of amphibious AGVs to traditional land-based AGVs and barges forms the core of this work. This comparison addresses a critical gap in the existing literature, which lacks comprehensive evaluations of amphibious AGVs and their potential benefits. Evaluating these benefits is crucial because amphibious AGVs offer unique capabilities that could significantly impact various application areas. By analyzing their performance across two distinct scenarios, this study aims to: By simulating two distinct scenarios, the base scenario and the AAGV scenario, the research can compare the efficiency, cost-effectiveness, and environmental impact of each approach while also identifying the potential benefits and challenges of implementing this new technology.. The findings of this research can inform decision-making processes and contribute to the adoption of innovative solutions for improving container terminal operations.

3.1. As-is Scenarios

In the simulation, The base case includes the simulation of unloading of a barge by 2 Quay cranes. The Quay cranes unload the containers onto AGVs which then proceed to the yard and are unloaded with the help of Reach Stackers [69]. The Reach stackers proceed to stack the containers in a yard block which has a maximum possible height of 3 containers [17].

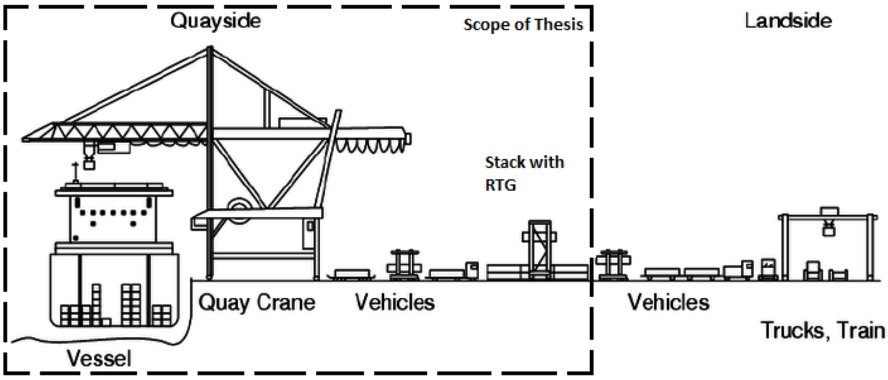


Figure 3.1: Container Terminal System [67]

3.1.1. As-is 1

This case involves the simulation of the combination of the AGV and Barge with Reach Stackers for unloading the AGV.

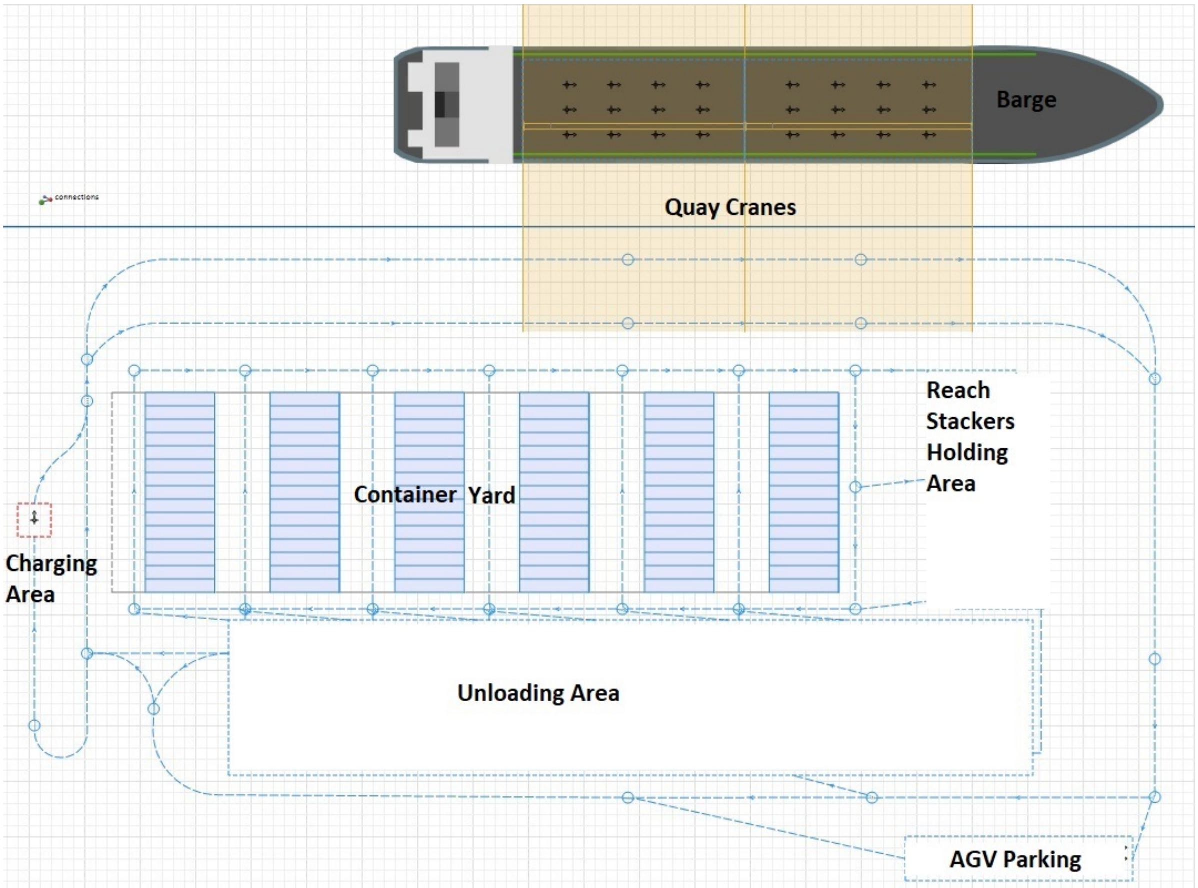


Figure 3.2: The Layout of As-is 1

If the layout is looked at, the Quay is north of the Container yard block, the unloading area is south of the yard block and the AGVs are parked in an area south east of the unloading area, with the dashed lines denoting the designated travel paths around the container terminal. The Reach Stackers are parked in a node east of the yard block. The unloading area is accessed by the reach stackers from the east and by the AGVs from the south. The exit is to the west, where they can return to the Quay to be loaded by a crane or return to the AGV park. The battery recharging facility is also present on the west of the yard block, which can be accessed upon exiting the unloading area. The entire route network is clockwise uni-directional, except for a single route which exists between the exit of the unloading area and the AGV park, which allows unloaded AGVs to return to the AGV park. There are two different lanes for the two Quay cranes, which are present on the northeast side of the yard block; and hence a delay in one lane does not delay the other lane unless the AGV traffic extends upto the split point of the 2 lanes which is at the northwest side of the yard block. A short delay might be observed when the lane to the unloading area contains loaded AGVs, preventing unloading of containers by the Quay Cranes till the time the AGV traffic clears up. The return lane from the charging station joins just before the split point on the north-west side of the yard block.

Such a layout of the terminal has been utilised since it is a generalisation of layouts that can be found in multiple container terminals around the world, including the Port of Saigon and DP World, Dubai. The Container Stack Layout utilised is Parallel to the Quay, with gaps between for reach stackers to access.

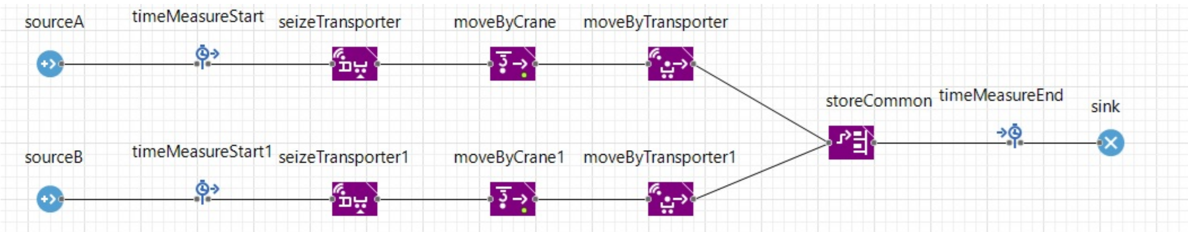


Figure 3.3: The Material Handling Library's Flowchart for the Base Scenario of AGV + Crane

In the Flowchart as seen in Figure 3.3, two sources are used to denote two different regions of the barges which are unloaded by two different Quay Cranes. Each source contains equal number of containers for each scenario of throughput . A total of 20 containers will split equally into 10 containers in both sources. The barge that is present is split into 2 different zones for both sources, leading to both zones and thereby Quay Cranes working independently of each other. On arrival of a container in the zone, the seizeTransporter block calls an AGV while the moveByCrane block lifts the container and places it onto the waiting AGV. The moveByTransporter block then sends in a request for the AGV to move to the unloading zone. The unloading time of the AGV is a uniform distribution of between 5 to 7 minutes, post which the storeCommon block sends the Reach Stacker to store the container in the yard block. This process repeats for all the containers in the process.

3.1.2. As-is 2

This case involves the simulation of the combination of the AGV and Barge with RTG Cranes for unloading the AGV.

The layout for As-is 2 is virtually the same as As-is 1, with the exception of the RS unloading area, the RS holding area and the Stackers being replaced by RTG serviced yard blocks. There are 3 yard blocks present with each yard block having 2 unloading nodes north of the yard blocks and each yard block having 2 RTGs to operate across the length of itself. The unloading nodes are accessed by inbound and outbound lanes, with each node having 2 lanes for inbound and outbound traffic.

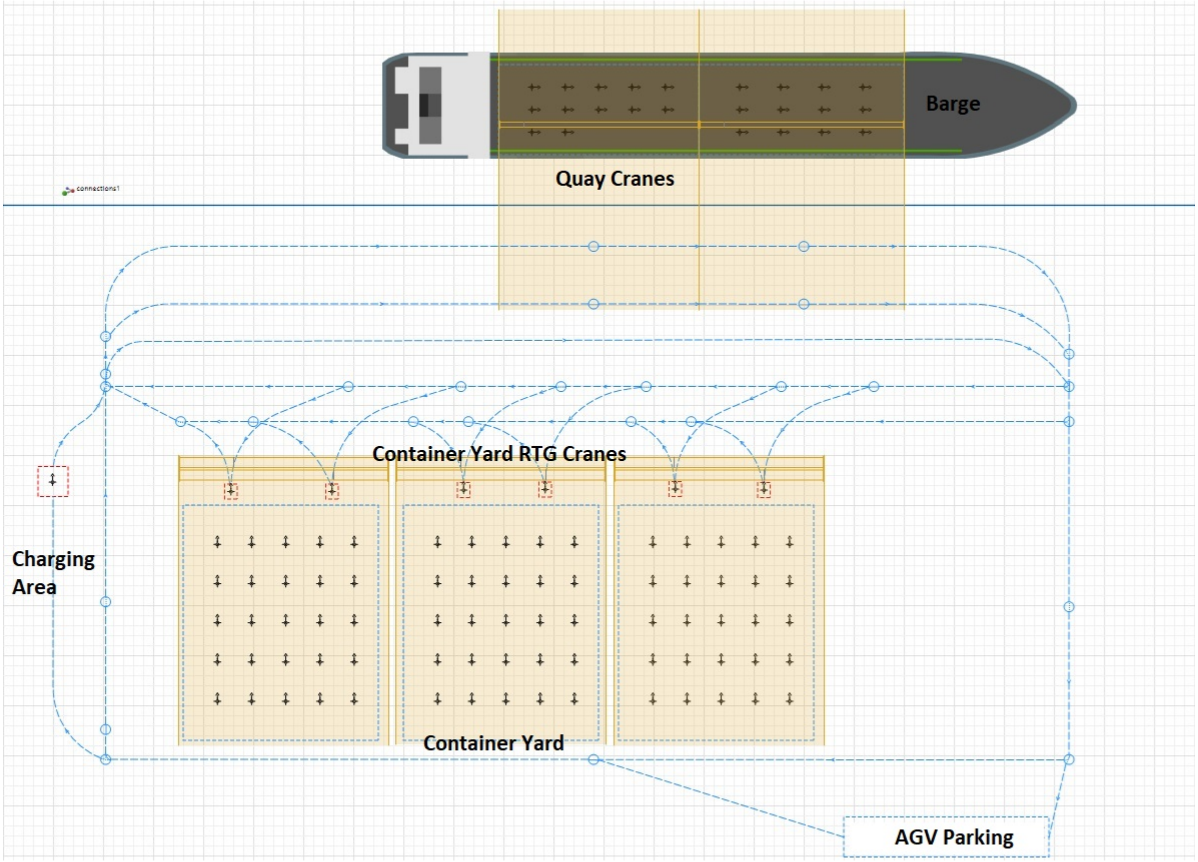


Figure 3.4: The Layout of As-is 2

In the Flowchart, as seen in Figure 3.5, two sources are used to denote two different regions of the barges which are unloaded by two different Quay Cranes. Each source contains equal number of containers for each scenario of throughput . A total of 20 containers will split equally into 10 containers in both sources. The barge that is present is split into different zones for both sources, leading to both zones and thereby Quay Cranes working independently of each other. On arrival of a container in the zone, the seizeTransporter block calls an AGV while the moveByCrane block lifts the container and places it onto the waiting AGV. The selectOutput block divides the containers between 5 of the 6 different unloading nodes of the 3 yard blocks. The division is as follows: the 4 unloading nodes of yard blocks 1 and 2 receive containers from both sources, but the 2 nodes from yard block 3 are divided between both sources, with each node getting containers only from one source. The moveByTransporter block then sends in a request for the AGV to move to the unloading node. The AGV is unloaded by the RTG crane via the moveByCrane block post which places the container in the stack within that yard block. This process repeats for all the containers in the process.

Such a layout of the terminal has been utilised since it is a generalisation of layouts that can be found in modern global container terminals, including the Port of Rotterdam; DP World, Dubai and the Port of Hamburg. The Container Stack Layout utilised is Perpendicular to the Quay.

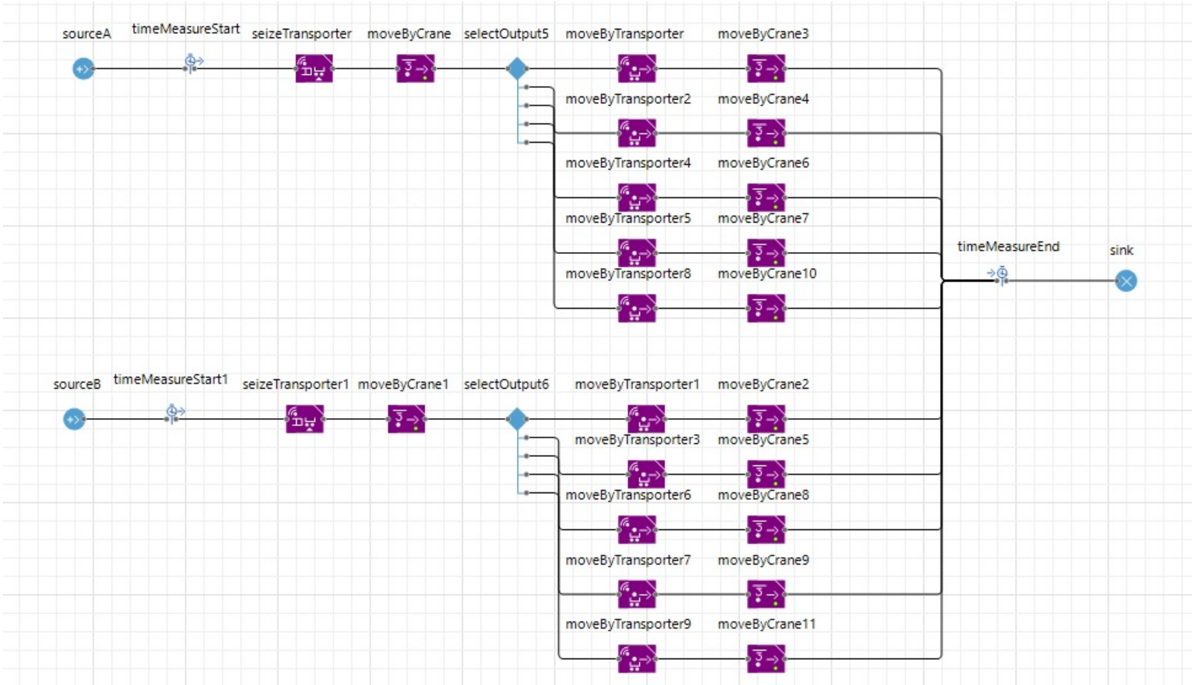


Figure 3.5: The Material Handling Library's Flowchart for As-is 2

3.2. To-Be Scenarios

In this simulation, the Quay cranes are replaced by a 100 meter long "ramp" connecting a terminal floor height of NAP+6.1 meters [52] with a 3.5 degree (approximately) incline, additional constraints of acceleration and traffic number provide for a realistic simulation of the scenario. The calculations for this data can be found in Section 4. Using this, AAGVs are able to travel from the source terminal to the destination terminal, "climb up" the ramp, and then be unloaded in the loading yard by the reach stackers or by gantry cranes. Post this, if there are still containers at the source port then they shall return to collect them and repeat the process. The ramp is dual-laned, one for climbing and the other for descending AAGV traffic. Both lanes are wide enough to accommodate AAGVs with sidepods deployed. Each lane of the ramp permits 3 AAGVs at a time so as to reduce traffic congestion on water.

The route between the 2 terminals simulates approximately 5 kilometers of travel accomplished on water. Simulation of loading of containers at the source terminal has not been simulated. This is keeping in line with the base scenario of only unloading of the barge being simulated and not loading, the major difference being that travel for the AAGV has been simulated since it was necessary for estimation of simulation of the battery consumption and the necessity of battery swapping, if needed.

3.2.1. To-Be 1

This case involves the simulation of the AAGVs carrying containers from the source to the destination terminal and then being unloaded by Reach Stackers.

For this simulation, as before, only the 40-foot container has been simulated since the AAGV has the same container carrying characteristics as an AGV. The standard dimensions and operating speeds as used in the base scenarios have been continued for every Reach Stacker. The Quay cranes are not not needed in this simulation.

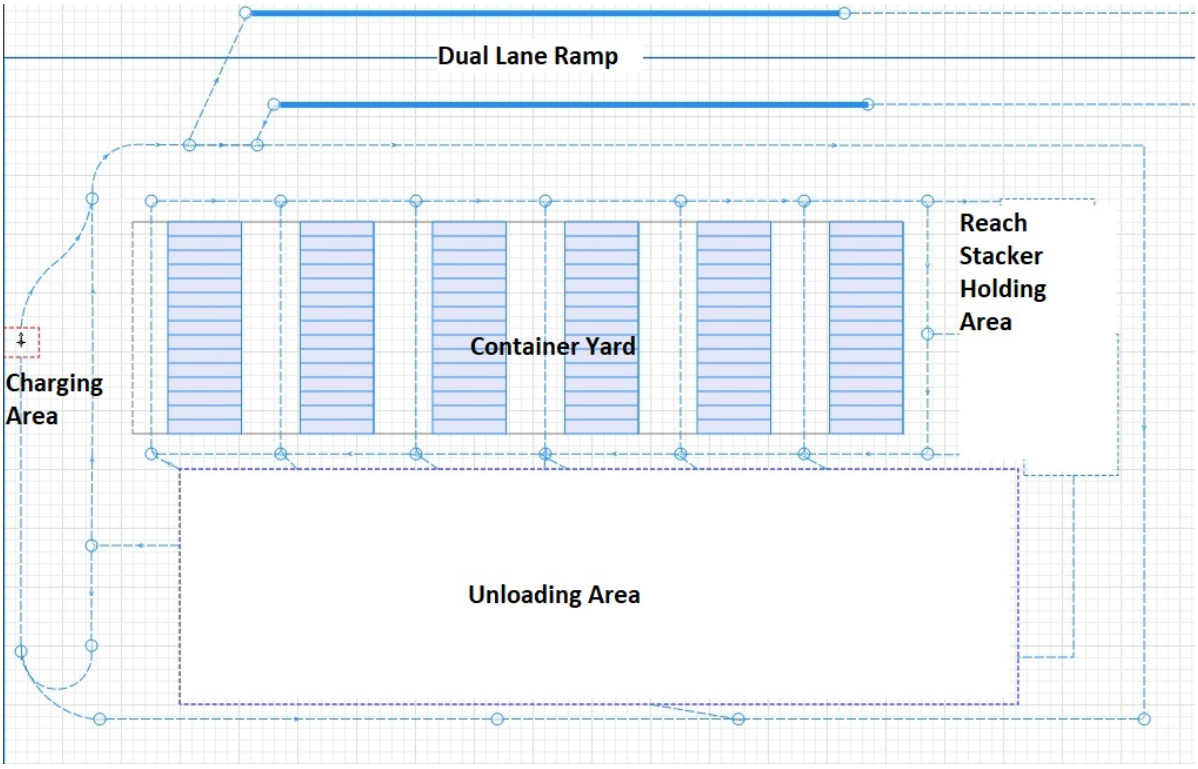


Figure 3.6: The Layout of To-Be 1

If the layout is looked at, the source terminal is located north of the sink terminal at a distance of approximately 5 kilometers. The AAGVs are parked in the source terminal, north of the loading area. In the sink terminal, the Quay is north of the yard block, the unloading area is south of the yard block and instead of Quay Cranes to the Northeast there is an inclined ramp that extends along the quay from the North to Northwest. The Reach Stackers are parked in a node east of the yard block. The unloading area is accessed by the reach stackers from the east and by the AGVs from the south. The exit is to the west, where they can return to the ramp. The battery recharging facility is also present on the west of the yard block, which can be accessed upon exiting the unloading area. The entire route network is clockwise uni-directional. There is just a single lane to the north and west of the yard block up to the unloading area and a delay in the unloading area should not affect traffic climbing the ramp since the space between can easily accommodate multiple AGVs. The return lane from the charging station joins before the ramp.

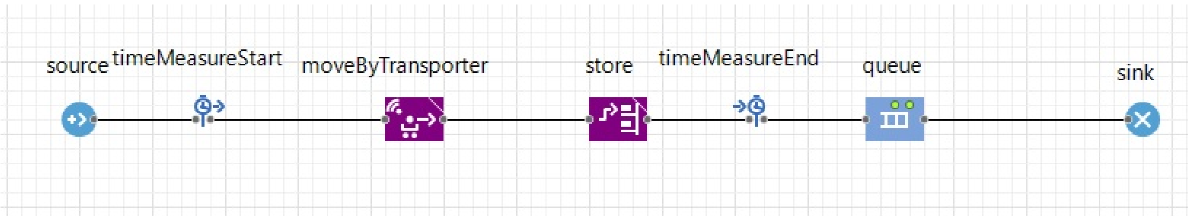


Figure 3.7: The Material Handling Library's Flowchart for To-Be 1

In Figure 3.7, The single source simulates the container presence in the source container terminal with AAGVs parked at the source terminal. On arrival of a container in the Terminal, the moveByTransporter block sends in a request for the AGV to move the container from that terminal to the unloading zone of the Base Terminal. The unloading time of the AAGV is a uniform distribution of between 5 to 7 minutes, post which the store block sends the Reach Stacker to store the container in the yard block. This process repeats for all the containers in the process. The queue block is used simply to make sure the container does not reach the sink block and disappear (since upon reaching the sink block, the containers are removed from the simulation), and therefore helps in visualisation.

3.2.2. To-Be 2

This case involves the simulation of the AAGV carrying containers involving Gantry Cranes.

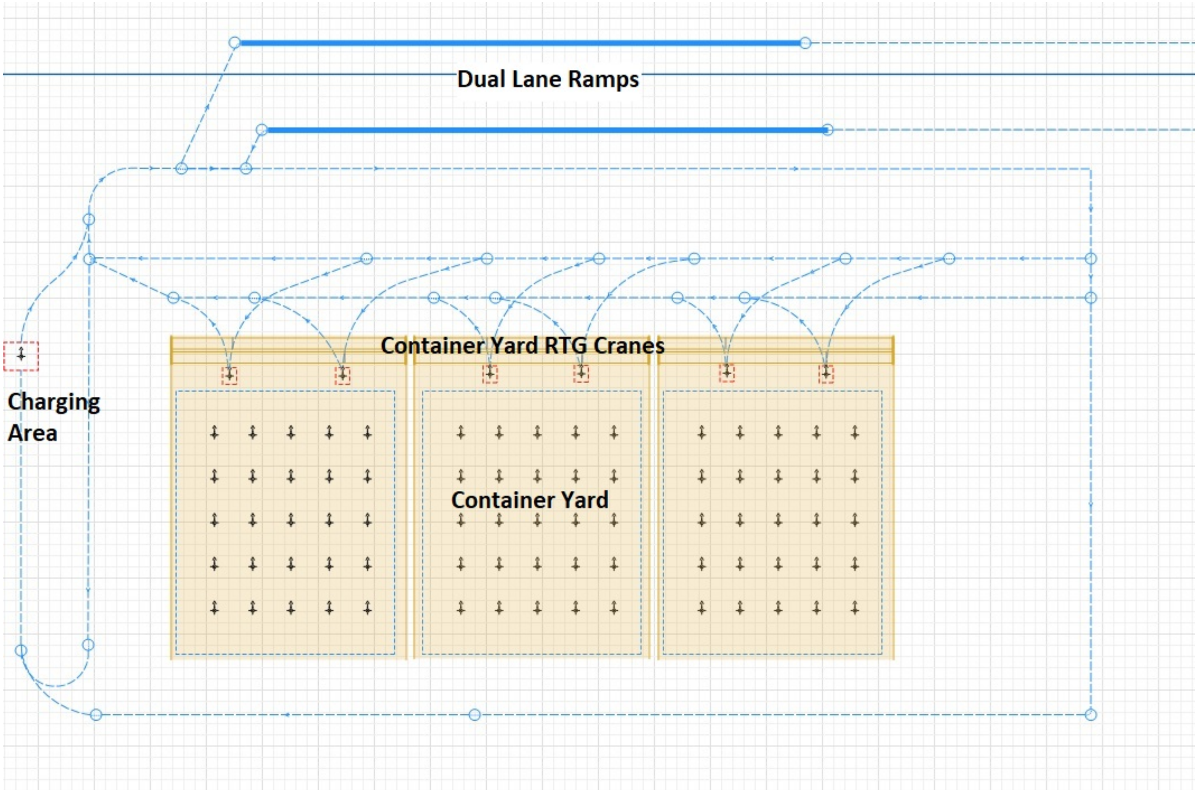


Figure 3.8: The Layout of To-Be 2

The layout for To-Be 2 is virtually the same as To-Be 1, with the exception of the RS unloading area, the RS holding area and the yard block being replaced by RTG serviced yard blocks. There are 3 yard blocks present, with each yard block having 2 unloading nodes north of the yard blocks and each yard block having 2 RTGs to operate across the length of itself. The unloading nodes are accessed by inbound and outbound lanes, with each node having 2 lanes for inbound and outbound traffic.

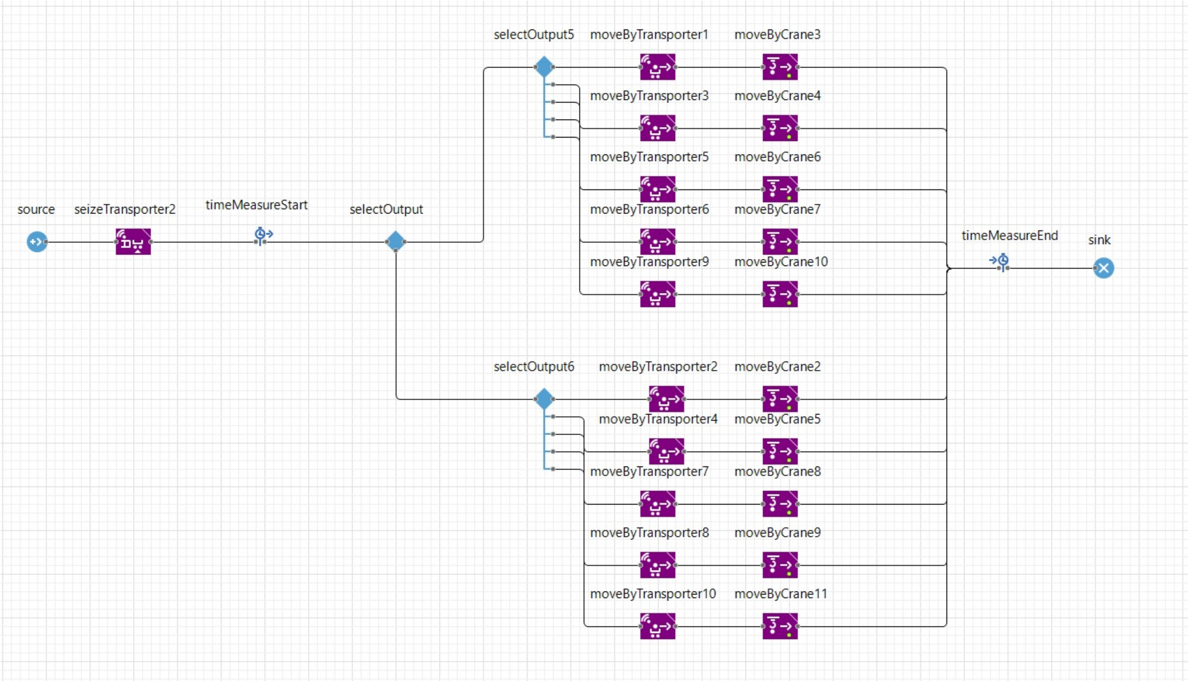


Figure 3.9: The Material Handling Library's Flowchart for To-Be 2

In the Flowchart seen in Figure 3.9, the single source simulates the container presence in the single source terminal with AAGVs parked at the source terminal. On arrival of a container in the zone, the seizeTransporter block calls an AGV. The primary selectOutput block decides which flow will a particular container follow with a probability of 0.5, thereby permitting flow either way equally. This primary block has been implemented to maintain commonality with the As-Is 2 flowchart. The secondary selectOutput blocks divide the containers between 5 of the 6 different unloading nodes of the 3 yard blocks, just as they did in As-Is 2. The 4 unloading nodes remain common for both sources, and the last nodes remain 1 each from the third yard block. The moveByTransporter block then sends in a request for the AGV to move to the unloading node. The AGV is unloaded by the RTG crane via the moveByCrane block which moves the container and places it into the yard block. This process repeats for all the containers in the process.

4
Data

This chapter is crucial for substantiating the research findings of the thesis. It provides a detailed overview of the data sources employed to evaluate the performance and potential benefits of amphibious AGVs. The data analysis encompasses throughput calculations and battery consumption values, enabling a comprehensive assessment of the efficiency and environmental impact of amphibious AGVs compared to traditional land-based AGVs and barges. The dimensions and designs of the AAGV used in these calculations are the same as in Appendix A, unless otherwise stated.

Throughput is a critical metric for evaluating the efficiency of container transport within and between container terminals, representing the total volume of containers handled per unit of time. By analyzing battery consumption, the thesis can assess the potential for amphibious AGVs to increase efficiency and improve the environmental sustainability of container terminal operations.

The integration of throughput calculations and battery consumption values provides a comprehensive evaluation of the performance and potential benefits of amphibious AGVs. This data-driven approach enhances the credibility of the research findings and contributes to a deeper understanding of the feasibility and impact of introducing amphibious AGVs in container terminals.

4.1. Container Terminals

There are many Container Terminals around the world which use a mix of RSs, RTGs, AGVs and ASCs for Container Terminal Operations. The Port of Rotterdam has multiple large container terminals which are some of the largest in the world. The Scenarios take into consideration prospective AAGVs being unloaded by both RSs or RTGs. A very good example for the RTG case is the Euromax Terminal and the ECT Delta Terminal in the Port of Rotterdam while a close example for the RS case is the Delta II Terminal. It is however not a perfect example, since the Delta II terminal utilises ASCs to load, transport and stack the containers as the primary operating equipment with RS in a secondary role, whereas the Scenarios utilise the AGVs to transport the containers to the unloading area next to the stack, with Reach Stackers being utilised to stack the containers. The RS Scenario is more likely for the Terminal D in the Laem Chabang Port in Thailand and to a smaller extent in the the DP World Container Terminal 1 in Dubai, UAE. The Layout for all Scenarios (As-Is and To-Be) is generic and is quite similar to the following examples:

4.1.1. Euromax Terminal, Rotterdam

The Euromax Container Terminal in the Port of Rotterdam is one of the most advanced and sustainable container terminals in the world. It is a fully automated terminal that can handle the largest container ships in the world. The terminal has a capacity of 5 million TEUs per year [18]. It is located on the Maasvlakte, a man-made peninsula in the Port of Rotterdam. The terminal has a quay length of 1,500 meters and a depth of 17.65 meters. This makes it one of the deepest container terminals in the world [18].

4.1.2. ECT Delta Terminal, Rotterdam

The Hutchison Ports ECT Delta Container Terminal in the Port of Rotterdam is the largest container terminal in Europe. It is a fully automated terminal that can handle the largest container ships in the world. The terminal has a capacity of 10 million TEUs per year [19].

The Hutchison Ports ECT Delta Container Terminal is located on the Maasvlakte and shares space with the Delta II Container Terminal. The terminal has a quay length of 3,600 meters and a depth of 16.65 meters. It shared the distinction of the deepest container terminal in the world with the ECT Delta II [19].

4.1.3. Delta II Terminal, Rotterdam

The Hutchison Ports ECT Delta II Container Terminal in the Port of Rotterdam is a state-of-the-art container terminal that can handle the largest container ships in the world, and shared its Quay depth with the ECT Delta Terminal. The terminal has a capacity of 3.35 million TEUs per year [20]. The Hutchison Ports Delta II Container Terminal is co-located with the ECT Delta Terminal with a quay length of 1,600 meters and a depth of 16.65 meters also making it one of the deepest container terminals in the world [19].

Figure 4.1: An aerial view of the Delta II Terminal on the MaasVlakte in the Port of Rotterdam with the Euromax Terminal visible (corner right). [3]

4.1.4. Terminal D, Laem Chabang

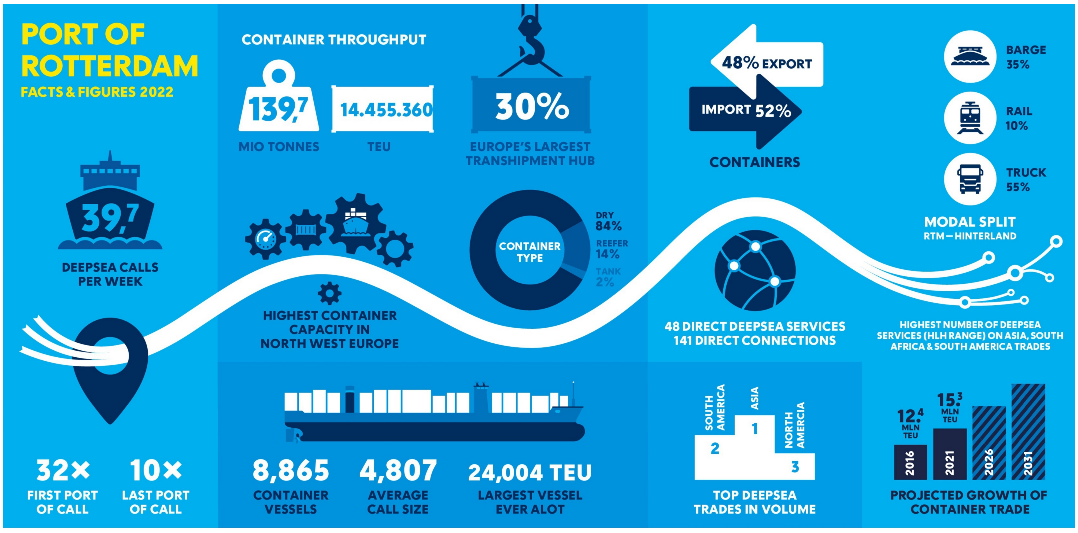
Terminal D of Laem Chabang Port is a state-of-the-art deep-sea container terminal situated at Basin 2 of the port. Upon full completion, it will boast a quay length of 1,700 meters, making it the largest and most advanced container terminal in Thailand [21]. Terminal D is equipped with cutting-edge technology, including 17 super post-panamax quay cranes and 10 Reach Stackers [21]. Terminal D's strategic location and deep-water berthing facilities enable it to handle the largest container vessels currently in operation, further strengthening Laem Chabang Port's position as a gateway to Southeast Asia. The terminal is set to accommodate a capacity of over 3.5 million TEUs, significantly expanding Thailand's container handling capabilities and facilitating maritime trade across the region and beyond [21].

4.1.5. DP World Container Terminal 1, Dubai

DP World Container Terminal 1 (T1) is one of the busiest and largest container terminals in the world, handling an average of over 12 million TEUs (twenty-foot equivalent units) annually. Located at Jebel Ali Port in Dubai, United Arab Emirates, T1 is a strategic gateway to the global trade routes, serving a diverse range of customers across various industries.

The terminal's exceptional capacity and efficient operations are attributed to its state-of-the-art infrastructure and advanced technology. T1 boasts a quay length of over 3,400 meters, which can accommodate the largest container ships in the world. It is equipped with super post-panamax quay cranes, many Reach Stackers and multiple rubber-tired gantry cranes (RTGCs), ensuring seamless cargo handling and expeditious terminal turnaround times.

4.2. Throughput Calculations



Port of Rotterdam

Figure 4.2: The Throughput Chart for the Port of Rotterdam [22]

According to the Port of Rotterdam Facts and Figures [22], the total annual container throughput for the year 2022 was 14455360 TEU.

$$\text{Containers} = \frac{14455360TEU}{2} = 7227680 \text{ Containers} \tag{4.1}$$

Since the number of containers via barges are 35% of the total:

$$\text{Containers by barges} = 7227680 \cdot 0.35 = 2529688 \text{ Containers} \tag{4.2}$$

Now an hourly rate of containers by barges can be derived as:

$$\text{Containers by barges} = 2529688 \cdot \frac{1}{365} \cdot \frac{1}{24} = 290 \text{ Containers per hour} \tag{4.3}$$

It can be assumed that 60% of the Barge traffic is for IWT and 40% is for ITT between the major Container Terminals in the MaasVlakte.

$$\text{Containers by barges in the MaasVlakte} = 290 \cdot 0.4 = 116 \text{ Containers per hour} \tag{4.4}$$

Since there are 5 Major Container Terminals in the MaasVlakte;

$$\text{Containers per terminal per hour} = \frac{116}{5} = 23 \text{ Containers per hour per terminal} \tag{4.5}$$

4.3. Handling Equipment Data

The parameters for each of the Quay Cranes for the Container Terminals are the same. The bridge speed is a uniform distribution ranging 1.1 to 1.7 m/s, the trolley speed is a uniform distribution from 1 to 1.5 m/s, the hoist speed 0.8 to 1.5 m/s. The length of the crane simulated is 74 meters. This includes an outreach of 36 meters which is currently used for barge cranes [13]. The distance between rails is kept as the remaining 38 meters, since the rails are maintained along the enter Quay length and utilised by larger cranes too. The height of the crane is kept as 30 meters. Since in AnyLogic the Cranes cannot simulate lateral movement along rails, the width of QC reach has been kept equivalent to the length needed to reach on the barge.

The parameters for each of the RTGs in the yards are the same. The bridge speed has been taken as a uniform distribution range of 1 to 2 m/s, the trolley speed is a uniform distribution from 1 to 1.5 m/s, the hoist speed is 0.5 to 1 m/s. The length of the runway is the same as the length of the stack which is 60 meters. The height of the crane is 20 meters catering for a stack of roughly 3 containers. It must be noted that even if the crane was higher, to cater for a higher stack height, the operational simulation would deal with a stacking operational height of 3 containers high. The width of the crane (the distance between wheels) is 42 meters. The Bridge width has been set to 2 meters. Each unloading Node in To-Be 2 is restricted by capacity to 1 Agent. This is to ensure that only one container agent can be at a particular node at a particular time.

In the given simulations, Reach Stackers have been presented instead of Automated Straddle Carriers. It should however be noted that both maintain the same functionality of picking up and placing containers. While ASCs straddle the container row, Reach Stackers use telescoping arms for reach. In the context of yard operations, both achieve the same function of container movement. It is essential to focus on the travel times of the platform which are similar. For the given simulation, ASC leg placement was not crucial and therefore representing it as a Reach Stacker simplifies the model while capturing the essential function and cycle time for container movement. The Reach Stackers used have an elevation speed ranging from 0.40 m/s to 0.24 m/s [23]. The total length of the truck itself is 12 meters and width is 4.2 meters, with the maximum achievable height of the boom being 18 meters [23]. The speed of travel is regulated by paths (vehicle is capable of travelling faster) to 11 kmph within the terminal [24].

Every AGV in both As-Is conditions and every AAGV in both To-Be conditions has the same dimensions and operating characteristics. Navigation Type for the the AGVs and AAGVs has been defined as path-guided with the Minimum Distance being set at 3 meters to obstacles whether the obstacles be other AGVs/AAGVs or other Agents. The length of each empty AGV and AAGV is 16.6 meters, the width is 3 meters and the height is 1.8 meters. The speed of the AAGV has been set at 13 kmph. This speed has been regulated by paths (vehicle is capable of travelling faster) to 11 kmph within the terminal and to 13 kmph on water according to current regulations [24].

Standard shipping containers come in two main sizes: 20-foot and 40-foot. 20-foot containers are 20 feet long, 8 feet wide, and 8.5 feet high, while 40-foot containers are 40 feet long, 8 feet wide, and 8.5 feet high [25]. For this simulation, only the 40-foot container has been simulated for the AGV. This is because the 40-foot container has reduced simulation efforts in the thesis by generalising container handling processes for the overall container terminal. Simulation of the 40-foot container ensures the implication that 20-foot containers with their shorter length and lower weight can be handled equally well.

4.4. Ramp Calculations

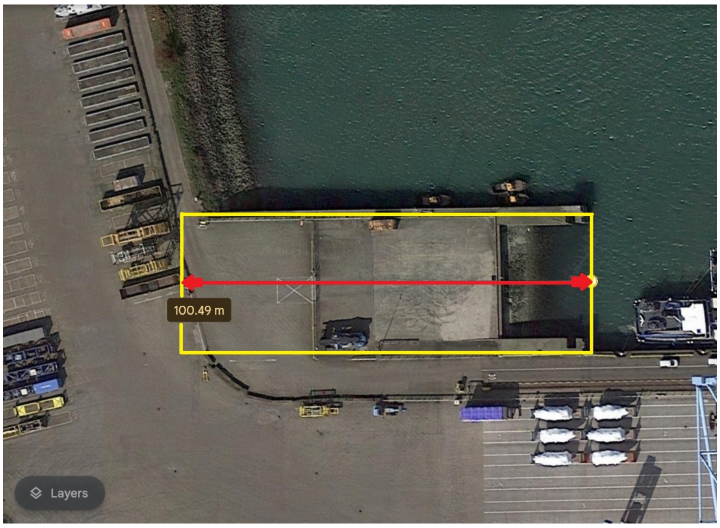


Figure 4.3: A possible location of a ramp installation site for the Delta II Hutchinson port terminal can be as shown above. Image has been taken from Google Earth

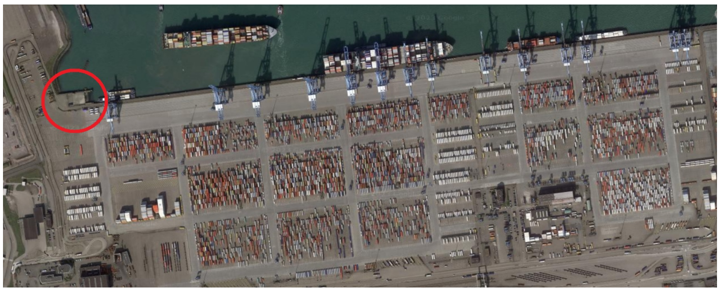


Figure 4.4: The location has been encircled with the rest of the container terminal in perspective. Image has been taken from Google Earth

For the AAGV to transfer from land to water, it will need a location to climb onto the terminal floor from the water. For this reason, there needs to be a ramp placed at every terminal to enable the AAGV to descend into water and climb back on [26].

However, for the AAGV, the ramp will not be so steep. The AAGV at the maximum would be around 100 tons with its payload and itself. The distance between the terminal floor and water is 6.1 meters [52].

Assuming a ramp inclination of 5°, ideal ramp length can be found as:

$$L = h/sin(\theta) \tag{4.6}$$
$$L = 6.1/sin(5) = \textbf{65.18 meters}$$

where ‘h‘ is the height between land and water (6.1 meters).

If the space constraint requires the terminal to use the shortest possible ramp length, then **a maximum inclination of 5°, allows the ramp length to be about 65 meters**.

Considering the maximum length available to be 100 meters,

$$\theta = \sin^{-1}(6.1/100) = 3.49 \approx \textbf{3.5 °} \tag{4.7}$$

Therefore, with a ramp length of 100 meters, the inclination possible is 3.5°. With this inclination, higher speeds on the ramp are attainable.

The simulation utilises a ramp length of 100 meters and an inclination of 3.5 °.

4.5. Battery Consumption and Swapping Simulation

The Battery operation has been simulated utilising the Fluid Library of AnyLogic [27] and the Material Handling library itself for the Battery Swapping simulation. The process of swapping the battery includes the BatterySwap block sending the the AAGV to the battery swapping station. There the battery is swapped, which is simulated as a fluid fill up in the battery by the Fluids Library.

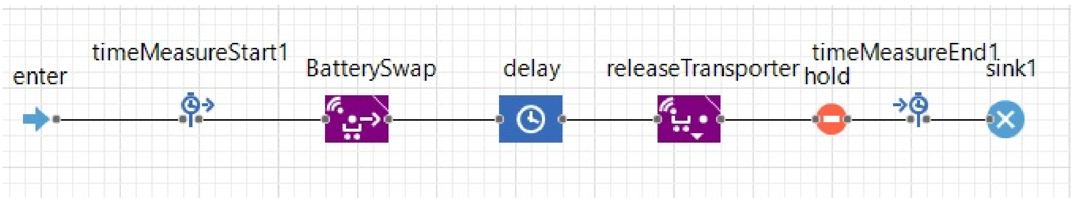


Figure 4.5: The Material Handling Library’s Flowchart for the Battery Charging Process in both Scenarios

The BatterySwap block refers the process to the Battery flowchart where the inlet valve is opened. While this is happening, the vehicle is delayed by the delay block and is released by the releaseTransporter as soon the battery is full. The hold block in the flow helps in simulation to prevent vehicles from being recharged if the stacking of containers is over. This prevents any battery swaps from occurring once the entire transfer of containers is complete. The battery is simulated as a fluid carrying tank, with the battery being full when the tank is full.

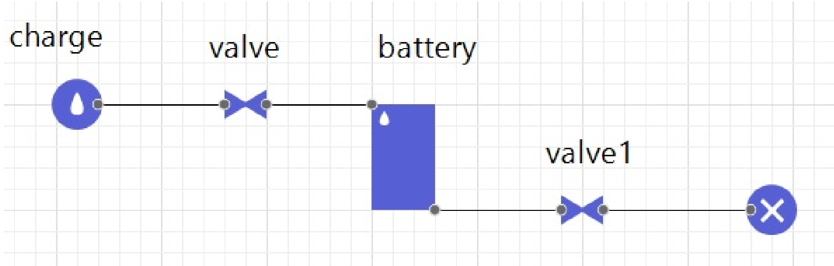


Figure 4.6: The Fluid Library's Flowchart for the Simulation of the Battery in both the AGV and AAGV

Fluid fill up simulates a battery swap and hence an extremely high flow value is provided to the inlet valve. The output valve (valve1) is open during operations and only closes when the inlet valve opens. This is when the AAGV is getting a battery swap at the battery swapping station. The removal of fluid from the tank simulates discharging and is continuous while in operation and only stops during the battery swapping procedure. Both valves are never open at the same time.

In the real world, the battery swapping method currently utilised for AGVs involves the battery being swapped from the side of the chassis [51]. For the AAGVs, such a scenario is possible, however it could possible lead to problems like improper sealing of the battery compartment door which could cause the sinking of the AAGV while on water due to ingress of water [35]. It must also be noted that such a compartment door will have to withstand water pressures to keep the AAGV floating and would drive up costs[49]. As such, a recommendation can be made for the battery to be vertically swapped where the battery is accessed and replaced from the top of the hull. Such a scenario will maintain the watertight nature of the AAGV hull and will make sure that a door failure of the battery compartment is not a critical issue for the operation of the AAGV. A small issue in this method will be that the AAGV cannot be carrying a container while the battery is being replaced, for the simple reason that a container on the top will not permit battery swapping of the AAGV.

Another consideration will have to be the level of charge below which the AAGV must proceed to a battery swapping station. The AGVs are set to a trigger of 23% of battery charge to make sure the battery does not go below 20% of the total charge [72]. It might however be necessary for the trigger level to be set much higher for the AAGV especially considering the fact that it shall be sailing through water and might need a higher charge to complete its journey if its a long distance, since if a trigger of 23% is utilised and it is far away from its battery swapping station, it runs the possible risk of losing power while on water [71].

Electric AGVs are powered by a "high-performance lithium-ion battery" [9] however their battery capacity has not been explicitly stated in any publicly available source. However, Kalmar has provided the battery capacity and consumption specifications for its all electric Reach Stackers [28]. In its publicly available specifications, it is stated that Kalmar produces reach stackers utilising the BoschRexroth Traction motors which consume 182kW [28] during standard continuous operation and 405kW at peak[28].

To find the energy needed by the AAGVs, the total resistance faced by the AAGV in water and on land will have to be found. The dimensions of the AAGV are already known, with a width of 3 m on land, and 6 m on water (with side-pods deployed), length of 16.6 m, unloaded height of 1.8 m and a loaded height of 4.4 m. The total weight of the vehicle is to be a maximum of 100 tons.

The Speed restrictions implemented on land and water are 10 km/h (2.78 m/s) and 13 km/h (3.61 m/s), respectively. The distance travelled by an AAGV on land can be taken to be 3 kms within each terminal (source and destination) and 5 kms of travel on water. The length of the ramp can be taken to be 65.18 meters at 5°of inclination (to estimate consumption figures for a steeper incline).

When the AAGV is in the water, the submerged height of the AAGV can be calculated as:

$$\begin{aligned} h_{submerged} &= \frac{mass}{width_{submerged} \cdot length \cdot \rho_{water}} \\ &= \frac{100000 \text{ kg}}{6\text{m} \cdot 16.6\text{m} \cdot 997 kg/m^3} \\ h_{submerged} &= 1.066 \approx 1.01 \text{ m} \end{aligned} \tag{4.8}$$

Frontal Area submerged when AAGV is in water is calculated as:

$$\begin{aligned} A_{underwater} &= h_{submerged} \cdot width_{submerged} \\ &= 1.0066\text{m} \cdot 6\text{m} \\ A_{underwater} &= 6.04\ m^2 \end{aligned} \tag{4.9}$$

Frontal Area above the water line, when AAGV is in water is calculated as:

$$\begin{aligned} A_{overwater} &= h_{loaded} \text{ - } h_{submerged} \cdot width \\ &= (4.40 - 1.0066)\text{ m} \cdot 3\text{ m} \\ A_{overwater} &= 10.18\ m^2 \end{aligned} \tag{4.10}$$

When the AAGV is on land, the Frontal Area of the AAGV can be calculated as:

$$\begin{aligned} A_{land} &= h_{loaded} \cdot width \\ &= 4.40\text{m} \cdot 3\text{m} \\ A_{land} &= 13.20\ m^2 \end{aligned} \tag{4.11}$$

Power needed on Water by the AAGV is calculated as:

$$\begin{aligned} P_{water} &= (0.5 \cdot \rho_{water} \cdot C_d \cdot v_{water}^3) \cdot A_{underwater} + (0.5 \cdot \rho \cdot C_d \cdot v_{water}^3) \cdot A_{overwater} \\ &= (0.5 \cdot 997 \cdot 0.75 \cdot 3.61^3) \cdot 6.04 + (0.5 \cdot 1.29 \cdot 0.75 \cdot 3.61^3) \cdot 10.18 \\ P_{water} &= 106.61\ kW \end{aligned} \tag{4.12}$$

Power needed on Land by the AAGV is calculated as:

$$\begin{aligned} P_{land} &= ((f_r \cdot mass \cdot g) + (0.5 \cdot \rho \cdot C_d \cdot v_{land}^2 \cdot A_{land})) \cdot v_{land} \\ &= ((0.02 \cdot 100000 \cdot 9.81) + (0.5 \cdot 1.29 \cdot 0.75 \cdot 2.78^2 \cdot 13.2)) \cdot 2.78 \\ P_{land} &= 54.64\ kW \end{aligned} \tag{4.13}$$

Power needed on an incline by the AAGV is calculated as (angle of 5°or 0.0873 radians):

$$\begin{aligned} P_{incline} &= ((f_r \cdot mass \cdot g \cdot \cos\theta) + (0.5 \cdot \rho \cdot C_d \cdot v_{land}^2 \cdot A_{land}) + (mass \cdot g \cdot \sin\theta)) \cdot v_{land} \\ &= ((0.02 \cdot 100000 \cdot 9.81 \cdot \cos(0.0873)) + (0.5 \cdot 1.29 \cdot 0.75 \cdot 2.78^2 \cdot 13.2) \\ &\quad + (100000 \cdot 9.81 \cdot \sin(0.0873))) \cdot 2.78 \\ P_{incline} &= 291.93\ kW \end{aligned} \tag{4.14}$$

Total Energy needed for a single trip of an AAGV, consisting of a maximum possible total journey length of 6 kms on land (3 kms within each terminal) and 5 kms on water, as well as an incline length of 65.18 meters, can be calculated as:

$$E_{aagv} = P_{water} \cdot (\frac{Dist_{water}}{v_{water}\text{(km/h)}}) + 2 \cdot P_{land} \cdot \frac{(Dist_{land,aagv} - ramp)}{v_{land}\text{(km/h)}} + 2 \cdot P_{incline} \cdot (\frac{\text{ramp}}{v_{land}\text{(km/h)}}) \tag{4.15}$$

$$\begin{aligned} &= 106.61 \cdot (\frac{5}{13}) + 2 \cdot 54.64 \cdot \frac{(3 - 0.06518)}{10} + 2 \cdot 291.9 \cdot (\frac{0.06518}{10}) \\ E_{aagv} &= 76.88\ kWh \end{aligned}$$

This is the estimated battery capacity needed for 1 trip, which is approximately 60 minutes. The AAGV is expected to be able to run at least 8 hours before needing to replace its battery. Therefore, with an additional safety buffer of 10% added, the battery capacity for an AAGV can be found to be:

$$\begin{aligned} C_{battery,aagv} &= \frac{E_{aagv} \cdot \text{Number of trips}}{\text{90\% safety limit}} \\ &= \frac{76.88 \cdot 8}{0.9} \\ C_{battery,aagv} &= 683.37\ kWh \end{aligned} \tag{4.16}$$

With these values, we can implement the Fluid Library of AnyLogic. The Battery is simulated as a tank of 1000 litres.

$$\begin{aligned} \text{Energy per liter ratio} &= \frac{\text{Battery capacity}}{\text{Tank capacity}} \\ &= \frac{683.37 \text{ kWh}}{1000 \text{ liters}} \\ &= 0.683 \text{ kWh/liter} \end{aligned} \tag{4.17}$$

The Energy required has been calculated assuming that the AAGV travels the entire time within the 60 minutes. However, in reality, we can allow for a stopping time of about 10 minutes in the whole trip to allow for the unloading of the AAGV. So the discharge rate for an AAGV with such a power requirement will be lower than the actual rate it consumes if 60 minutes is taken. Therefore, it can be calculated by adding 10 minutes of stopped time to the 60 minutes of travel time as:

$$\begin{aligned} \text{Power consumption per minute} &= \frac{\text{Power consumption}}{60 + 10 \text{ minutes}} \\ &= \frac{76.88 \text{ kWh}}{70 \text{ minutes}} \\ &= 1.09 \text{ kWh/minute} \end{aligned} \tag{4.18}$$

$$\begin{aligned} \text{Volume of fluid consumed per minute} &= \frac{\text{Power consumption per minute}}{\text{Energy per liter ratio}} \\ &= \frac{1.09 \text{ kWh/minute}}{0.683 \text{ kWh/liter}} \\ &= 1.60 \text{ liters/minute} \end{aligned} \tag{4.19}$$

Therefore, the simulated fluid consumption for in an AAGV is **1.60 liters per minute**.

5
Results

The chapter presents the key findings of the research conducted in this thesis. It delves into the performance and potential benefits of implementing amphibious AGVs in container terminals, drawing upon the insights obtained from throughput calculations, battery consumption values, and simulation modeling. The chapter systematically examines the impact of amphibious AGVs on efficiency compared to traditional land-based AGVs and barges.

It addresses the research questions outlined in the thesis, specifically focusing on how amphibious AGVs can potentially revolutionize container terminal operations. Crucially, this chapter fills a gap in the current literature by quantifying the efficiency gains and presenting a systematic and data-driven comparison of amphibious AGVs with existing solutions, highlighting their potential to enhance terminal throughput and resource utilization; and by secondly, providing for the modifications to achieve operational feasibility through comprehensive simulations, investigating the practical integration of amphibious AGVs into existing terminal layouts and workflows, addressing concerns about real-world implementation.

5.1. As-Is 1 Results

The Results for As-Is 1 in 60 minutes for different Container Throughput and varying number of AGVs and Reach Stackers can be seen in Table 5.1:

Table 5.1: The Results for As-Is 1

Average Container Transport Time (mins, with Barge Travel of 30 minutes approximately)					
	Throughput				
AGVs | RSs	**10**	**15**	**20**	**25**	**30**
10					
10	47.76	52.03	58.11	55.85	63.65
15	48.52	52.51	56.81	64.14	68.63
20	47.41	51.73	56.5	61.51	65.28
15					
10	47.92	58.48	56.93	68.7	70.47
15	48.24	52.9	59.2	60.03	65.13
20	48.28	54.71	60.15	64.7	68.32
20					
10	53.21	50.73	56.23	62.97	70.41
15	49.25	55.59	62.5	64.13	65.77
20	47.39	51.18	55.27	63.12	68.81
25					
10	48.62	58.1	59.47	64	64.4

15	48.48	55.5	59.45	57.42	65.17
20	47.98	56.49	56.37	61.54	65.94
30					
10	47	55.91	52.96	61.56	67.09
15	47.52	57.57	55.74	59.69	66.95
20	48.1	52.93	54.18	63.37	70.69
35					
10	48.96	51.61	56.72	60.4	68.55
15	49.57	56.1	61.75	59.52	68.17
20	53.4	60.25	58.29	59.09	68.76

It should be noted that the simulation only included every container being handled from the barge to the stack. The travelling of the barge has not been simulated and therefore an extra travel time of 30 minutes has been added to the average container time, to give a realistic view of the time travelled per container. According to simple calculations, it can be seen that it takes 23 minutes for the Barge to travel a distance of 5 kilometers at a speed of 13kmph, which is the maximum speed allowed on inland waterways within the port area. A few more minutes have been added to cater for its acceleration, deceleration and docking on either side, thereby rounding it off to 30 minutes of travel.

It is clearly visible from the results given above that most of the time, almost double in some cases, is spent by the containers travelling on the water. The unloading process by Quay Cranes further adds to the average time taken per container to be stored.

The above results can be graphically visualised in the following graphs:

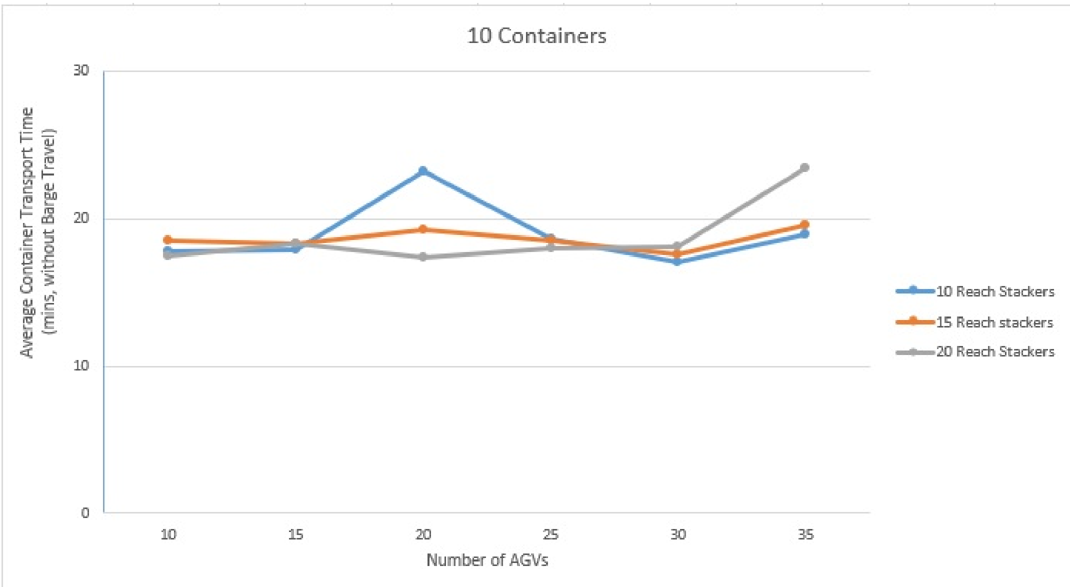


Figure 5.1: AGV with 10 Containers

The fact that the trends are still increasing suggests that even with more reach stackers, they cannot fully address the bottlenecks or limitations. However, the rate of increase is different between graphs with different reach stacker quantities. This indicates that more reach stackers help alleviate the bottleneck to some extent compared to fewer reach stackers.

Figure 5.2: AGV with 15 Containers

All graphs show increasing trends in container delivery time as the number of AGVs increases. However, the rate of increase differs between the graphs. The number of reach stackers (represented by the line colors) seems to have an impact on the rate of increase.

Figure 5.3: AGV with 20 Containers

Figures 5.3, 5.4, and 5.5 might be exhibiting the effects of bottlenecks in the system that are not mitigated by adding more AGVs. Even with more vehicles, the underlying limitations prevent significant improvement in delivery times.

Figure 5.2 suggests a more efficient system where additional AGVs can lead to faster deliveries, although the increasing trend indicates there might still be limitations.

Figure 5.4: AGV with 25 Containers

Figure 5.4 might show how the type or number of reach stackers affects AAGV utilization. If the orange or grey lines (more reach stackers) increase slower than the blue line (fewer reach stackers), it suggests better utilization with more reach stackers.

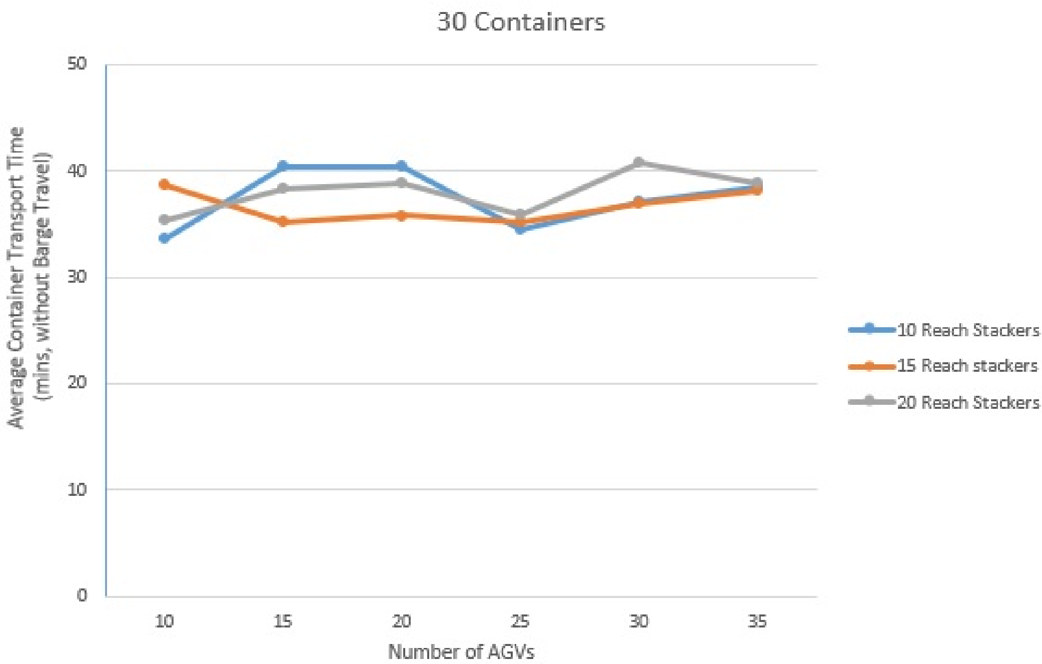


Figure 5.5: AGV with 30 Containers

At certain throughputs, it can be noted that 15 Reach Stackers work better than 10 because of increase handling capacity and better than 20 because of lower relative congestion.

5.2. To-Be 1 Results

The results of To-Be 1 in 60 minutes for different Container Throughput and varying number of AAGVs and Reach Stackers can be found in Table 5.2:

Table 5.2: The Results for To-Be 1

Average Container Transport Time (mins)					
AAGVs | RS	**Throughput**				
	10	**15**	**20**	**25**	**30**
10					
10	35.70				
15	35.00				
20	35.99				
15					
10	35.17	39.05			
15	35.05	37.52			
20	35.63	36.88			
20					
10	34.71	40.61	42.48		
15	36.58	37.23	44.26		
20	35.39	39.39	41.81		
25					
10	33.30	38.47	38.00	44.94	
15	33.32	36.09	43.01	47.54	
20	33.98	36.45	41.60	45.86	
30					
10	35.06	41.39	40.26	49.34	48.15
15	36.13	38.86	47.45	48.90	
20	33.54	40.12	42.33	51.33	49.42
35					
10	34.71	39.87	46.25	50.23	46.45
15	34.48	40.55	41.56	43.56	46.46
20	35.87	39.50	43.11	50.83	49.17

The above simulation results include the time taken by the AAGVs to travel from the source terminal to the sink terminal, be unloaded and then the stacking time for every container. It does not simulate the loading time at the source terminal since it has also not been included in As-Is 1.

For the Scenario of 10 AAGVs, it was observed that the average transport time generally remains consistent across different numbers of Reach Stackers (10, 15, and 20) for each throughput level. This suggests that with a low number of AAGVs, adding more Reach Stackers may not significantly affect the transport time. Observations for 15 AAGVs are similar to the 10 AAGVs, the impact of Reach Stackers on transport time seems to be minimal. There are some variations in the data, but no clear trend is evident. This is mainly because within 60 minutes, the AAGVs can complete only one single trip if the throughput is greater than the AAGVs available, allowing only the number of containers equal to the number of AAGVs being delivered at the end of 60 minutes, and not the complete throughput.

For the Scenario of 20 AAGVs, one can start to see a more noticeable influence of Reach Stackers on transport time. At throughputs of 15 and 20 containers per hour, having 15 or 20 Reach Stackers reduces the transport time compared to using only 10 Reach Stackers. This indicates that a higher number of Reach Stackers can be beneficial with a moderate number of AAGVs.

For all the Scenarios including 25, 30, and 35 AAGVs, the impact of Reach Stackers becomes more pronounced. In most cases, using 15 or 20 Reach Stackers leads to a significant reduction in transport time compared to using only 10 Reach Stackers. This suggests that with a sufficient number of AAGVs, having more Reach Stackers can significantly improve efficiency in handling container movements.

Overall, the data implies that the effectiveness of AAGVs depends on the number of Reach Stackers in operation. Their contribution to reducing transport time becomes more apparent with a higher number of AAGVs, particularly at higher throughputs.

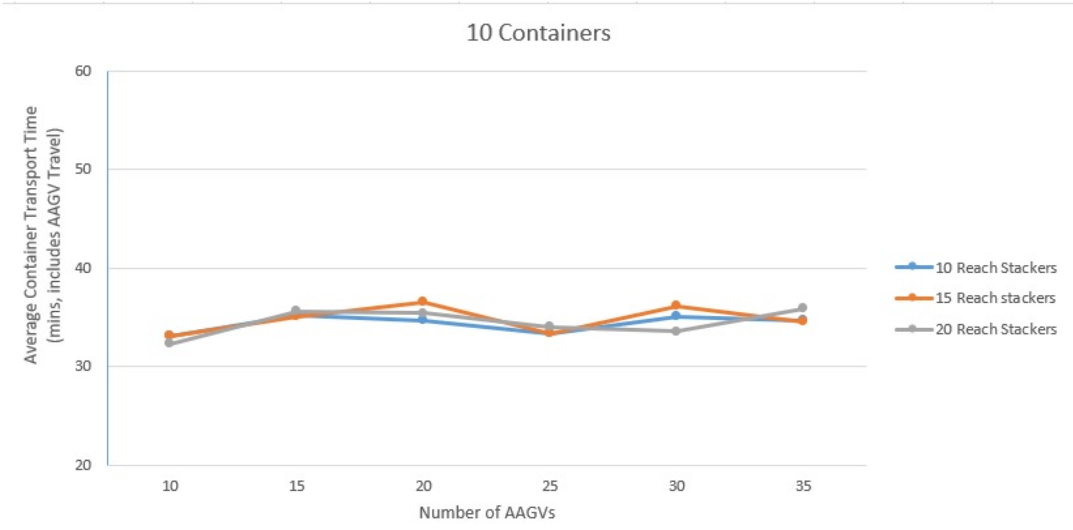


Figure 5.6: AAGV with 10 Containers

In figure 5.6, all three lines (10, 15, and 20 Reach Stackers) show a general maintenance in transport time as the number of AAGVs increases. This suggests that with a fixed throughput of 10 containers, adding more AAGVs can improve the efficiency of container movement between terminals. With more AAGVs, containers likely experience less waiting time as there are more vehicles available to transport them.

A rate of decrease in transport time seems to be observed as the number of AAGVs increases when compared to the same for As-Is 1. This indicates that there might be a point of diminishing returns. While adding more AAGVs initially leads to significant reductions in transport time, the benefit tapers off at higher numbers of AAGVs.

The line for 20 Reach Stackers appears to have the lowest average transport time across all AAGV levels. This suggests that for a throughput of 10 containers, using 20 Reach Stackers alongside AAGVs is the most efficient configuration in terms of transport time.

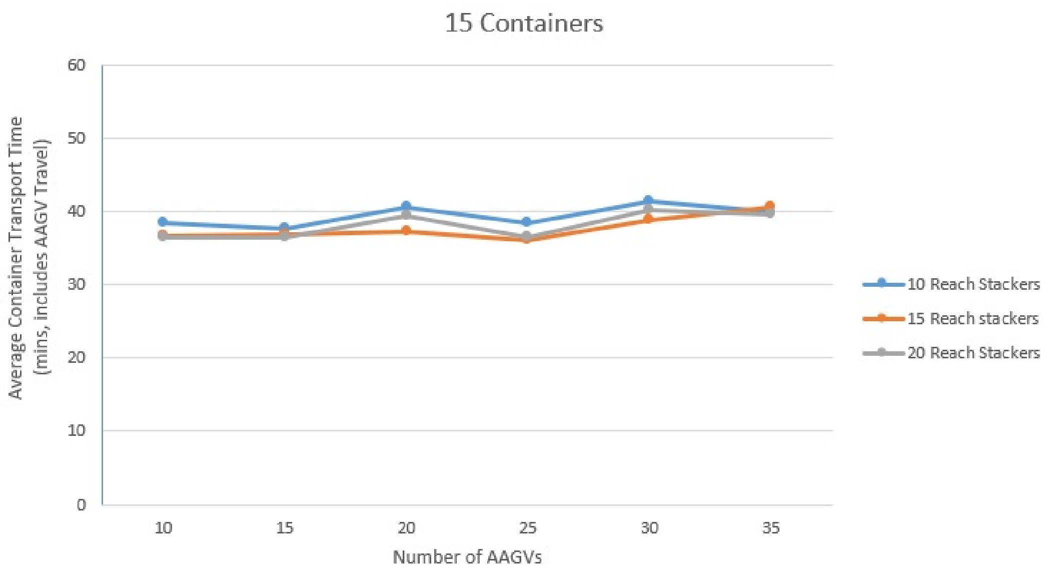


Figure 5.7: AAGV with 15 Containers

The observations from figure 5.7 are very similar to figure 5.6. However, there are a couple of minor differences to note. The transport time in this graph appears to be higher overall compared to a throughput of 10 containers. This might be due to the inherent inefficiency of handling a higher throughput (15 containers). The data point for 10 AAGVs with 10 Reach Stackers is slightly higher than the data point for 15 AAGVs with 10 Reach Stackers. This is because with 10 AAGVs only 10 containers out of 15 can successfully be delivered within 60 minutes.

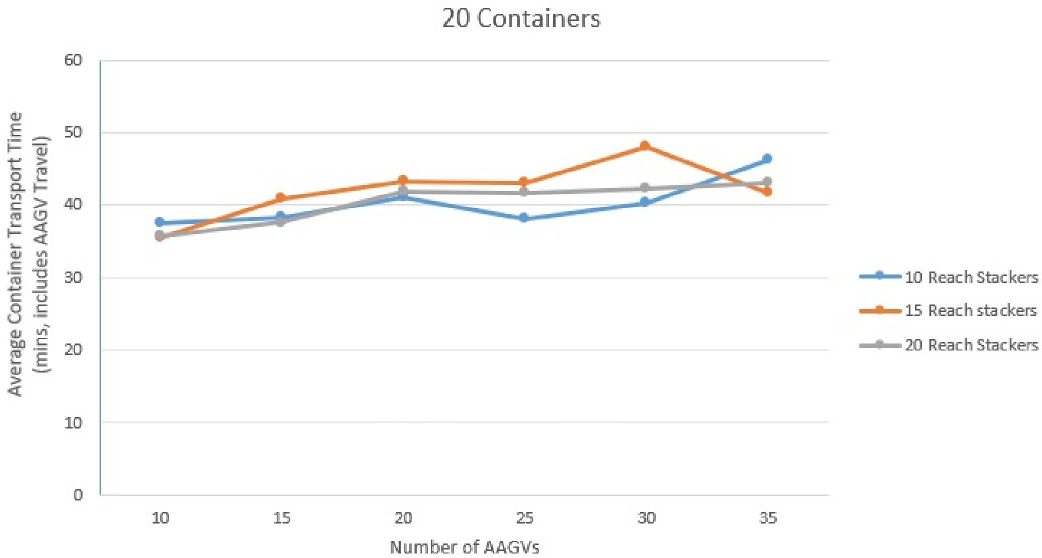


Figure 5.8: AAGV with 20 Containers

In contrast, it can be noted in Figure 5.8, the overall transport time across all AAGV configurations (with 10, 15, and 20 Reach Stackers) appears to be higher compared to the throughputs of 10 and 15 containers. This is likely because more containers need to be transported, leading to increased congestion and potentially longer wait times.

The general trend of increasing transport time with more AAGVs remains consistent. However, the impact of adding Reach Stackers seems less pronounced in this graph compared to the previous graphs. For example, the difference in transport time between using 10 Reach Stackers and 20 Reach Stackers is smaller for the 20 container throughput scenario. This suggests that the benefit of additional Reach Stackers diminishes at higher throughputs, where the system might be limited by other factors like operating space or congestion.

Figure 5.9: AAGV with 25 Containers

Similar to previous data, Figure 5.9 is consistent with the observations from the previous 10, 15, and 20 containers throughputs. It shows a general decrease in transport time as the number of AAGVs increases as compared to As-Is 1. This indicates that with more AAGVs available, there's less waiting time for containers, leading to faster throughput transport times as compared to the same in As-Is 1. As observed before, the rate of decrease in transport time with more AAGVs appears to be even smaller in this graph compared to the previous ones. Even with more AAGVs, efficiently handling a high throughput of 25 containers might become challenging due to factors like terminal congestion or limitations of the AAGVs themselves. It must be remembered that these factors would also exist for the same number of AGVs.

The impact of using more Reach Stackers seems even less noticeable compared to the previous throughputs (10, 15, and 20 containers). The lines for the different Reach Stacker configurations are much closer together, indicating that adding more Reach Stackers has minimal influence on reducing transport times at this high throughput.

With a high traffic of 25 or even using 30 AAGVs, the terminals or the overall system might become congested, limiting the effectiveness of additional Reach Stackers. Even with more Reach Stackers to assist with loading and unloading containers, the AAGVs might have to wait for space to become available at the terminals, negating the potential benefit of extra Reach Stackers, making it possible that the AAGVs themselves become a bottleneck at high throughputs. They might have limitations in terms of speed or handling capacity, and adding more Reach Stackers won't address these limitations.

It must be clarified that in real world scenarios, AAGV arrival timings would be spaced enough to prevent congestion. The simulations do not possess this spacing due to the fact that loading has not been simulated at the source terminal, thereby eliminating the inherent gap in start times for transportation for each AAGV from the source terminal.

It should be noted that within 60 minutes, every AAGV is able to complete a minimum of 1 trip between the source and the sink container. As such the results are not affected by the loading time for the second trip, since the AAGVs never return for a second trip within 60 minutes. This can be explained by a simple comparison with the Base case where it was calculated that it takes 23 minutes for a Barge to travel between two terminals. This proves that a second trip for the remaining containers (in cases where source containers outnumber available AAGVs) would be impossible to simulate due to the 60 minute simulation time.

Figure 5.10: AAGV with 30 Containers

5.3. Comparison of As-Is 1 and To-Be 1

If we combine the above results into the same graph to get a differential comparison along the same axis for every throughput value, we shall be able to visualise:

The above results can be graphically visualised as:

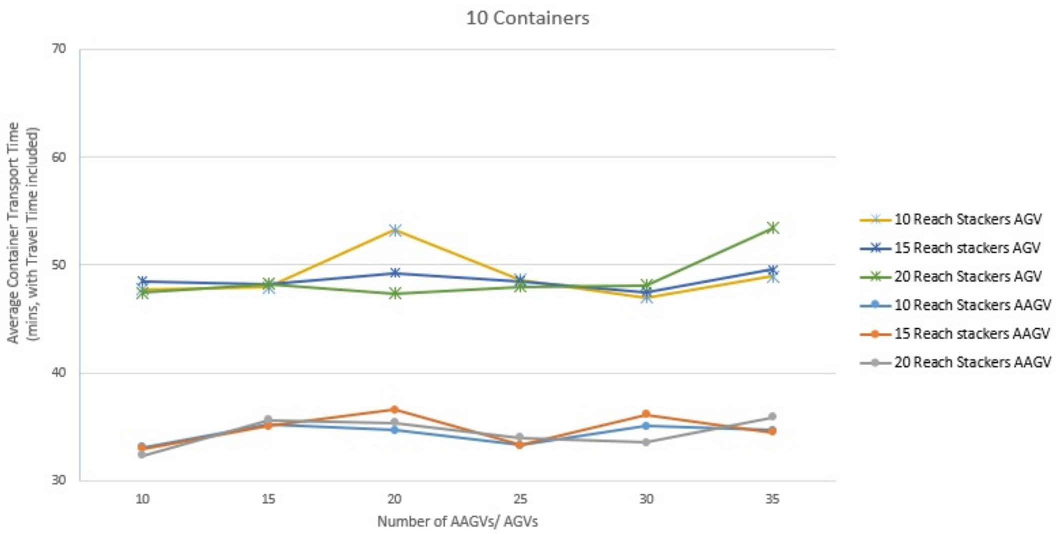


Figure 5.11: AGV vs AAGV with 10 Containers

For a throughput of 10 containers, the average container transport time in As-Is 1 ranges from approximately 47 to 53 minutes, with an overall average of around 49 minutes. This duration encompasses the time for the containers to travel on the barge, unloading time using quay cranes, and transportation to the stack, along with all congestion connected delays in-between. In contrast, To-Be 1 demonstrates a consistently lower average container transport time, ranging from approximately 33 to 37 minutes, with an overall average of around 35 minutes.

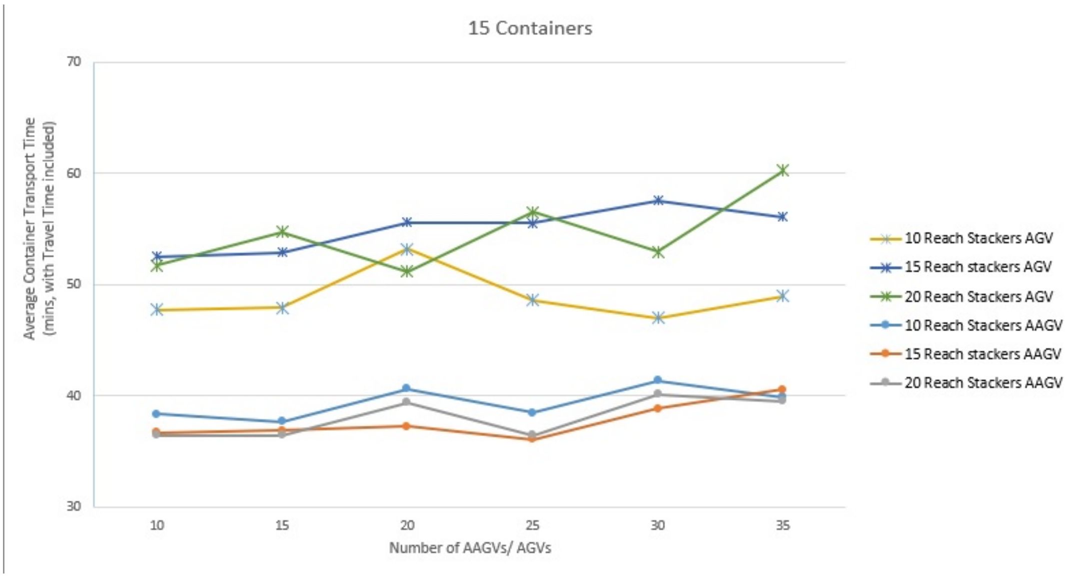


Figure 5.12: AGV vs AAGV with 15 Containers

For 15 containers, in As-Is 1, the average container transport time ranges from approximately 47 minutes to 53 minutes, with an overall average of around 48.5 minutes. This is significantly higher than To-Be 1, where the average container transport time ranges from approximately 36.5 minutes to 40.5 minutes, with an overall average of around 38 minutes.

The reduced time frame is attributed to the absence of barge-related delays, as AAGVs can directly travel to the container storage area and unload containers without relying on quay cranes. To-Be 1 emerges as the more efficient and time-saving approach for container transport within the port area. The elimination of barge unloading and the direct travel capabilities of AAGVs significantly contribute to reducing the overall container transport time.

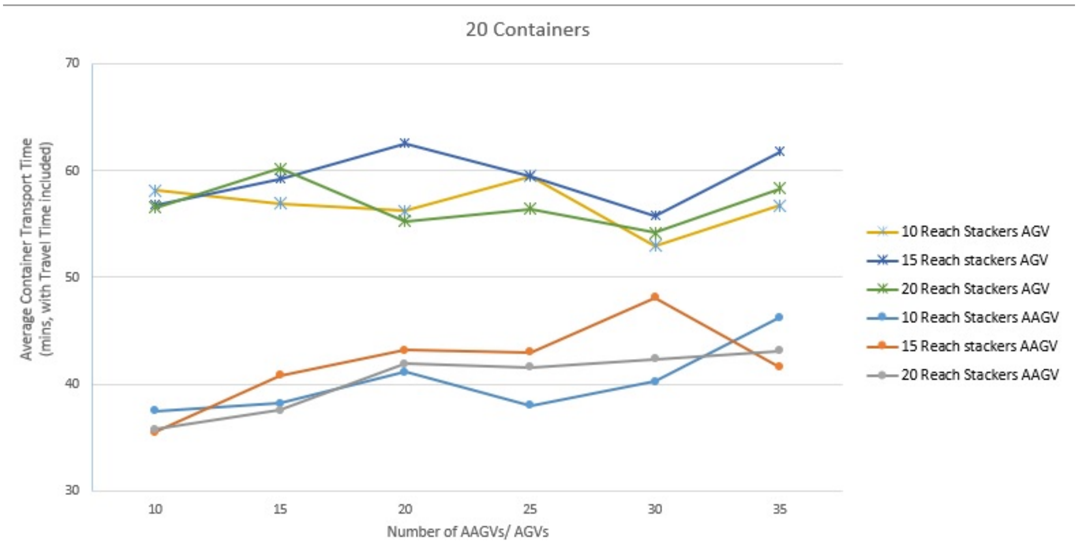


Figure 5.13: AGV vs AAGV with 20 Containers

The average container transport time for As-Is 1 decreases with an increase in the number of RS. This is due to the greater availability of RS for unloading containers from AGVs, resulting in reduced waiting time for unloading and subsequently lowering the average container transport time. This phenomenon is equally observable in To-Be 1.

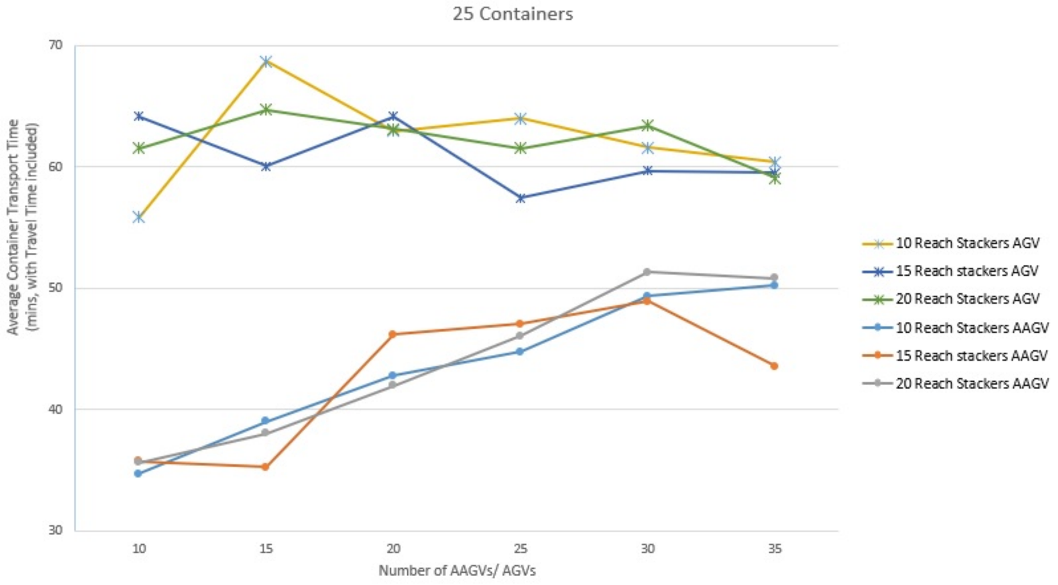


Figure 5.14: AGV vs AAGV with 25 Containers

To-Be 1 is the faster of the two scenarios. This is attributed to the fact that although the travel time from the source terminal to the sink terminal is the same for both scenarios, unloading containers from AAGVs onto reach stackers takes less time compared to unloading containers from a barge onto AGVs and then to Reach Stackers.

The difference in average container transport time between the two scenarios is due to the fact that the AAGVs can travel directly to the reach stackers, while the barges must first unload the containers onto AGVs, which then transport the containers to the reach stackers. This additional step in As-Is 1 adds to the average container transport time.

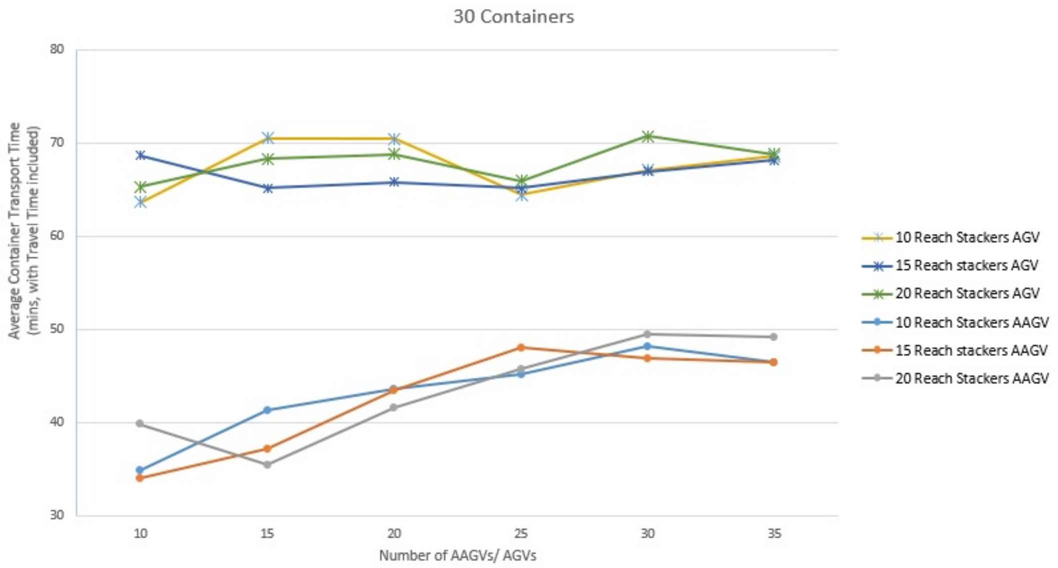


Figure 5.15: AGV vs AAGV with 30 Containers

Both scenarios entail the movement of containers within a port using automated guided vehicles (AGVs). However, in As-Is 1, containers need to be unloaded from a barge for transportation by AGVs, whereas AAGVs are capable of traveling directly to the container storage area. The graph reveals that To-Be 1 consistently outperforms As-Is 1 in terms of average container transport time. This is primarily due to the elimination of the time-consuming barge unloading process via Quay Cranes, which significantly impacts As-Is 1.

All figures when compared to the same in As-Is 1, exhibit a clear increase in efficiency. As the number of AAGVs increase, the gap in the time taken to deliver all containers increases rapidly. This suggests that adding more AAGVs leads to faster delivery times, likely due to increased capacity and parallelism in container movement. It would also ensure complete delivery of the throughput in least number of trips.

5.4. As-Is 2

Table 5.3 shows the results for As-Is 2, which includes AGV operations with barges using RTGs.

The table captures the maximum average container transport time in minutes for various throughputs (number of containers handled within 60 minutes) and numbers of AGVs deployed.

The first column contains the number of AGVs used in the operation while the other columns are representative of the various throughputs which are the desired number of containers to be handled within the time period of 60 minutes. The maximum average time (in minutes) to transport a container includes the Barge travel time and container exchange duration at the RTG crane. It must be noted that the Barge wait time experienced at the Quay Crane might be much higher.

Table 5.3: The Results for As-Is 2

Average Container Transport Time (mins, with Barge Travel of 30 minutes approximately)					
AGVs	**Throughput**				
	10	**15**	**20**	**25**	**30**
10	39.82	41.57	43.16	44.92	46.61
15	40.35	41.1	43.65	45.3	47.2
20	39.93	41.33	43.75	45.57	47.43
25	40.03	41.61	43.33	44.87	46.93
30	40.07	41.23	43.24	45.07	47.34
35	40.49	41.95	43.85	45.36	47.13

As the throughput increases, the maximum average transport time generally increases for all numbers of AGVs. This is because more containers compete for the resources (AGVs, RTGs) leading to potential congestion and waiting times. The effect of the number of AGVs on transport time is not entirely monotonic. In some cases, adding more AGVs might not significantly reduce transport time, especially for higher throughputs. This could be due to factors like Yard layout limitations where additional AGVs might not improve efficiency if the yard layout restricts their movement; or perhaps due to bottleneck formation, where managing a larger number of AGVs might introduce a bottleneck at the few RTGs and Quay Cranes needed to carry out container operations, potentially negating the benefit of increased resources.

The data suggests that there is a complex relationship between the number of AGVs, throughput, and average container transport time. While adding more AGVs can generally improve efficiency; yard layout, bottleneck management, and barge congestion time play a significant role in determining the overall transport time.

5.5. To-Be 2

Table 5.4 shows the results for the To-Be 2 scenario, investigating how efficient AAGVs are in moving containers between terminals without quay cranes.

The rows represent the number of AAGVs used in the simulation while the columns represent the container throughput (number of containers). The indicates the longest average time a container spent in transit between terminals for a specific combination of AAGVs and for a given Throughput.

Table 5.4: The Results for To-Be 2

Average Container Transport Time (mins)					
AAGVs	**Throughput**				
	10	**15**	**20**	**25**	**30**
10	26.72				
15	26.39	28.19			
20	26.76	27.16	28.50		
25	26.60	28.22	28.85	29.27	
30	25.76	27.41	27.93	28.45	28.99
35	26.09	26.92	27.99	28.74	30.41

Generally, increasing the number of AAGVs reduces the average container transport time. This makes sense because more vehicles can handle the container flow, reducing congestion and wait times. However, it can be observed that while adding AAGVs always reduces the transport time initially, the benefit slightly diminishes as the number increases. For example, going from 20 to 25 AAGVs at a throughput of 20 has a smaller impact on reducing transport time compared to going from 15 to 20 AAGVs.

The impact of AAGVs on transport time seems to depend on the throughput. At lower throughputs (10 and 15), increasing the number of AAGVs has a more significant impact on reducing transport time. At higher throughputs (25 and above), the impact is less pronounced. This suggests that even with a high number of AAGVs, high container volumes can lead to congestion and longer waiting times. This can be the result of congestion at the RTGs to unload the containers into the yards from waiting AAGVs and congestion at the Quay Cranes while unloading the containers.

Overall, the data suggests that AAGVs are a viable solution for transporting containers between terminals without quay cranes. The optimal number of AAGVs depends on the desired throughput and equipment available for container operations.

5.6. Comparison of As-Is 2 and To-Be 2

Figure 5.16 shows the comparison between the average container transport time for different throughputs of AGVs and AAGVs via RTG operations.

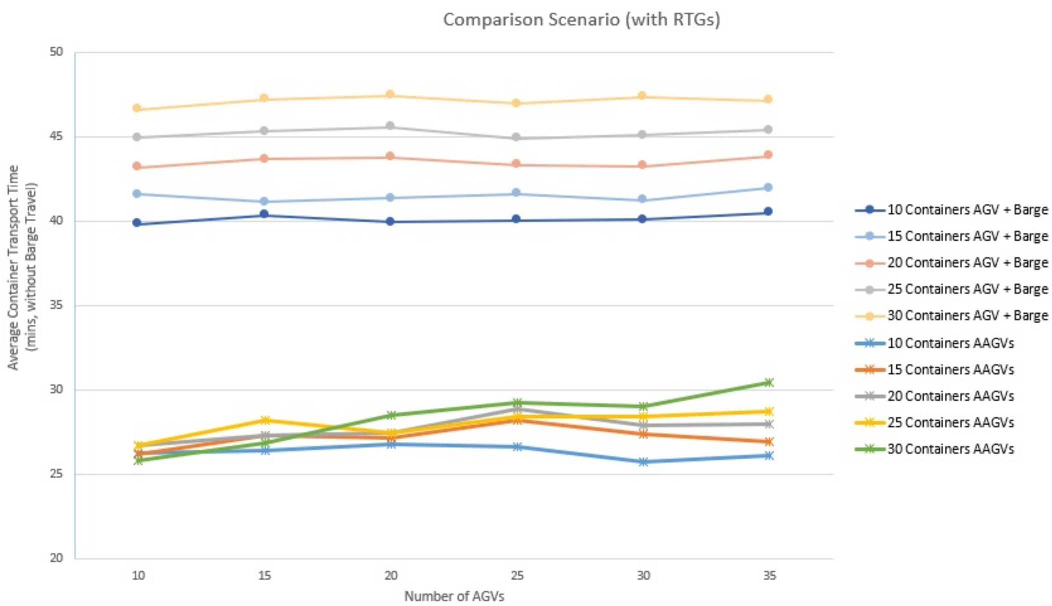


Figure 5.16: A Visual Comparison of As-Is 2 and To-Be 2

There are two data sets in Figure 5.16, one for the As-Is 2 and the other for To-Be 2. The As-Is 2 data set shows the average container transport time for five different throughputs, ranging from 10 to 30 containers within an hour. The To-Be 2 set also shows the average container transport time for five different throughputs, ranging from 10 to 30 containers. This enables a reasonable comparison between the two scenarios.

The x-axis shows the number of AGVs or AAGVs, and the y-axis shows the average container transport time in minutes.

It can clearly be seen that the AAGVs have a shorter average container transport time than As-Is 2 for the same throughput. For example, at 15 containers, the average transport time for As-Is 2 is around 32 minutes, while the average transport time for AAGVs Scenario is around 22 minutes.

The graph suggests that AAGVs offer faster average container transport times compared to AGVs for similar throughputs. This is mainly due to the fact that AAGVs eliminate the need for barge unloading times at the quay and barge congestion times. Since the AAGVs can directly access the RTG crane for container exchange, it removes a step (loading/unloading containers onto/from a barge) from the process. It also removes the waiting time due to barge congestion that is encountered at the Quay Cranes. It is important to note that the barge travel time of approximately 30 minutes, could be much greater with greater amounts of barge congestion if the QCs at the terminal are not available on time.

6
Conclusion

6.1. Conclusions & Discussions

It can be seen that the usage of AAGVs is better for every throughput ranging from 10 to 30 containers within a time period of 60 minutes due to lower average container transport times for each throughput. This is clearly attributable to the time spent on unloading each container via the quay crane from the barge onto the AGVs with no such operation being required for the AAGV. While the travel time of the AAGV is simulated in the model, the travel time of the barge has been added separately as part of post-processing of the data. If the barge travel was simulated as part of the model, it would never have resulted in the complete stacking of all containers due to the stacking time and travelling time combined going beyond the 60 minute limitation of the Material Handling Library of AnyLogic. It is for the same reason that the loading process has not been simulated at the source terminal for both As-Is and both To-Be scenarios.

Therefore it can be seen that, AAGVs remove the need to unload containers from a barge onto AGVs using QCs, before they can be transported within the terminal. Unloading containers from a barge is a time-consuming process that is avoided when using AAGVs, eliminating the requirement for QCs. This answers the first research question and proves that the AAGVs have provided a better solution to increasing efficiency in container terminal operations in the given case scenarios.

In the As-Is, it takes longer for a barge to travel from the source terminal to the sink terminal compared to the time taken for an AAGV to travel the same distance, since the barge needs to dock and takes a longer time to accelerate and decelerate due to its size. Additionally, the process of unloading containers from a barge onto AGVs is takes up time which is skipped by the AAGV at the Quay, and conducted directly within the yard. The average container transport time for the As-Is diminishes with an increase in the number of RS. This is due to the greater availability of RS for unloading containers from AGVs, resulting in reduced waiting time for unloading and subsequently lowering the average container transport time. However, the average container transport time also decreases with an increase in the number of AGVs. This is because a higher number of AGVs results in improved capacity for container transportation within the sink terminal, leading to reduced waiting time for unloading by the Quay Cranes and a subsequent decrease in the average container transport time.

In contrast, the To-Be is the faster of the two scenarios. This is attributed to the fact that although the travel time from the source terminal to the sink terminal is the same for both scenarios, unloading containers from AAGVs onto reach stackers takes less time compared to unloading containers from a barge onto AGVs and then to Reach Stackers. The average container transport time for the To-Be also decreases with an increase in the number of RS, as it leads to more RS being available for unloading containers from AAGVs, thereby reducing waiting time and subsequently lowering the average container transport time.

The mean duration for container transportation in the To-Be increases with the growing number of AAGVs. This is attributed to the higher competition for the same RS when more AAGVs are present, a situation not observed in the case of RTGs. Consequently, this competition may result in congestion, leading to an elevation in the mean container transport time. Nevertheless, it is necessary to have an equal number of AAGVs to the number of containers at the minimum for a single trip within 60 minutes.

It is not feasible to transport 30 containers with 10 AAGVs in a single trip within 60 minutes. The data indicates that the To-Be is more effective than the alternative scenario for container transportation at any given throughput. However, as exists, a minimum number of AAGVs are needed for the throughput transportation to be successfully possible.

As an outcome to the second research question, it can be seen that to implement AAGVs in container terminals, several modifications and additional infrastructure will be needed. Firstly, ramps will need to be installed at every terminal to allow the AAGVs to enter and exit the water. These ramps won't be steeper than about 5°and ideally less than 100 meters long to conserve space at the terminal. The height of the ramp will need to be 6.1 meters to match the distance between the terminal floor and the water. Secondly, the battery swapping infrastructure will need to be modified. Unlike traditional AGVs that swap batteries from the side, AAGVs will need a top-swap system to maintain a watertight seal in their hull and reduce the risk of an AAGV sinking. This also means that an AAGV cannot be loaded with a container for its battery to be replaced. Finally, the battery trigger level for AAGVs might need to be set higher than the 23% used currently for AGVs depending on the distance travelled. This is because AAGVs will be traveling through water and a lower trigger level may result in the risk of the AAGV losing power while on water.

In conclusion, this thesis found that AAGVs outperform a combination of AGVs and Barges in container transportation within a terminal for the given case scenarios. This is because AAGVs eliminate the time-consuming process of unloading containers from barges via QCs, leading to faster overall transport times. However, there is a trade-off between the number of AAGVs used and the throughput achieved. However, implementing AAGVs require modifications to the terminal infrastructure, including a one time investment in ramps for entering and exiting the water, and adjustments to battery swapping systems.

6.2. Assumptions & Limitations

Modeling time in all libraries of AnyLogic except the Process Modeling Library is limited by 1 hour (3600 seconds)[4]. This limitation may impact the accuracy of the model results, especially for systems that operate over longer periods of time. However, it is perfectly accurate for the 60 minutes simulated. The simulation software 'Arena' was not used as an alternative software because it has a limitation on the number of entities it can use rather than time and therefore would not be suited for the characteristics of the given model.

It must be noted that this research takes into account 5 kilometers of travel on water which is more than and therefore inclusive of the distance between the Euromax and ECT Delta as well as between Euromax and Delta II Container Terminals in the Port of Rotterdam. However, it also includes many other terminals in ports throughout the world including the terminals in DP World, Dubai thereby making it non-port specific.

The current battery capacity figures and charging figures cannot be taken from the AGVs currently deployed by ECT, which controls both the Euromax and Delta Terminals, since they are diesel-electric [15]. The Port of Singapore utilises purely electric AGVs, but utilise battery charging rather than battery swapping [1].

The simulation caters for the the AGV and AAGVs carrying the maximum possible weight of the 40 foot container and therefore the simulations will contain conservative figures on battery consumption and range of transportation.

Both Scenarios simulate the closest distance of travel to the stack. So for the As-Is, it assumes the unloading Quay Cranes are closest to the stack. It also assumes the same for the location of ramp to the stack.

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A

Integration Project Report

Amphibious Hive-Minded AGV

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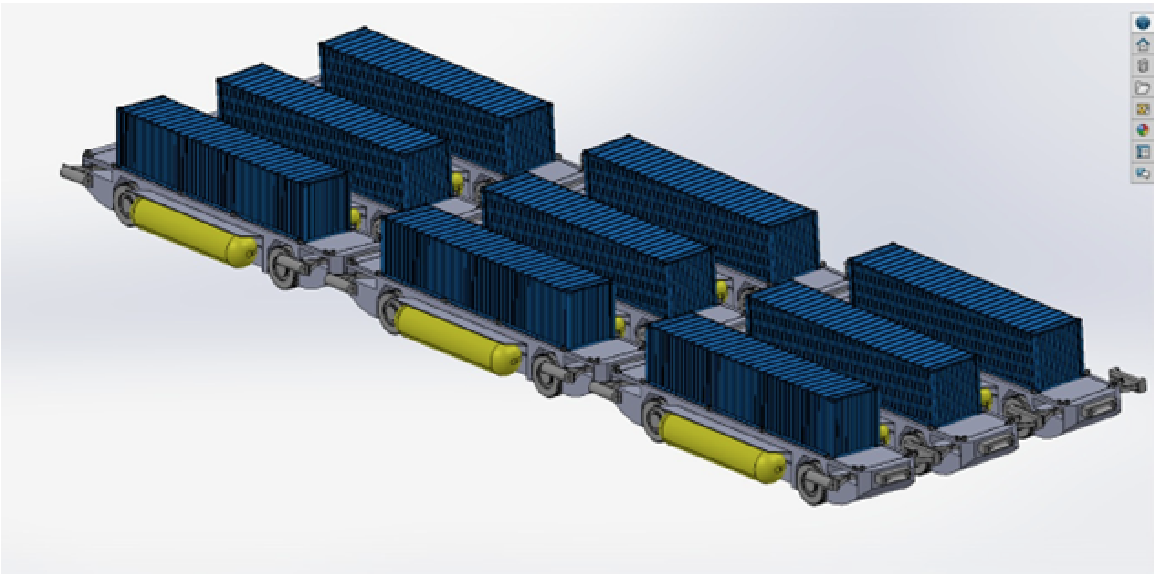
29 April 2022



Abstract

An international alliance of 45 companies, knowledge institutes and port authorities have created the MAGPIE project to shape green ports of the future. As an attempt to improve inter terminal container transport within the Port of Rotterdam between the deep sea terminals at the Maasvlakte and the inland container terminals near Eem- and Waalhaven, an Amphibious Automatic Guided Vehicle (AAGV) with HIVE minded control capabilities is designed. According to a carefully chosen design methodology, requirements are set up, subsystems are determined, a morphological chart is made, three concepts are designed and a final concept is chosen making use of a criteria concept scoring table. The final design includes a floating AGV form factor with inflatable side pods and extending electromagnetic/mechanical locking system, featuring two 360 degrees rotating propulsion jet pumps. A basic control system is setup and calculations are made to verify the flotation of the vehicle, the power of the jet pumps, the power train and the battery capabilities.

Integrated Design Project for Multi-Machine Systems (ME44110 Q3)
Supervisors: Ir. Wouter van den Bos, Dr. Jovana Jovanova

Contents

1 Introduction

With an ever growing need for the delivery of products, the container transport business is at an all time high. Most of these containers are shipped overseas and they arrive at container terminals. The Port of Rotterdam is the largest port in all of Europe and is one of the largest ports in the world and with more than 20 container depots, it is safe to say that the container transport section of the port of Rotterdam is of significant size. The port of Rotterdam offers 24/7 fast, efficient and reliable container handling.

In order to improve the overall port performance and efficiency, an international alliance of 45 companies, knowledge institutes and port authorities has created the MAGPIE project. Multiple pilot and demonstration projects are set up with the ambition to shape green ports of the future. As part of the MAGPIE project and the course Integrated Design Project for Multi-Machine Systems, the students were challenged to come up with and design a solution for an autonomous transshipment system. This entails designing a way in which the containers are transported from sea transport to land transport. More precisely this means designing a solution for the transshipment system between autonomous barges or container vessels to autonomous trucks or trains.

This report aims to deliver a solution for the transshipment problem in the form of a conceptual design of an amphibious AGV with hive-minded control. This AAGV will be able to operate on land as an already existing AGV using the already available infrastructure of the port, but it will also be able to operate on the water as a 2 TEU barge. HIVE indicates an intelligent decentralized beehive minded control system which creates the possibility for multiple AAGVs to lock together on the water and travel as one, ensuring a more energy efficient means of transport. This AAGV could improve travel times between terminals significantly by retrieving a container on land in one terminal, driving into the water and moving in a platoon formation with other AAGVs to the desired terminal, going ashore again and integrating into the quay infrastructure again.

In this report, the design methodology shall be further discussed, the requirements of the (sub)systems are identified, multiple solutions are evaluated and multiple concepts are created and finally the design of the best concept has been finalized and created.

1.1 Design Methodology

Tackling the elaborate challenges of improving the overall port design and making it more efficient and greener requires a clear and structured design methodology. The design methodology that is followed throughout this report is based on the Lean Six Sigma principle:

- Define the problem
- Explore the possibilities
- Specifying the requirements
- Design
- Verify the design
- Refine
- Final design

1.2 Problem Definition

The problem as it is stated in the MAGPIE project is to force a breakthrough in the supply and use of green energy carriers in transport to, from and within ports. It is up to us to come up with an innovative solution for the transshipment problem as stated above.

1.3 Exploration

A further assessment of the current processes taking place during the transshipment process in a port is necessary in order to identify possible problems and solutions within this transshipment process.

First of all, the loading and unloading of large container vessels is done by fully automated ship-to-shore cranes, whose main objective is to load or unload a vessel as fast as possible. Secondly, the transport of containers at the quay and the rest of the container terminals is done by Automated Guided Vehicles (AGVs). As a result of the size of the port, these AGVs occasionally have to travel large distances between terminals. Currently, these AGVs travel on predetermined roads and are not free to stray from these paths. The possibility of autonomous transport of containers within the port over water could potentially save time, energy and money.

1.4 Requirements

Due to the structure and the existing infrastructure of the port of Rotterdam, a couple of design boundaries can be specified. On top of that, a couple of design wishes have been constructed. These boundaries and wishes are translated into the following requirements that must be kept in mind while designing the amphibious AGV (AAGV).

- On land, the AAGVs will need to be able to work with all the existing infrastructure
- The AAGVs need to be able to interlock in grid format on the water
- The AAGVs need to be able to robustly operate in moderate wavy conditions
- The AAGV needs to be prepared to transfer autonomously between water and land
- The AAGV should be able to carry 1 40 ft. container or 2 20 ft. containers
- The AAGVs should be able to manoeuvre precisely on the water

These requirements form the basis for the design of the AAGVs and will be kept in mind at all times. Guided by these requirements, different subsystems have been identified and multiple solutions have been created.

2 Subsystems

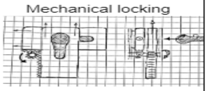
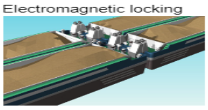
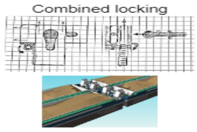
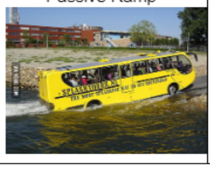
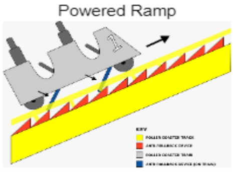
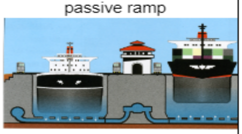
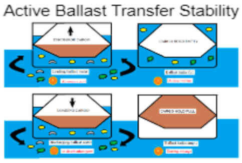
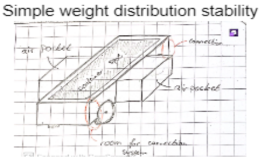
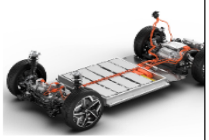
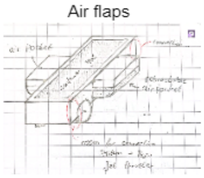
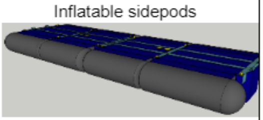
The requirements stated in the previous part demand a number of different subsystems. First of all, the AGV will be amphibious and thus will have to be able to traverse in water. Some form of propulsion for this is needed as the land traversing system will not be sufficient. Secondly, the system should be prepared to be HIVE minded. This means that the AAGVs should be able to interlock with each other. In this report, it is assumed that the locking and unlocking will happen on the water only. Thirdly, the vehicles must be able to autonomously transfer between water and land. However, some concepts have been presented but the exact design is beyond the scope of this project. In the rest of the report, it is assumed that the AAGV will be able to autonomously and efficiently transfer between land and water. Fourthly, the dimensions of a 40 ft. container will not result in a stable platform in the water, so a ballast system should be implemented. Fifthly, the overall form factor of the AAGV should be defined. Sixthly, the communication hardware of the AAGV shall be defined. Seventhly, the power source for delivering energy to the whole system shall be designed. Eighthly, land traversing options should be considered and lastly, an additional buoyancy passive stability system for the AAGV should be considered.

This results in the following subsystems:

- water traversing system
- locking system
- water/land transfer system
- ballast system
- AAGV form factor
- communication
- power system
- land traversing system
- passive stability and buoyancy system

Next up, options have been designed for the different subsystems and have been implemented in a morphological chart. Then, 3 complete AAGV concepts are defined from the concepts in the morphological chart. Consecutively, these complete concepts are scored based on differently rated aspects and the best concept is defined.

2.1 Morphological Chart

	Option 1	Option 2	Option 3	Option 4
Subsystem 1 Water Traversing options	Azipod Thrusters 	Jet pumps 	Fixed shaft water propeller 	Air propelled thruster 
Subsystem 2 Locking system	Mechanical locking 	Electromagnetic locking 	Hook locking 	Combined locking 
Subsystem 3 Transfer System (Secondary)	Passive Ramp 	Powered Ramp 	Double Waterlocks + small passive ramp 	Crane transfer 
Subsystem 4 Ballast system	Active Ballast Transfer Stability 		Simple weight distribution stability 	
Subsystem 5 AGV	Standard AGV 	Catamaran AGV 	Hovercraft AGV 	
Subsystem 6 Networking Options	Wireless Network 		Wired Plug and Socket 	
Subsystem 7 Power Options	Battery Powered 	Fuel Cells 	Fossil fuels 	Solar Powered 
Subsystem 8 Land Traversing Options	Wheels 	Caterpillar Tracks 	Hovercraft 	
Subsystem 9 Retractable side stability options	Air flaps 	Inflatable sidepods 	Scissor mechanism 	

2.2 Concepts

With regards to the designs of the amphibious AGV, three varying designs were thought through selection from the morphological chart, of which employed many common concepts used in the maritime industry and in some cases the military/Navy.

Concept 1
This concept consists of the following features:

- Jet pumps
- Standard AGV form factor
- Combined electromagnetic/mechanical locking
- Inflatable sidepods
- Battery powered
- Wheels

This concept is the most straightforward of all the three ideas with least difficulties. The idea involves the modified design of a standard AGV that is used in the port of Rotterdam with essential modifications to accommodate the locking system and stability systems such as the air pontoons and batteries.

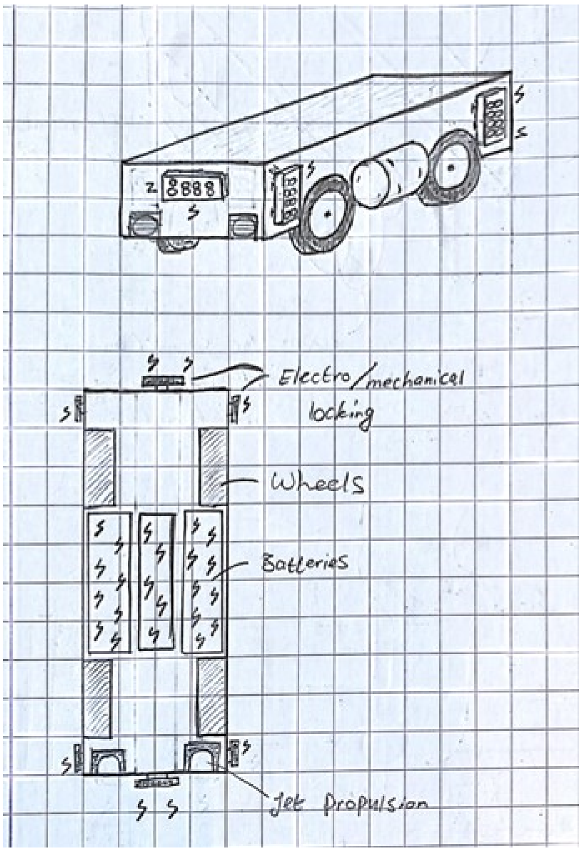


Figure 1: Concept 1

This design is based on standard AGV which is capable of carrying two twenty foot equivalent containers(TEU) of 6.1m long, 2.44m wide and 2.59 m high. This can also carry one 40 foot container of dimensions 12.2 m x 2.44 m x 2.59 m. In order to make this stable on water, the use of air pontoons were analysed and implemented. Two cylindrical air volumes are kept in two cavities on either side to keep the AAGV afloat under maximum load. These will be deployed before the AAGV enters the water.

The locking system between AAGVs will be done electromagnetically but Mechanically secured. The electromagnets will accurately guide the locks in place even in unstable environments such as the sea. This will later be clamped mechanically and secured with a pin, such that bending moments can be eliminated.

The battery system for this concept is placed completely on the floor, with the system incorporating a simple battery- swap approach when the AAGV runs dry. The powertrain of the AAGV would use permanent magnet AC motors which have high power density, high efficiency over regular AC motors. Furthermore, they require less cooling since they do not have any extra core losses which are usually seen in induction motors.

The propulsion system of the AAGV on water involves the use of pump jets which take in water from the centre and displace them tangentially, producing the thrust. Two of these would be needed, one at the front and the other at the rear of the AAGV.

The advantage of such a system is that it uses a standard AAGV base and builds upon that with modifications. This becomes economically and logistically feasible as it heavily adheres to standards. One disadvantage here is that the AAGV system would need additional stability solutions such as pontoons.

Concept 2
This concept consists of the following features:

- Fixed shaft water propeller
- Mechanical locking
- Passive stability
- Catamaran
- Fuel cell powered
- Caterpillar tracks

This concept adapts the shape of a catamaran and has the caterpillar tracks for Manoeuvrability. This concept uses passive stability for balancing itself on water, the aforementioned being provided by the wide structure of the catamaran and also the placement of the fuel cells to compliment the above purpose. This concept houses the mechanical locking system which consists of the vertical and the horizontal sliding plates. When the pin slides in, the plates move in relative motion thats actuated by rotary or pneumatic actuators, which causes the locking of the amphibious AGVs. For the propulsion of water a fixed shaft water propeller is used, which has a simple design and operation. Simple operation in the sense of the minimal input required for the operation. The Catamaran shaped AAGV is powered by the fuel cell, which helps us use their high power density.

The above concept also comes with its own downsides. The Width of the catamaran makes it too hard for the manoeuvrability of the vehicle on land. The mechanical locking comes with quite a lot of moving parts which decreases the reliability of the system. The propulsion is fixed and doesnt offer flexibility as that of azipods or jet thrusters. The cost of the fuel cells and considering the early stages in the research of it, the choice of fuel cells is not ideal.

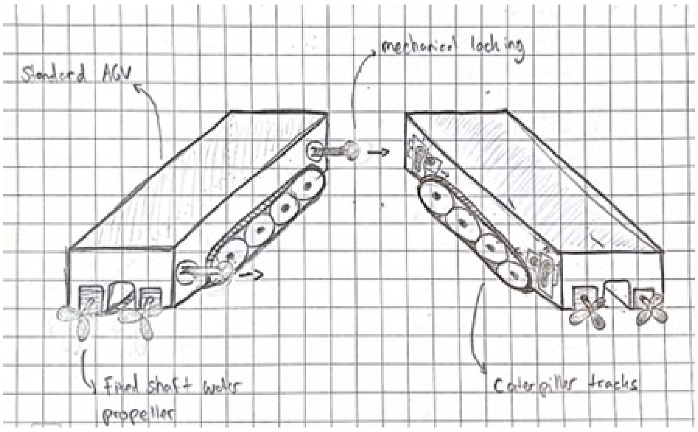


Figure 2: Concept 2

Concept 3

- Air propeller
- Electromagnetic locking
- Passive stability
- Hovercraft
- Fossil fuels

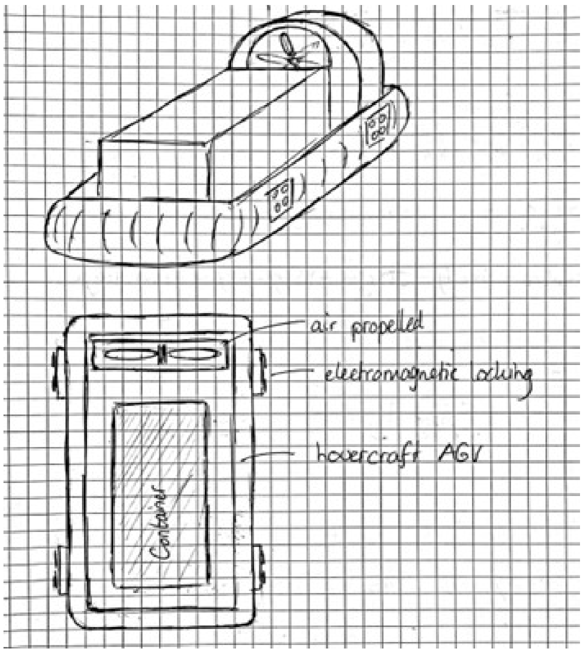


Figure 3: Concept 3

The Hovercraft was considered since it could simply glide off on a cushion of air. Inspiration for the use of hovercrafts came from The United States Marine Corps usage of LCACs (Landing Craft Air Cushions) as ship-to-shore connectors to transport equipment from ships for deployment on shore.

These LCACs are capable of carrying 60 tons of payload onboard for a range of 200 nautical miles at a maximum speed of 40+ knots; so making a prototype which can carry a maximum allowable weight of 54 tons for a range of tens of miles was considered feasible.
The concept includes a single large air propeller (center-rear) to propel the AAGV forward on land as well as on the waters. Since the AAGV will be riding on a cushion of air, there shall be no resistance to the AAGV from the land. This permits a high achievable speed, however acceleration and deceleration will be directly dependent on wind conditions and would not be as quick as needed. Power consumption will be of concern, since two separate engines will be needed for the lift and motion fans. It also was noted that when stationary on the water, the lift fan(s) will need to be on continuously, with the motion fan being sporadically used to keep it at the same position.
Battery power would not be possible in such a vehicle, and fossil fuels would have to be used since power consumption would be really high. Electromagnetic Locking is going to be used, which is power consuming although it is extremely convenient to engage and disengage. The biggest advantage of such a system would be its speed, since it would travel extremely fast.

2.3 Scoring Concepts

In this section, the different concepts are scored. First, the different scoring criteria are defined. Then, the weight of the criteria are determined using a trade-off table. Lastly, the concepts are scored and their weighted score is added up. This results in the final concept choice.
The different criteria are the following:

- Complexity
- Reliability
- Stability
- Manoeuvrability
- Efficiency
- Safety
- Price
- Availability of components

The concept eventually chosen was concept 1 which satisfied all key performance indicators. With regards to complexity, despite some logistical difficulties the standard AAGV presented the best compromise since it is based on a widely adopted standard design that fits all spaces while being the most reliable of all designs.

An important indicator for the AAGV is the system stability. To recall, the first concept used a semi passive stability by employing pontoons, the second concept focused on passive stability by having a much wider AAGV. Finally the third design concept used a hovercraft for keeping it afloat. Analysing these designs, it becomes clear that passive stability such as a wider AAGV is not always practical since AAGVs have to obey existing infrastructure on the quay, thereby rendering the AAGV worthless. As for hovercraft it becomes impractical to create a separate inflatable system for the entire AAGV when on water. An air pontoon design on the side can be inflated on demand and easily stored within the cavities, ensuring better packaging.

Due to better packaging and stability, the manoeuvrability of the system is also inherently much superior compared to other concepts, with its narrow main body form factor and better side stability. The use of Jet pumps makes this design easily manoeuvrable and reliable, with lesser moving parts, which would have been the case if Azi-Pods were used. Since the floor is used to house the pump jets completely, it is more space efficient while ensuring all powertrain and propulsion systems remain inside the AAGV at all times, with no moving parts and nothing exposed apart for the pump inlets. The concept with its increased stability also provides an increased level of safety with the stable pontoon design and better packaging of battery, powertrain and propulsion system. The Criteria weight of matrix and the weight matrix help determine the scoring table Table 4 and Table 5.

		Concept 1 - Standard AAGV		Concept 2 - Catamaran		Concept 3 Hovercraft	
	Weight:	**Score**	**Weighted score:**	**Score**	**Weighted Score:**	**Score**	**Weighted Score:**
Complexity	6	4	24	5	30	2	12
Reliability	8	5	40	2	16	3	24
Stability	7	4	28	3	21	3	21
Maneuverability	5	4	20	2	10	1	5
Efficiency	3	2	6	4	12	1	3
Safety	4	5	20	2	8	3	12
Price	2	3	6	4	8	1	2
Availability of components on the market	1	2	2	4	4	2	2
Total		**146**		**109**		**81**	

Table 1: Scoring table

3 Detailed design

AAGV body outside

For the chosen concept, a Solidworks model is made. The body of the AAGV is changed in such a way that it can work on land as well as in the water. As shown in the picture below the front and the end of the AAGV are rounded of to let the AAGV be more efficient in the water, also four holes have been made for the locking mechanism to fit in, last on the sides notches have been made and at the bottom a slot has been made for the air pockets to fit in.

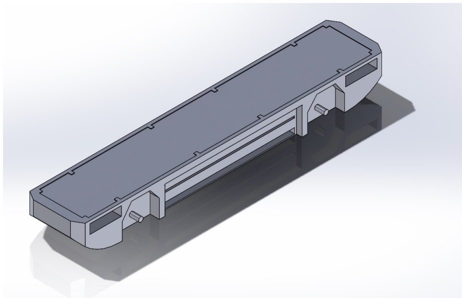


Figure 4: AAGV body outside

AAGV body inside

In order to make the AAGV frame strong enough to carry the weight of the containers a beam structured frame is needed on top of the AAGV. This beam structure is going to be similar as the one of a container trailer shown in Figure 6. In Figure 5 this beam structure is visible in black in the top view of the AAGV. In the AA section view the blue rectangles represent the area used for the batteries. The red squares represent the space for the drive engines. The holes visible in the BB section view are going to be used for the propulsion system.

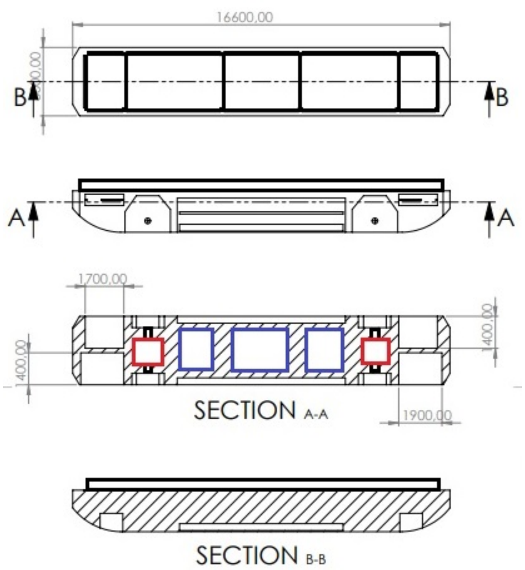


Figure 5: AAGV body inside

Figure 6: Frame container trailer

Locking mechanism
In water mode, the air pockets and the locking mechanism are extended out so that the AAGV will be stable and buoyant enough in the water and can interlock. The electromagnetic/mechanical locking is shaped in such a way that it allows for some guidance when locking. One half is shaped like half a cylinder (male part) and the other half like half a moon (female part) shown below. The parts will first interlock by the integrated magnets in both parts. After they are interlocked by the magnets two pins will mechanically lock both AAGV's with ensures that the magnets can be turned off. The connection will have a rotational degree of freedom to free the connection from stresses resulting from moments created by waves

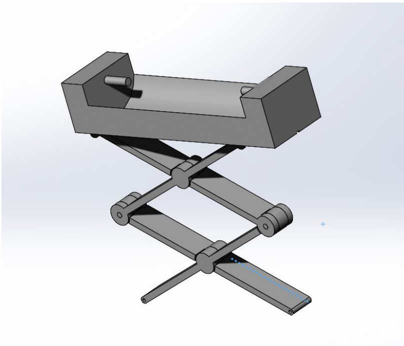


Figure 7: Female part

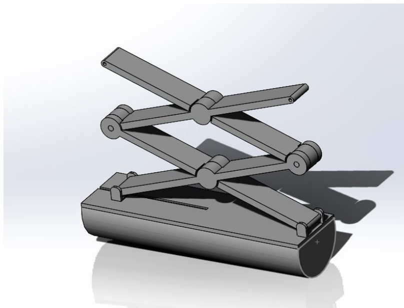


Figure 8: Male part

Water drive
When the AAGV is in the water a jet propulsion system shall be used resulting from the scoring. to make sure the AAGV can move in all directions when in the water a jet pump in the back and front is used as shown below. The jet pump can move 360 degrees making the AAGV flexible to move in all directions needed.

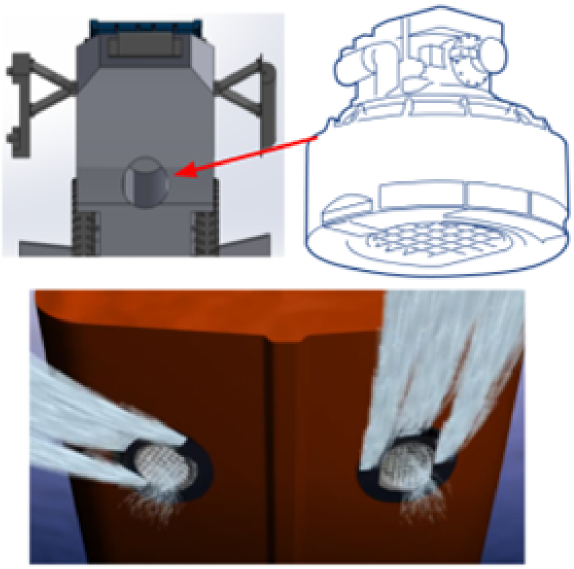


Figure 9: Jet pump

Masses of all subsystems

S.No	Type of Mass	Mass(Tonnes)
1	AAGV Chassis	8
2	Pontoons with support structures	1
3	E-Drives(Battery+ motor)	8
4	Propulsion	4
5	Load on AAGV	54
6	Total Mass	75

Table 2: Masses of AAGV components

The AAGVs will have two states: land mode and water mode. In land mode the AAGVs will have the locking mechanism and the air pockets retracted into the body so that the width of the AAGV will be sufficient to work with all the existing infrastructure on the quay. All dimensions of the AAGV can be found in Appendix B.

3.1 Land Mode

When the AAGV is on land, it will be in the land mode. Meaning the locking mechanism and the air pockets are retracted. The locking mechanism is retracted due to its scissor mechanism, which will be extended and retracted using pneumatic actuators. These actuators will share pressure pumps with the side pockets. While the air pockets will be retracted due to a belt that is connected on the end of the air pockets and a torsion spring that is located at the center of the AAGV. When the air pockets are blown up the spring will be under tension, so that when the air pockets get deflated the spring with the belt will retracted the air pockets. The retracting is needed for the AAGV to work in the existing infrastructure.

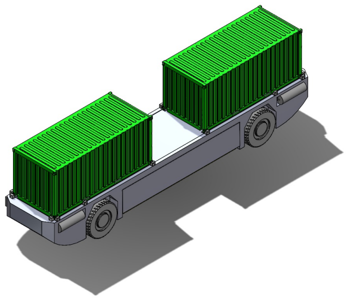


Figure 10: Isometric

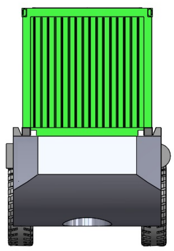


Figure 11: Front

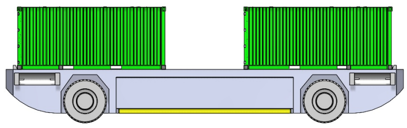


Figure 12: Side

3.2 Water Mode

When the AAGV is on the water the side covers open and the yellow air pockets on the side are inflated for buoyancy and stability. The same way the locking mechanism can retract, it can also extend in order to connect with other AAGV's.

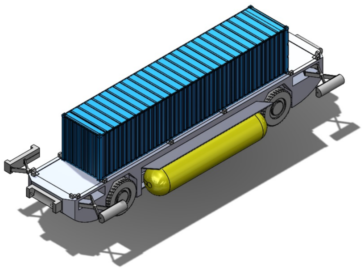


Figure 13: Isometric

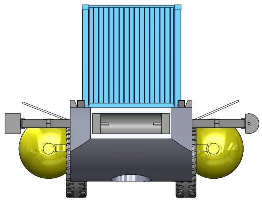


Figure 14: Front

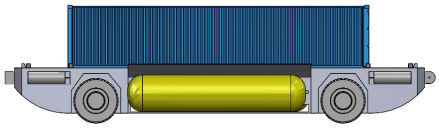


Figure 15: Side

3.3 Grid Formation

When the AAGV's are interlocked with one another, the grid formation on the water will look like the image in Figure 3. When the AAGV's have reached their destination they can disconnect from the grid, go on the quay and drive to the exact desired location.

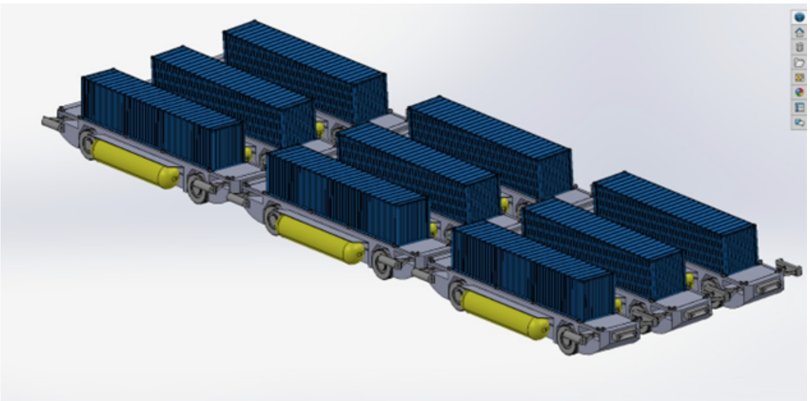


Figure 16: AAGV grid formation

3.4 Materials

The Amphibious HIVE minded AAGV consist of 3 main components: the body of the AAGV, the locking mechanism and the air pockets. For these 3 components its important to decide from what kind of material they will be made off.

The AAGV body will first be looked at. Because the AAGV is amphibious it will also be in contact with water, therefore it is important that the body is water resistant. The body of the AAGV will be made out of carbon steel to ensure that the body is strong and stiff enough. Stainless steel would be better to protect against corrosion in the severe seawater environment, however this would not be cost efficient as the price of stainless steel is much higher. Therefore the coating for the frame is very important in order to protect it against corrosion. For the AAGV frame an epoxy based paint is chosen, as this is the most common coating for small metal boats.

For smaller moving parts like the locking mechanism the same coating is used. However the coating on these parts is more likely to get damaged, as these parts are in contact with each other when locking. To ensure these parts are not sensitive for corrosion, but still strong enough, Stainless steel SAE 316 is chosen. This steel grade is widely used of maritime purposes, for it is very corrosion resistant in salt water.

The pontoon has to be inflated and deflated so the material needs to be flexible. It also needs to be strong enough to resist the inside air pressure and the buoyancy force to keep the AAGV floating. For inspiration we looked at the fabric of a hovercraft skirt, as this material has to be very strong and flexible as well. For the material we found a high strength coated fabric consisting of a nylon base cloth and an elastomer coating. The coating consist of Neoprene and Natural Rubber.[4]

3.5 Control System

The intelligence in the system are

- Overall routing
  1. Autonomously Avoid Obstacles
  2. Using optimized trajectories with respect to time and energy.
- Localising themselves
- Communicate with each other
  1. Grid Formation
  2. Systematic operation
  3. Location Identification
- Identifying the Mode at which the AAGV should transverse

Sensors Used:

- High Speed Depth Camera
- Global Positioning System
- Guides for the Grid Formation
- Guides for the Battery Replacement
- Infrared Sensors for Collision Avoidance
- Ultrasonic Sensors for Collision Avoidance

Control System Architecture
The Control System architecture is largely based on the Logistics plan which has the tasks like the transportation of a container from a certain ship or terminal to a certain depot along with the timing stamps. These operational orders are then categorised based on the similarities between the origin or destination, this information is then linked to the location of the AAGV's such that each vehicle is then assigned a task based on its location such that the current location of the vehicle is the closest possible to the origin location of the assigned task.

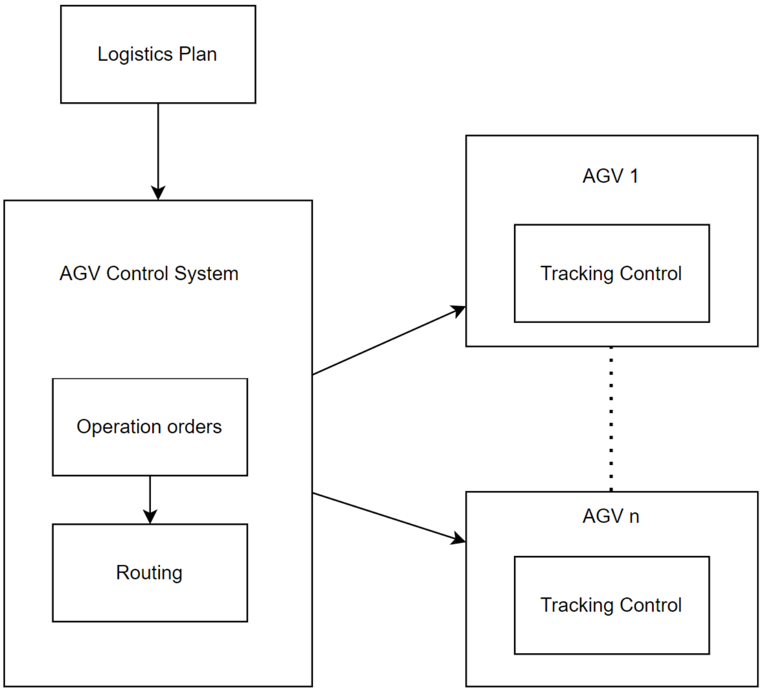


Figure 17: Control system architecture

4 Calculations

4.1 Floatation and buoyancy Calculations

Specifications	Value
Dimensions (L*W*H)	16m*3m*1.8m
Payload Tonnage	75 tonnes
Density of Sea-Water	1026 kg/m^3
Percentage afloat	25%($75\% underwater$)
Length of Pod	7.2m

$$VolumeofDesignedModel = Length * Width * Height = 72.96m^3$$

$$VolumeInsideWater = 0.75 * VolumeoftheDesignedModel = 0.75 * 75.96 = 54.72m^3$$

$$BuoyantForceMass = DensityofSeaWater * VolumeInsideWater = 1026 * 54.72 = 56142.72Kg$$

$$AdditionalMassRequired = PayloadTonnage - BuoyantForceMass = 75000 - 56142.72 = 18857.28Kg$$

$$RequiredVolumeofSidePod = \frac{AdditionalMasstoFloat}{DensityofSeaWater * PercentageBelowWater} = \frac{11896.18}{1026 * 0.75} = 24.5058894m^3$$

$$VolumeofEachPod = \frac{RequiredVolumeofSidePod}{2} = \frac{24.5058894}{2} = 12.2529m^3$$

$$RadiusoftheCylindricalPontoon = \sqrt{\frac{VolumeofEachPod}{\pi * LengthofPod}} = \sqrt{\frac{12.2529}{\pi * 7.2}} = \mathbf{0.736\ m}$$

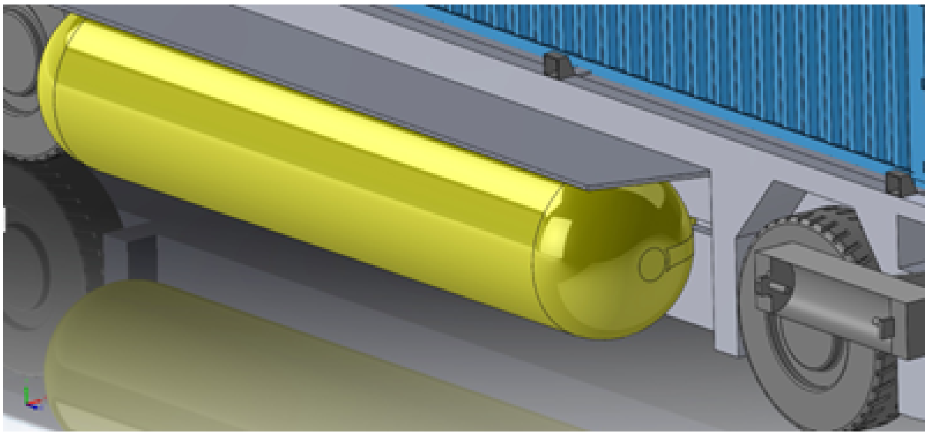


Figure 18: Air pocket

4.2 Jet pump Calculations

Specifications	Values
Power	100kW
Pressure (p)	135 psi = 9.3072 bar
Mechanical efficiency ($\eta(m)$)	83%
Flow rate (Q)	3000 gpm = 11.36 m^3/min
Volumetric efficiency ($\eta(v)$)	85%
Design Speed (v)	6-8 knots

Table 3: Jet pump specifications [2]

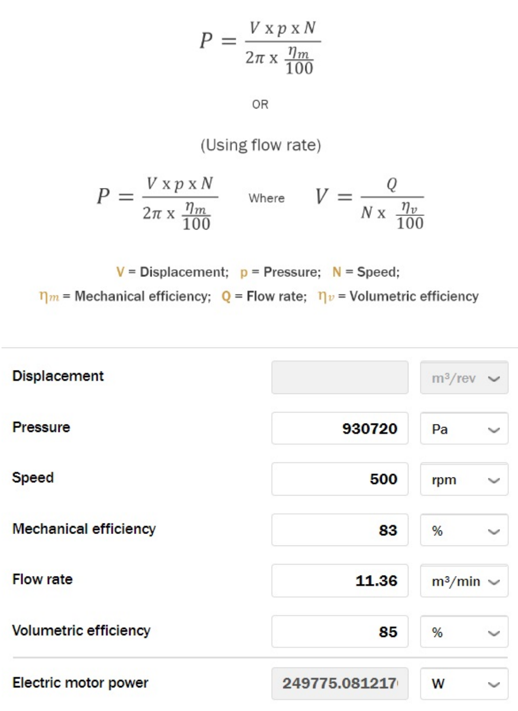


Figure 19: Motor power calculation

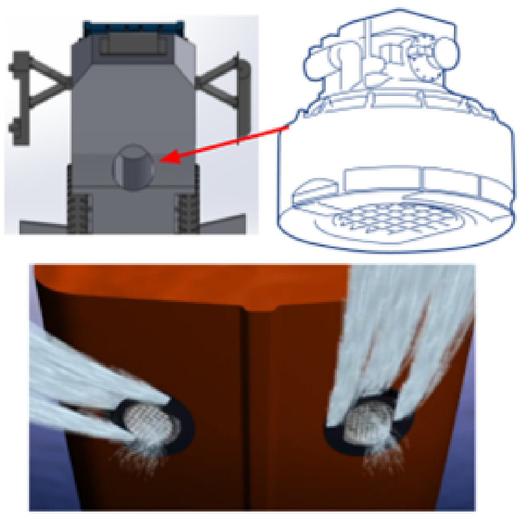


Figure 20: Jet pump

4.3 Powertrain Calculations

Specifications	Values
Mass	75tons
Wind Velocity	$20m/s$
Acceleration	$1m/s^2$
Slope	0-3 degrees
Speed	$12km/hr$

$$Forceduetogravity = Mass * Gravity = 75000 * 9.81 = 736kN$$

No Slope Condition at Max weight

$$CUMULATIVEFORCE = AAGVMass * f_{rolling} + F_{wind} + F_{roll} + F_{slope} = 102kN$$

$$PowerOutput = CumulativeForce * Speed = 331kW$$

With Slope Condition at Max weight

$$CUMULATIVEFORCE = AAGVMass * f_{rolling} + F_{wind} + F_{roll} + F_{slope} = 140.5kN$$

$$PowerOutput = CumulativeForce * Speed = 457kW$$

On Slope with one container Condition

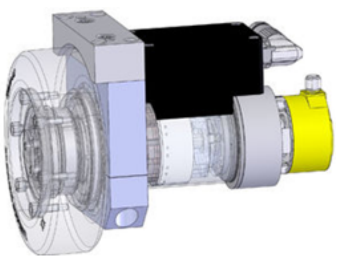
$$CUMULATIVEFORCE = AAGVMass * f_{rolling} + F_{wind} + F_{roll} + F_{slope} = 91.7kN$$

$$PowerOutput = CumulativeForce * Speed = 298kW$$

No Slope with one container Condition

$$CUMULATIVEFORCE = AAGVMass * f_{rolling} + F_{wind} + F_{roll} + F_{slope} = 67kN$$

$$PowerOutput = CumulativeForce * Speed = 218kW$$



4.4 Battery Calculations

Specifications	Values
Battery Voltage	720V
Motor Power Rating(without slope)	331000W
Motor Power Rating(with slope)	457000W
Motor Maximum Loading Capacity	750000Kg
Total Loading on Vehicles	540000Kg
Distance Covered in a single charge	40Km
Speed on Land	12Km/hr
Operational Hours per day	24 hours
Working days in a year	315 days
Operating Hours in a year	7500 hours
Travel in a year	100000Km

An industrial source (PSPowers Ltd.) was utilised to calculate the battery Capacity Required To Cover Distance In Single Charge (Ah) : **827.437Ah (595.8kWh)** [3]

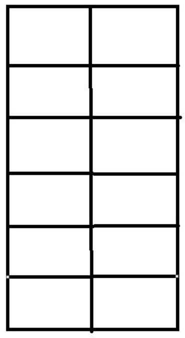
4.4.1 Battery Charging

AAGV being fully electric, brought in the need to consider the ways to rejuvenate the battery. Two methods in consideration were the direct charging of the batteries and the other option was the battery swapping. Direct charging meant that the AAGV would be alerted when the battery is low and would be directed to the charging station to charge the battery. This process would take over 60 mins to charge the battery.
Battery swapping takes about 6 - 7 minutes and this would also be initiated by the AAGV being alerted. This process can be done by swapping the batteries on the side of the AAGV or the top. Due to its interaction with water, this design has to have its sides sealed and house the pods for the flotation. The battery swapping process is done on the top using an overhead crane to lift and replace the batteries. Battery swapping is used instead of charging, because its time-efficient and also reduces downtime of the AAGVs which increases the working efficiency.

4.4.2 Battery Configurations and placement

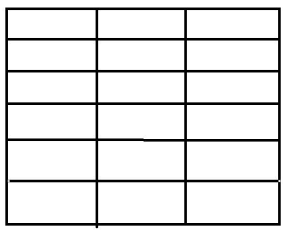
The batteries of the AGV are split into three different modules so we can allocate space for the stability systems such as pontoons to be stored. Furthermore retrieving the battery becomes easier with the use of lighter cranes. An added advantage is that the system would not need all three batteries to be replaced at one go if it is not needed. A disadvantage here is that the separate modules would be inefficient therefore a sum of more than 600 kWh would be needed to achieve the desired figure. Therefore an 8 percent buffer has been given such that an effective output of 600kWh can be obtained. To give a background , every battery pack is divided into sub modules and here the Tesla Model S's 6.3kWh module(for the 100kWh pack) will be taken as the building block reference. The three blocks are as follows:

- **Block 1 and Block 3**
  Block 1 is the first block placed just after the front wheels . This battery pack would be of two layers. Each layer would comprise of a 6x2 setup of 6.3kWh modules which would sum up to 24 such blocks for two layers. Block 3 is a similarly built setup placed near the rear wheels of the AGV The total Capacity of each block would be 6.3x2x6x2 = 151.2kWh For both blocks together this is: 302.4 kWh



x

- **Block 2**
  This would be the heaviest block of all housing for battery pack. This will be in a 6x3 configuration with three layers stacked upon each other. The total Capacity would be 6.3x3x3x6 = 340.2 kWh.



Cumulatively the whole battery pack will have **642.6kWh** but with the efficiency loss in splitting, effective output will be approximately 600kWh.

4.5 Time Advantages of AAGVs over a sample distance in Port of Rotterdam

The container transfer in the port of Rotterdam through trucks range from 10km to 50 km end to end. This can be reduced drastically when the amphibious AGVs run on water. An example of commute from the Hutchinson ports Euromax terminal to the ECT delta can be considered. The travel takes a normal container carrying truck through the Maasvlakteweg , past Amaliahaven and Alexiahaven and finally through APM terminals to the access points in the ECT delta. At the farthest point, this could easily take 25km to Gebouw 34. When we use the same case scenario through an amphibious AGV the distance from drop off points at Euromax to Gebouw 34 can be recorded as 4km when taken on the sea. Taking in account the overall savings in travel, that is almost by 20 percent which will be shown. Thereby AAGVs can ensure a reduction of the carbon emissions currently experienced by the ports due to trucks while also saving on valuable time. When compunded with the hive minded system, the efficiency is much more.

Land transport through trucks.
Truck Distance = 22 km (22000 meters)
Speed of truck = 50 km/h (13,89 m/s)
Driving time = 1583 seconds

Driving time + traffic waits = 1583*1,2 = 1900 seconds
Transfer time from regular AGV to truck = travel time gantry
crane to truck side = 260 m / 2,25 m/s = 116 seconds
Transfer time truck to AGV at ECT Delta = 60 seconds

Total + 1900 + 116 + 60 = **2076 seconds**

Water Transport Through AAAGVs
Amphibious AGV Distance from Mid point at Euromax Terminal to Ramp= 1.7km
Speed of the AGV= 12Km/hr
Time in Euromax to ramp (driving time + buffer) = 550 s
Time on ramp (1,67 m/s for 120 meters + buffer) = 90 s
Time over water (3 km + jackup time) = 1000 s

Total = 1000 + 550 + 90 = **1640 seconds/AGV**
Comparing the truck and AGV metrics we have a 21 percent time save.

4.6 Cost estimation

The cost estimation of the AAGV can be built up as follows.

- 80.000 EUR for the 8000kgs of the AAGV body at the average rate of 10EUR per kg.
- 140.000 EUR for the 2 Schottel SPJ B pumps.
- 80.000 EUR for the 2 motors and associated hardware connected to the wheels.
- 30.000 EUR for the 2 pontoons.
- 60.000 EUR for the battery pack.
- 50.000 EUR for the gearbox, transmission and the wheels.
- 60.000 EUR per AAGV for the locking system.
- 50.000 EUR per AAGV for the navigation and motion control equipment.

This comes down to a total cost of around **550.000 EUR**.

5 Conclusion

The current AGVs are powered by hybrid power modules consisting of diesel engines as well as electric battery powered motors. In todays age of high pollution and versatility, the requirement for a new type of AGV was felt. For this reason, it was felt that designing a completely new AGV which would be wholly electric and amphibious was the need of the generation. Such an AAGV would save on fossil fuel usage by using electricity that can be generated from renewable sources as well as be capable of complementing or even superseding barges. This would result in massive reductions in pollution and even savings since the usage of barges for inter-terminal transportation would reduce up to a large extent.

Since using individual Amphibious AGVs on the water when multiple containers have to be transported is an inefficient prospect, it was concluded that multiple AAGVs carrying containers could be linked together to form a platoon of AAGVs controlled by a centralised system to maximise efficiency in transportation. This would be achieved by only a few AAGVs utilising their propulsion system to travel on the water when they are connected together, thereby saving power for the other AAGVs and saving a lot of energy overall and resulting in greater availability resulting in huge savings.

A possibility also arises that the AAGV platoon could eventually be used to travel inland waterways directly to factories so as to pick up the container from the delivery floor directly, swim back to the port area and then climb onto land to position themselves under the cranes. This could result in major savings since extra hardware needed for the transportation can be eliminated, and the time spent in shifting goods between the different modes of transport would be brought down to negligible. Since barges run on fossil fuels and human operators; replacing them with the amphibious AGVs will result in huge savings in operating costs.

By combining the capabilities of the AGV and the barge, it is believed that a completely new generation of integrated autonomous operations can be carried out in a much more efficient way by removing the human operator from most of the locations on a micro-managerial level, and putting them in a position of monitoring daily operations and overall management of the secondary tasks like emergency response and maintenance.

The replacement of the hybrid drive AGV with the completely electric AAGV will lead to a significant amount of air pollution removal from the port area as well as significant savings in the logistics since supply and storage of fuel facilities for the AGVs will not be needed any longer. The removal of storage facilities for the fuel of the AGVs will free up space on the port and also eliminate a source of fire that would have been present in the port area as a safety risk. Elimination of the diesel motors will also result in significant reduction of noise pollution since the electric motors operate in near silence.

6 Appendix

6.1 Appendix A: Scoring Concepts

	Comp lexity	**Reli ability**	**St ability**	**Maneuver ability**	**Effici ency**	**Safety**	**Price**	**Avail ability**	**Total**
Complexity	-	0	0	1	1	1	1	1	5
Reliability	1	-	1	1	1	1	1	1	7
Stability	1	0	-	1	1	1	1	1	6
Maneuver ability	0	0	0	-	1	1	1	1	4
Efficiency	0	0	0	0	-	0	1	1	2
Safety	0	0	0	0	1	-	1	1	3
Price	0	0	0	0	0	0	-	1	1
Availability of components	0	0	0	0	0	0	0	-	0

Table 4: criteria weight trade-off table

The weights are concluded below.

	Weight
Complexity	5
Reliability	7
Stability	6
Maneuverability	4
Efficiency	2
Safety	3
Price	1
Availability of components	0

Table 5: Weights

6.2 Appendix B: Dimensions of the design

Dimensions of the Land mode:

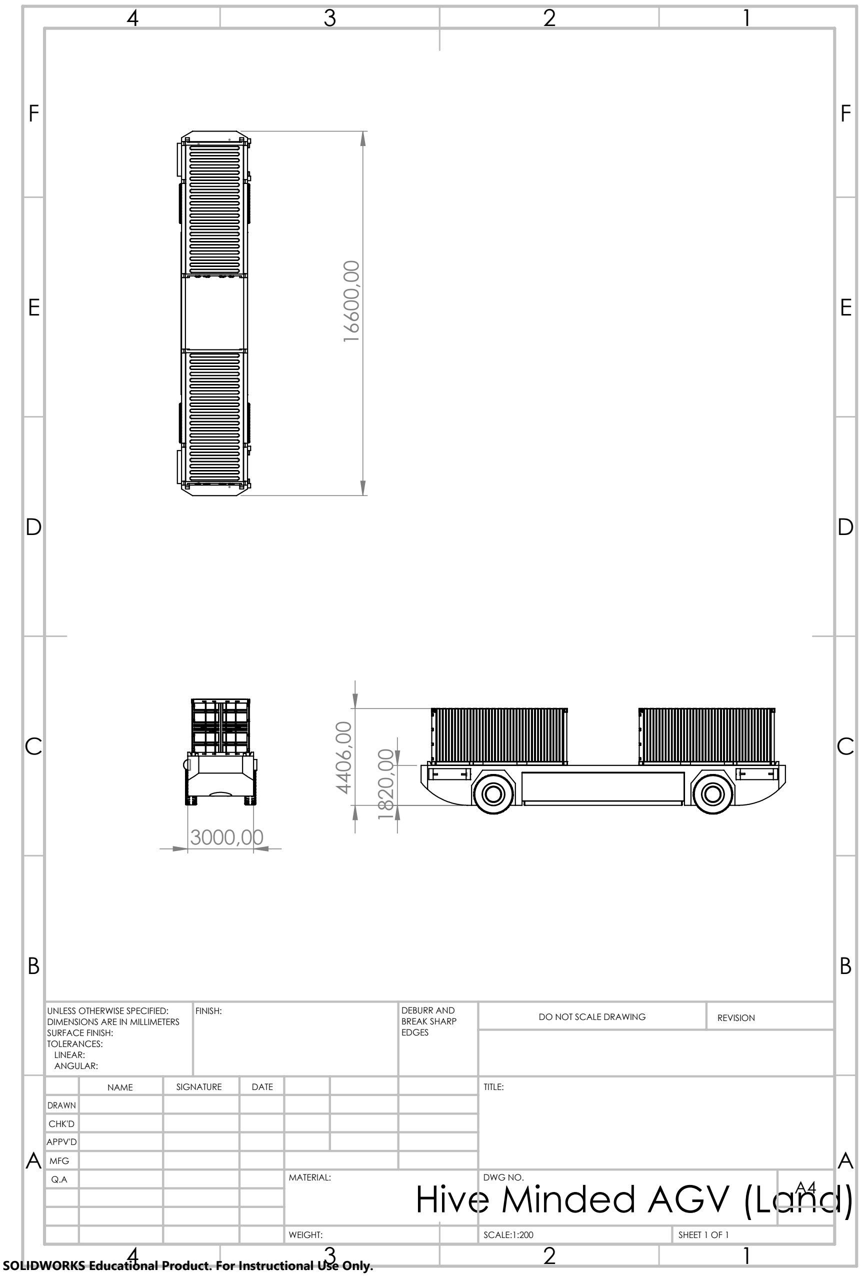


Figure 21: Drawing Land mode

Dimensions of the Water mode:

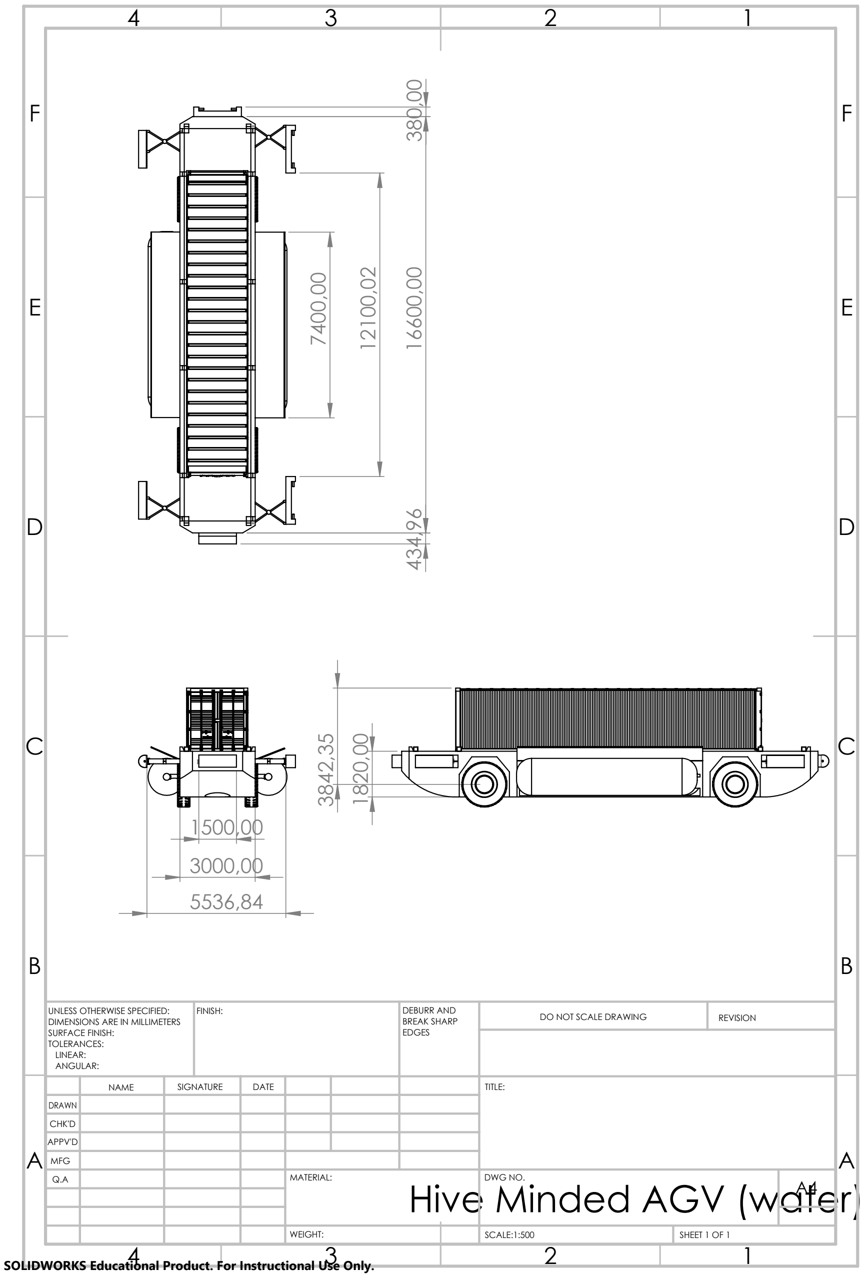


Figure 22: Drawing Water mode

Dimensions of the Grid formation:

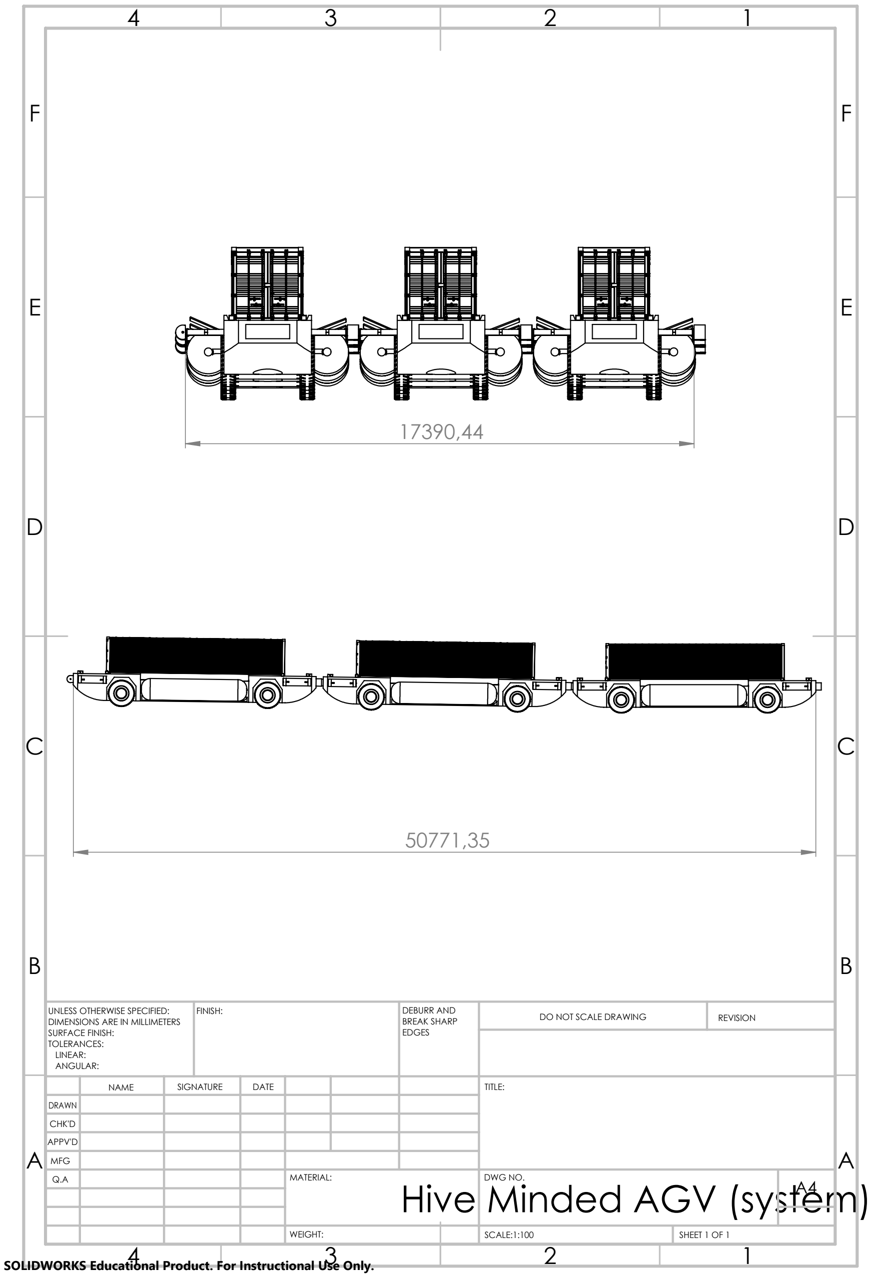


Figure 23: Drawing Grid formation

Dimensions of the Locking mechanism:

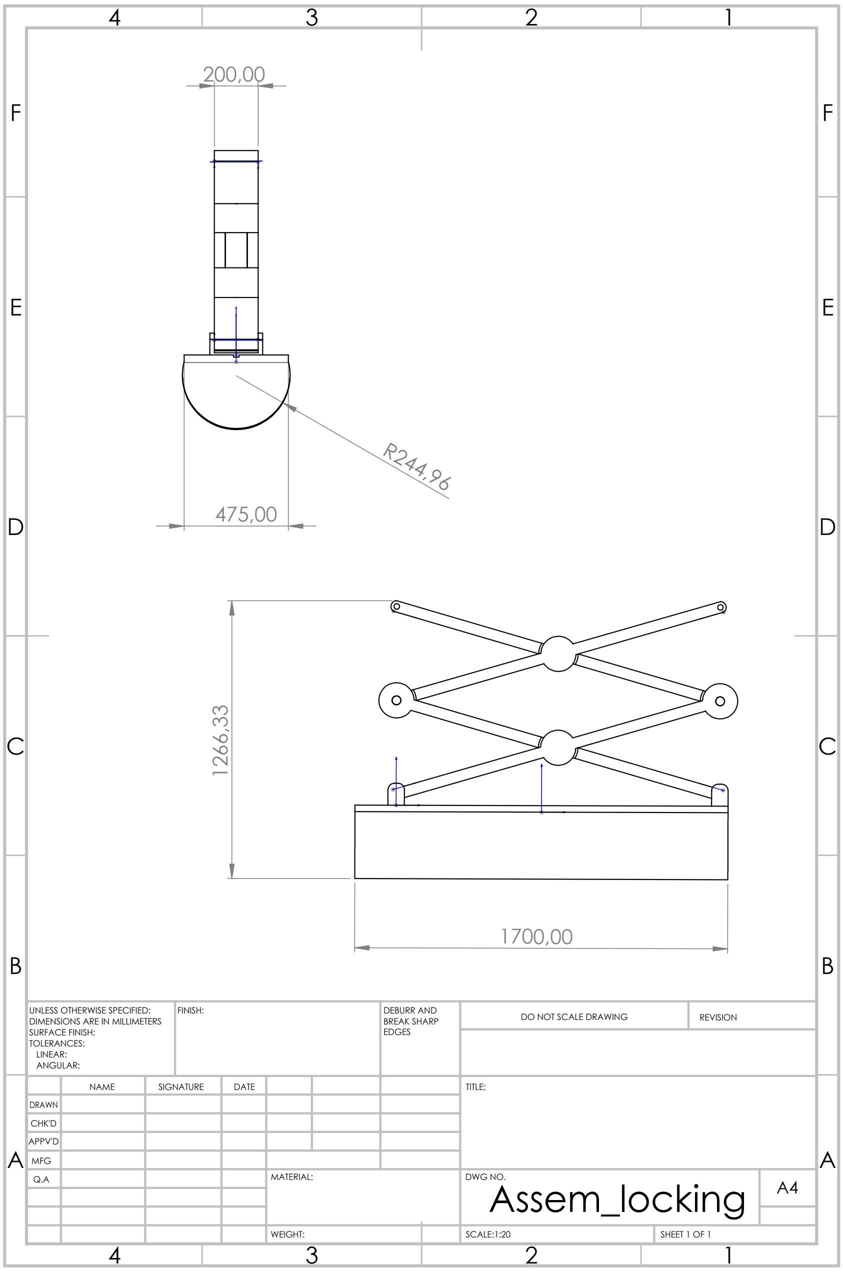


Figure 24: Drawing Locking mechanism

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B

Research Paper

Adaptability of Container Terminals for Amphibious AGVs

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***Abstract*—As global trade intensifies, container terminals grapple with congestion and operational bottlenecks, particularly during transshipment and inter-terminal container transportation. This paper investigates the potential of Amphibious Automated Guided Vehicles (AAGVs) as a solution to these challenges, fostering a shift towards autonomous operations within container terminals. Driven by the need to optimize space utilization and reduce dependence on conventional port equipment, the study leverages agent-based modeling (ABM) to assess the efficacy of Amphibious AGVs. The formulated ABM is then applied to a case study encompassing a generalised layout of container terminals found in international ports. Through a comprehensive review of existing literature, the study constructs a generalized simulation model that incorporates critical factors such as transportation time and throughput. Further requirements needed by the AAGVs, such as ramps, and Power consumption figures have also been looked into. This research offers valuable insights that can influence the evolution of container terminal operations, paving the way for increased autonomous, efficient, and sustainable transshipment practices.**

***Index Terms*—Container Transhipment, Amphibious AGV, Inter Terminal Transportation, Agent Based Modelling, Ramps, Power Consumption, Sustainability**

I. Introduction

Automation is transforming port operations worldwide. Container terminals are becoming increasingly digitized and automated, with over 60 already in various stages of automation and an additional 100 planned for implementation by 2030 [2]. While Asia has the highest number of automated terminals, Europe is not far behind.

The impact of automation on port efficiency is not entirely clear. Studies have shown that automation has a limited effect on productivity, with factors like the size and specialization of a container terminal playing a more significant role [2] [1]. Additionally, automation introduces challenges such as cybersecurity threats and the need for integration with existing port infrastructure [3].

The Port of Rotterdam, the largest port in Europe, is a prime example of a port that is both highly automated and a major hub for transshipment, which is the process of transferring cargo from one ship to another within the same port [22]. While the port utilizes automated container handling equipment like straddle carriers, automated stacking cranes, and automated guided vehicles (AGVs) for efficient movement within the terminal yard, barges are still the primary mode of transporting containers between terminals, which is a slow and inefficient method [24] [6].

This inefficiency calls for further automation in water-based container transportation systems. Barges, currently operated by human personnel, cannot provide the benefits of automation to improve efficiency, safety, and reduce operational costs [8] [25].

II. Literature Review

This chapter examines the challenges within container terminals and the potential of Amphibious Automated Guided Vehicles (AAGVs) in addressing them. These challenges include congestion [6] [7], delays experienced by barges [8], inefficient equipment [20], and the environmental impact of current operations [23]. AAGVs, with their ability to navigate both land and water, could eliminate the need for barges, improving efficiency and reducing reliance on fossil fuels [45].

A. Congestion in Container Terminals

Larger container ships strain landside infrastructure, causing congestion at handling nodes [7]. This congestion delays container movement and disrupts port operations. Efficient landside container handling is vital for overall port function [6]. Barge congestion on the seaside of terminals adds to congestion issues [8]. Inefficient operations [20], inadequate infrastructure [24], and environmental regulations contribute to barge congestion. Strategies to mitigate this include improved operations, infrastructure expansion, and promoting alternative transport methods.

The flow of containers through the terminal significantly impacts performance. Quay cranes, yard cranes, and automated guided vehicles play a key role [20]. Unbalanced task assignment, container batch arrival patterns, and berth/yard layouts can all influence congestion [7]. Optimizing these factors can lead to higher productivity and capacity. The growing focus on environmental sustainability presents a challenge. Implementing ecological measures, while necessary, can disrupt operations and lead to congestion. Careful planning and management are crucial to minimize this disruption [23].

B. Barges and their Disadvantages

Existing research suggests that barge handling efficiency suffers when terminal operators prioritize sea vessels [8]. This congestion can be mitigated by dedicating specific berthing facilities for barges [8] [27]. Studies have shown that the main constraint on barge operations is not the barge capacity itself, but rather the lack of sufficient handling equipment [6], leading to underutilization of barges [28]. Barge transportation offers significant advantages over trucking in terms of cost and energy efficiency [6] [8].

One successful example of improving barge operations is the APM Terminals Maasvlakte II terminal, which boasts dedicated barge berths and automated barge cranes [26]. This terminal also offers a fixed window system for barge handling, ensuring predictability for both barge operators and the terminal itself [26]. However, challenges arise when barges experience delays, highlighting the need for improved coordination between terminal operators and barge operators [26].

Research points to a paradox in the container barging sector. While various stakeholders attempt to improve coordination through institutional means, a lack of urgency and cooperation hinders the sector's potential [41]. Therefore, fostering a sense of urgency and collaboration among stakeholders appears to be crucial for enhancing the performance of container barging in Rotterdam [41] [18]. It is important to acknowledge the environmental impact of barges, as they emit harmful pollutants and pose a risk of oil spills [29].

C. AGV Power Options & Battery Swapping

Automated Guided Vehicles (AGVs) are used in container terminals to transport shipping containers between the quayside and the yard [20]. There are two main types of AGVs: diesel-electric hybrid and purely electric [15] [14] [16]. Diesel-electric hybrid AGVs can operate for longer periods of time without needing to be recharged, but they produce emissions [35]. Purely electric AGVs are more environmentally friendly, but they have a shorter operating range and need to be recharged more frequently [17].

Battery swapping is a method of recharging an AGV by exchanging a depleted battery for a fully charged one. This process is done automatically using a battery swapping station [37]. Battery swapping stations are typically located in strategic locations throughout a port. When an AGV needs to swap its battery, it simply drives into the station and the process is initiated automatically [36]. The AGV's depleted battery is removed and replaced with a fully charged one in a matter of minutes. The AGV can then continue operating without any interruption [36] [37] [38].

Fig. 1. Battery swapping stations are used to swap depleted batteries from AGVs [16]

Battery swapping has a number of benefits for port AGVs. First, it allows AGVs to operate for longer periods of time without any downtime needed to charge. This can lead to increased productivity and efficiency in the port [38]. Second, battery swapping can reduce the overall cost of operating AGVs. This is because battery swapping stations are cheaper to build and maintain than traditional charging stations [38] [39]. Third, battery swapping can help to reduce the environmental impact of port operations. This is because battery swapping stations can use renewable energy sources, such as solar and wind power, to charge their batteries [34].

D. Amphibious AGV

Amphibious Automated Guided Vehicles (AAGVs) are a novel concept in container transportation. They are designed to operate on both land and water, eliminating the need for intermediate barge transshipment [45]. This can significantly reduce shipping times and costs as containers can be moved directly between terminals. Additionally, AAGVs alleviate congestion at ports by reducing reliance on cranes and trucks. Their amphibious nature makes them particularly suitable for island ports with limited road infrastructure [45].

Existing research [45] provides the foundation for the AAGV model used in this study. This research refines the data from previous studies to create a more precise model.

The AAGV operates like a normal AGV on land. When entering water, inflatable sidepods stored onboard deploy to provide buoyancy. Water pumpjets propel the AAGV while in

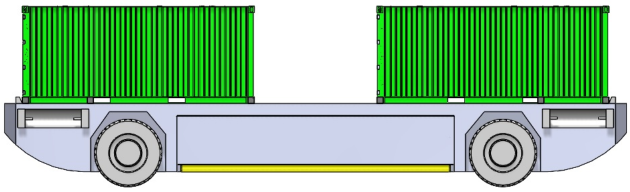

Fig. 2. Amphibious AGVs in land configuration and carrying 2 twenty foot containers [45]

water. To exit the water, the AAGV utilizes a combination of wheel and pumpjet power to ascend a ramp. The sidepods then retract, and the AAGV resumes its land-based configuration [45].

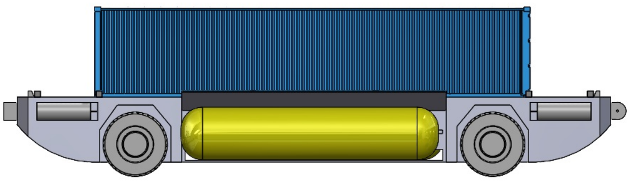

Fig. 3. Amphibious AGVs in waterborne configuration and carrying 1 forty foot container [45]

E. Agent Based Modelling

ABM (Agent Based Modeling) creates a virtual environment where individual agents, representing elements like containers, equipment, and transportation modes, interact and make decisions based on predefined rules [4]. This approach captures the system's complexity and dynamics by considering various interacting factors [30] [32]. ABM facilitates investigation into how information about further transportation modes impacts container outflow and overall equipment effectiveness within the terminal [32]. This method provides a theoretical framework to understand the effects of different scenarios and can be used to optimize terminal operations and inform decision-making [33].

Prior research has applied ABM to simulate operations in an automatic container terminal (ACT) with quayside container cranes (QCs), automatic guided vehicles (AGVs) and automatic rail mounted gantry cranes (ARMGs) [31] [33]. ABM is preferred because conventional modeling methods struggle to accurately represent the intricate interactions between QC/AGV/ARMG operations and port traffic flow [31]. ABM allows for modeling individual agents, such as container ships, AGVs, and ARMGs, and their interactions with each other and the environment [31] [30]. The resulting simulation model provides a realistic representation of discharging and loading operations in the ACT, allowing for decision support in designing and managing ACTs with QCs, AGVs, and ARMGs [31] [32].

Research has also explored multi-agent systems (MAS) to model container terminal operations in a distributed and changing seaport environment. The MAS-based dynamical model is commonly used to depict the interactions and processes among various agents, including ships, port captains, terminal managers, stevedores, quay cranes, straddle carriers, customs, and trucks [31] [4]. These agents interact in processes like ship arrival sequencing, determining ship service time, and container picking [4]. The simulation results are used to evaluate the effectiveness of the proposed methods in increasing terminal operations efficiency and to demonstrate that consensus can be achieved by all the agents in the model [32] [4].

III. Methodology

A case study methodology is used to explore the use of Amphibious Automated Guided Vehicles (AAGVs) in container terminals. This method allows for an in-depth examination of the subject matter in a real-world context. The research will also develop a general guide for the modifications required at container terminals to implement AAGVs [30]. Agent-based modeling (ABM) will be utilized to simulate container terminal operations with both traditional land-based AGVs and barges and AAGVs. The ABM will allow for a detailed modeling of the movement, interactions, and decision-making processes of various entities within the terminal. This will enable the identification of bottlenecks and inefficiencies in the current system and the potential improvements achievable with AAGVs [32].

The research will compare the efficiency, cost-effectiveness, and environmental impact of traditional AGVs and barges with AAGVs. This comparison addresses a gap in the existing literature, which lacks comprehensive evaluations of AAGVs. By analyzing the performance of these two approaches, the research aims to identify the potential benefits and challenges of implementing AAGVs in container terminals. The findings of this research can inform decision-making processes for improving container terminal operations.

All data used in the Scenarios can be found in Section IV.

A. As-Is Scenarios

In these scenarios, two quay cranes unload containers from a barge. Automated guided vehicles (AGVs) then transport the containers from the quay cranes to the yard for further processing. Reach stackers or Rubber Tired Gantry Cranes then unload the containers from the AGVs and stack them within the yard block. The maximum stacking height for containers in the yard is typically three containers.

This configuration reflects a common practice in container terminal operations, where quay cranes handle the ship-to-shore movement of containers, AGVs provide efficient yard transportation, and reach stackers enable flexible container stacking within the yard [20].

1) As-Is 1: This scenario simulates a container terminal layout that is commonly found around the world. The layout consists of a quay, a container yard block, an unloading area, an AGV park, a battery recharging facility, and reach stacker parking. The entire route network is clockwise uni-directional,

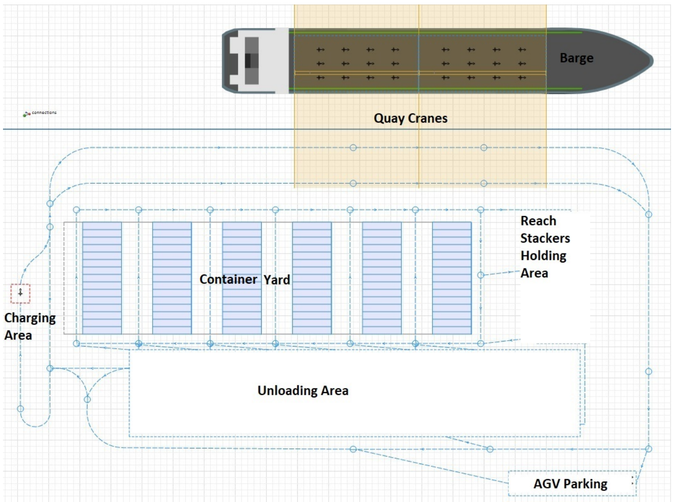

Fig. 4. The Layout of As-is 1

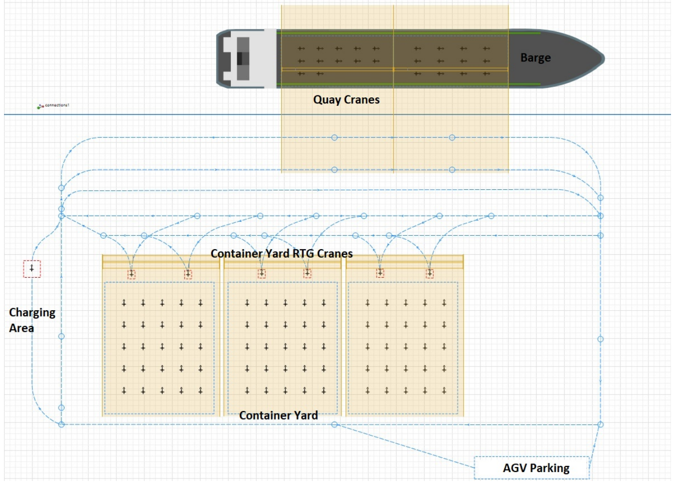

Fig. 6. The Layout of As-is 2

except for a single route that allows unloaded AGVs to return to the park. Quay cranes unload containers from barges onto AGVs which are then transported to the unloading area. Reach stackers then take the containers from the unloading area and store them in the container yard block. The simulation will model the interaction between AGVs, barges, reach stackers, and quay cranes.

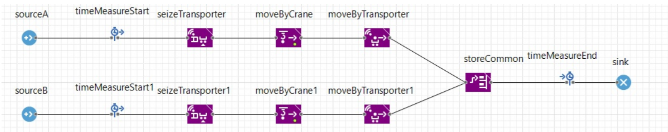

Fig. 5. The Material Handling Library's Flowchart for As-Is 1

Fig. 7. Material Handling Library's Flowchart for As-is 2

The base scenario for the simulation involves two barges that are unloaded by two quay cranes. Each barge is split into two zones, with each zone being serviced by a dedicated quay crane. When a container arrives in a zone, a quay crane unloads it onto a waiting AGV. The AGV then transports the container to the unloading area, where it is unloaded by a reach stacker and stored in the container yard block. This process is repeated for all the containers on the barges.

2) As-Is 2: This scenario simulates a container terminal layout involving Automated Guided Vehicles (AGVs), barges, and Rubber Tired Gantry (RTG) cranes (instead of Reach Stackers). The layout replicates a general configuration found in modern container terminals featuring three yard blocks, each with dedicated RTGs for unloading AGVs. The unloading zones are accessible by inbound and outbound lanes and can be assigned containers from two separate sources on the barge via quay cranes. This design mirrors real-world operations observed in major ports like Rotterdam, Dubai, and Hamburg.

The simulation process involves two sources representing different barge regions unloaded by separate quay cranes. Containers are divided between these sources and then further allocated to specific unloading nodes within the yard blocks. AGVs are called upon to transport containers from the barge to designated unloading zones. RTG cranes then take over, moving the containers from the AGVs and placing them within the respective yard block stacks. This cycle repeats until all containers are processed.

B. *To-Be Scenarios*

In this simulation, the Quay Cranes are replaced by a ramp. The ramp is 100-meters long and connects the terminal to the water with an incline of 3.5 degrees. The ramp is designed to accommodate two lanes of traffic, one for AAGVs traveling uphill and the other for AAGVs traveling downhill. Each lane can hold up to 3 AAGVs at a time.

The simulation focuses on the transportation of containers from the source terminal to the destination terminal. The loading of containers at the source terminal is not simulated, as the same has not been simulated in the As-Is Scenarios. The simulation considers the travel distance between the terminals, which is approximately 5 kilometers, and takes this into account when estimating battery consumption and the need for battery swapping.

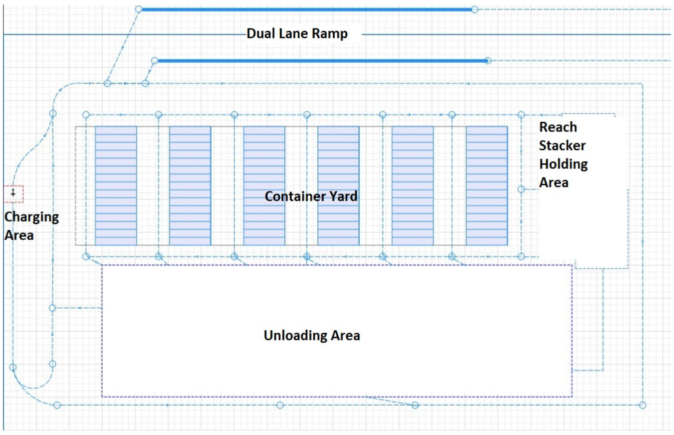

Fig. 8. The Layout of To-Be 1

1) To-Be 1: The research simulates the Automated Guided Vehicles (AGVs) transporting containers from a source terminal to a destination terminal. Reach Stackers unload the containers at the destination terminal. The layout consists of a source terminal located north of the destination terminal at a distance of approximately 5 kilometers. The AGVs are parked in the source terminal, north of the loading area. In the destination terminal, the Quay is north of the yard block, the unloading area is south of the yard block and there is an inclined ramp that extends along the quay from the North to Northwest. The Reach Stackers are parked in a node east of the yard block. The entire route network is clockwise unidirectional. There is just a single lane to the north and west of the yard block up to the unloading area. The return lane from the charging station joins before the ramp.

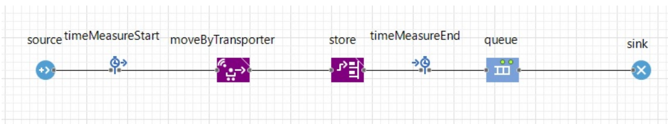

Fig. 9. The Material Handling Library's Flowchart for To-Be 1

The Material Handling Library's flowchart simulates the container presence in the source container terminal with AGVs parked at the source terminal. On arrival of a container in the Terminal, the moveByTransporter block sends in a request for the AGV to move the container from that terminal to the unloading zone of the Base Terminal. The unloading time of the AGV is a uniform distribution of between 5 to 7 minutes, after which the store block sends the Reach Stacker to store the container in the yard block. This process repeats for all the containers in the process.

2) To-Be 2: It has the same layout as As-Is 2 with three designated yard blocks, each containing two unloading nodes accessible from designated inbound and outbound lanes. The unloading process involves the AAGVs fetching containers from a designated source terminal and delivering them to the assigned unloading nodes, replacing Quay Cranes with Ramps.

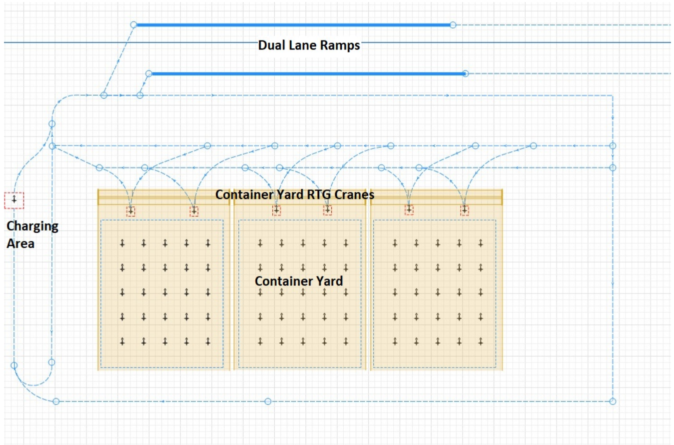

Fig. 10. The Layout of To-Be 2

Upon arrival at the node, the RTG cranes then unload the containers and place them within the designated yard block. This process is repeated for all containers.

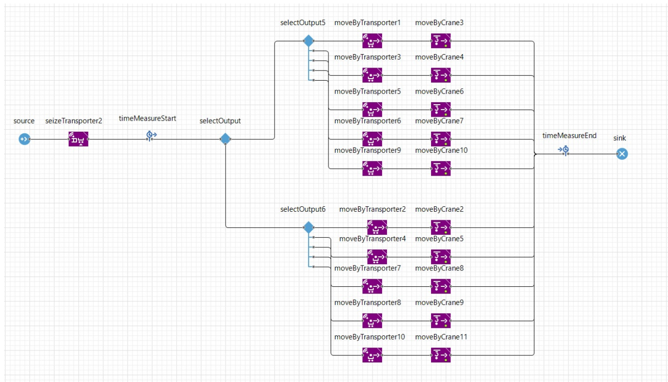

Fig. 11. The Material Handling Library's Flowchart for To-Be 2

Similar to As-Is 2, a common source for containers is maintained and a system of random probabilities assign a flow direction for each container. Additionally, consistency with As-Is 2 is maintained by assigning containers to four common unloading nodes across all three yard blocks and the remaining two unloading nodes, one to each of the third yard block.

IV. Data Used

This chapter presents an overview of input data sources used to evaluate the efficiency and environmental impact of amphibious automated guided vehicles (AAGVs) in container terminals. Throughput calculations and battery consumption values are analyzed to provide for AAGVs to enable a more accurate comparison via simulation with traditional land-based AGVs and barges.

Throughput, a key metric representing the volume of containers handled per unit time, is crucial for assessing container transport efficiency within and between terminals. By analyzing battery consumption, the research investigates the potential of AAGVs to improve efficiency and environmental sustainability in container terminal operations. The data aims to provide a comprehensive evaluation of AAGV performance and potential benefits, ultimately contributing to a deeper understanding of their feasibility and impact on container terminals.

TABLE I
SYMBOLS USED WITHIN CALCULATIONS

Symbol	Unit	Definition
g	[m/s^2]	Acceleration due to gravity
L	[m]	Length of ramp
h	[m]	Height of ramp
$mass$	[kg]	Weight of AAGV
$length$	[m]	Length of AAGV
$h_{submerged}$	[m]	Height of AAGV which is submerged
h_{loaded}	[m]	Height of AAGV when loaded
$Dist_{water}$	[km]	Distance travelled by AAGV on water in single trip
$Dist_{land,aagv}$	[km]	Distance travelled by AAGV on land within a single terminal in a single trip
$ramp$	[km]	Distance travelled by AAGV on single ramp in single trip
$width$	[m]	Width of AAGV on land
$width_{submerged}$	[m]	Width of AAGV submerged
v_{water}	[m/s]	Maximum permitted speed on water
v_land	[m/s]	Maximum permitted speed on land
$A_{underwater}$	[m^2]	Frontal Cross Sectional Area of AAGV submerged
$A_{overwater}$	[m^2]	Frontal Cross Sectional Area of AAGV exposed over water
A_{land}	[m^2]	Frontal Cross Sectional Area of AAGV when on land
P_{water}	[kW]	Power needed by AAGV on water
P_{land}	[kW]	Power needed by AAGV on land
$P_{incline}$	[kW]	Power needed by AAGV on incline
E_{aagv}	[kWh]	Total Energy consumed by an AAGV in a single trip
$C_{battery,aagv}$	[kWh]	Capacity of AAGV Battery
C_d	[no unit]	Drag coefficient
f_r	[no unit]	Coefficient of Rolling friction
θ	[°]	Angle of inclination of ramp
ρ	[kg/m^3]	Density of Air
ρ_{water}	[kg/m^3]	Density of Water

A. Throughput Calculations

For this research, the Throughput of the Port of Rotterdam is looked to as an example to use as a foundation. According to the Port of Rotterdam Facts and Figures [19], the total annual container throughput for the year 2022 was 14455360 TEU.

$$\text{Containers} = \frac{14455360TEU}{2} = 7227680 \text{ Containers}$$

Since the number of containers via barges are 35% of the total:

$$\begin{aligned}\text{Containers by barges} &= 7227680 \cdot 0.35 \\ &= 2529688 \text{ Containers}\end{aligned}$$

Now an hourly rate of containers by barges can be derived as:

$$\begin{aligned}\text{Containers by barges} &= 2529688 \cdot \frac{1}{365} \cdot \frac{1}{24} \\ &= 290 \text{ Containers per hour}\end{aligned}$$

It can be assumed that 60% of the Barge traffic is for IWT and 40% is for ITT between the major Container Terminals in the MaasVlakte.

$$\text{Containers by barges in the MaasVlakte} = 290 \cdot 0.4$$
$$= 116 \text{ Containers per hour}$$

Since there are 5 Major Container Terminals in the MaasVlakte;

$$\text{Containers per terminal per hour} = \frac{116}{5}$$
$$= 23 \text{ Containers per hour per terminal}$$

B. Handling Equipment Data

The simulation models two types of cranes: Quay Cranes (QC) and Rubber Tired Gantry cranes (RTG). QC has a bridge speed of 1.1-1.7 m/s, trolley speed of 1-1.5 m/s, and hoist speed of 0.8-1.5 m/s. It has a length of 74 meters of which the outreach is 36 meters, and a height of 30 meters. Each RTG has a bridge speed of 1-2 m/s, trolley speed of 1-1.5 m/s, and hoist speed of 0.5-1 m/s. It has a runway length of 60 meters, height of 20 meters, and bridge width of 2 meters.

Automated Guided Vehicles (AGV) are used for transporting containers. They have a length of 16.6 meters, width of 3 meters, and height of 1.8 meters. Their speed is regulated to 11 kmph within the terminal and 13 kmph on water. The simulation only considers 40-foot containers [9].

Reach Stackers are used to pick up and place containers. The simulation focuses on their travel times, which are similar to Automated Straddle Carriers (ASC). ASC leg placement is not crucial for this simulation, so Reach Stackers are used to simplify the model. They an elevation speed ranging from 0.40 m/s to 0.24 m/s, with the total length of the truck itself being 12 meters and width 4.2 meters. The maximum achievable height of the boom is 18 meters [5].

C. Ramp Calculations

The research investigates the feasibility of using ramps to enable Autonomous Amphibious Ground Vehicles (AAGVs) to transition between land and water at container terminals. The methodology involves calculating the ideal ramp length based on the specified height difference between the terminal floor and water level, and a chosen ramp inclination. The impact of space constraints on ramp inclination is then explored by considering a maximum feasible ramp length and calculating the corresponding achievable inclination.

For the AAGV to transfer from land to water, it will need a location to climb onto the terminal floor from the water. For this reason, there needs to be a ramp placed at every terminal to enable the AAGV to descend into water and climb back on.

The AAGV at the maximum would be around 100 tons with its payload and itself. The distance between the terminal floor and water is 6.1 meters [44].

Assuming a ramp inclination of 5°, ideal ramp length can be found as:

$$L = h/sin(\theta) \tag{1}$$
$$L = 6.1/sin(5) = \textbf{65.18 meters}$$

where ‘h‘ is the height between land and water (6.1 meters).

If the space constraint requires the terminal to use the shortest possible ramp length, then a maximum inclination of 5°, allows the ramp length to be about 65 meters.

Considering the maximum length available to be 100 meters,

$$\theta = \sin^{-1}(6.1/100) = 3.49 \approx \textbf{3.5}\ ^{\circ} \tag{2}$$

Therefore, with a ramp length of 100 meters, the inclination possible is 3.5°. With this inclination, higher speeds on the ramp are attainable.

Finally, the chosen simulation parameters are a ramp length of 100 meters and an inclination of 3.5 degrees.

D. Battery Calculations

A simulation model is built in AnyLogic to simulate the battery swapping process for Amphibious Automated Guided Vehicles (AAGVs). The BatterySwap block sends the vehicle to the battery swapping station where a fluid fill up process is utilized by the Fluids Library to simulate the battery swap [40]. The hold block prevents vehicles from being recharged if the stacking of containers is complete.

In the real world, AGVs utilize a side-swap method for battery replacement [37]. This method however poses challenges for AAGVs due to potential water ingress due to battery compartment door failure [11] [12]. An alternative top-swap method is recommended for AAGVs to maintain the watertight integrity of the hull. However, this method would require the AAGV to be empty of containers during battery swapping.

The battery swapping trigger level needs to be adjusted for AAGVs compared to AGVs. While AGVs typically swap batteries at 23% charge [10], AAGVs operating on water may require a higher trigger level to ensure they reach the swapping station before battery depletion.

The research paper suggests further investigation into the battery capacity of electric AGVs. While publicly available information does not specify the battery capacity of AGVs, specifications for Kalmar’s electric Reach Stackers are used as a reference point. The Reach Stackers utilize BoschRexroth Traction motors that consume 182kW during standard operation and 405kW at peak [43].

To determine the total energy required by Autonomous Amphibious Ground Vehicles (AAGVs) during operation, the resistance experienced by the AAGV while travelling on land and water needs to be investigated.

The AAGV’s dimensions are known: a width of 3 meters on land and 6 meters on water (when side-pods are deployed), a length of 16.6 meters, and a height above ground that can vary between 1.8 meters (unloaded) and 4.4 meters (loaded). The maximum total weight of the vehicle is set at 100 tons [45].

Speed limitations are also in place for both land and water travel. The maximum allowable speed is 10 kilometers per hour (2.78 meters per second) on land and 13 kilometers per hour (3.61 meters per second) on water [42]. The travel distance for an AAGV is estimated to be 3 kilometers within each terminal (source and destination) on land, and 5 kilometers on water. Additionally, a ramp with a length of 65.18 meters and an inclination of 5 degrees will be considered when calculating energy consumption for steeper inclines.

When the AAGV is in the water, the submerged height of the AAGV can be calculated as:

$$\begin{aligned} h_{submerged} &= \frac{mass}{width_{submerged} \cdot length \cdot \rho_{water}} \\ &= \frac{100000 \text{ kg}}{6\text{m} \cdot 16.6\text{m} \cdot 997 kg/m^3} \\ h_{submerged} &= 1.066 \approx 1.01 \text{ m} \end{aligned} \tag{3}$$

Frontal Area submerged when AAGV is in water is calculated as:

$$\begin{aligned} A_{underwater} &= h_{submerged} \cdot width_{submerged} \\ &= 1.0066\text{m} \cdot 6\text{m} \\ A_{underwater} &= 6.04\ m^2 \end{aligned} \tag{4}$$

Frontal Area above the water line, when AAGV is in water is calculated as:

$$\begin{aligned} A_{overwater} &= h_{loaded} \text{ - } h_{submerged} \cdot width \\ &= (4.40 - 1.0066) \text{ m} \cdot 3 \text{ m} \\ A_{overwater} &= 10.18\ m^2 \end{aligned} \tag{5}$$

When the AAGV is on land, the Frontal Area of the AAGV can be calculated as:

$$\begin{aligned} A_{land} &= h_{loaded} \cdot width \\ &= 4.40\text{m} \cdot 3\text{m} \\ A_{land} &= 13.20\ m^2 \end{aligned} \tag{6}$$

Power needed on Water by the AAGV is calculated as:

$$\begin{aligned} P_{water} &= (0.5 \cdot \rho_{water} \cdot C_d \cdot v_{water}^3) \cdot A_{underwater} \\ &\quad + (0.5 \cdot \rho \cdot C_d \cdot v_{water}^3) \cdot A_{overwater} \\ &= (0.5 \cdot 997 \cdot 0.75 \cdot 3.61^3) \cdot 6.04 \\ &\quad + (0.5 \cdot 1.29 \cdot 0.75 \cdot 3.61^3) \cdot 10.18 \\ P_{water} &= 106.61\ kW \end{aligned} \tag{7}$$

Power needed on Land by the AAGV is calculated as:

$$\begin{aligned} P_{land} &= ((f_r \cdot mass \cdot g) \\ &+ (0.5 \cdot \rho \cdot C_d \cdot v_{land}^2 \cdot A_{land})) \cdot v_{land} \\ &= ((0.02 \cdot 100000 \cdot 9.81) \\ &+ (0.5 \cdot 1.29 \cdot 0.75 \cdot 2.78^2 \cdot 13.2)) \cdot 2.78 \\ P_{land} &= 54.64\ kW \end{aligned} \quad (8)$$

Power needed on an incline by the AAGV is calculated as (angle of 5°or 0.0873 radians):

$$\begin{aligned} P_{incline} &= ((f_r \cdot mass \cdot g \cdot \cos\theta) \\ &+ (0.5 \cdot \rho \cdot C_d \cdot v_{land}^2 \cdot A_{land}) \\ &+ (mass \cdot g \cdot \sin\theta)) \cdot v_{land} \\ &= ((0.02 \cdot 100000 \cdot 9.81 \cdot \cos(0.0873)) \\ &+ (0.5 \cdot 1.29 \cdot 0.75 \cdot 2.78^2 \cdot 13.2) \\ &+ (100000 \cdot 9.81 \cdot \sin(0.0873))) \cdot 2.78 \\ P_{incline} &= 291.93\ kW \end{aligned} \quad (9)$$

Total Energy needed for a single trip of an AAGV, consisting of a total journey length of 6 kms on land (3kms within each terminal) and 5 kms on water, as well as an incline length of 65.18 meters, can be calculated as:

$$\begin{aligned} E_{aagv} &= P_{water} \cdot (\frac{Dist_{water}}{v_{water}\text{(km/h)}}) \\ &+ 2 \cdot P_{land} \cdot \frac{(Dist_{land,aagv} - ramp)}{v_{land}\text{(km/h)}} \\ &+ 2 \cdot P_{incline} \cdot (\frac{\text{ramp}}{v_{land}\text{(km/h)}}) \\ &= 106.61 \cdot (\frac{5}{13}) \\ &+ 2 \cdot 54.64 \cdot \frac{(3 - 0.06518)}{10} \\ &+ 2 \cdot 291.9 \cdot (\frac{0.06518}{10}) \\ E_{aagv} &= 76.88\ kWh \end{aligned} \quad (10)$$

This is the estimated battery capacity needed for 1 trip, which is approximately 60 minutes. The AAGV is expected to be able to run at least 8 hours before needing to replace its battery. Therefore, with an additional safety buffer of 10% added, the battery capacity for an AAGV can be found to be:

$$\begin{aligned} C_{battery,aagv} &= \frac{E_{aagv} \cdot \text{Number of trips}}{\text{90\% safety limit}} \\ &= \frac{76.88 \cdot 8}{0.9} \\ C_{battery,aagv} &= 683.37\ kWh \end{aligned} \quad (11)$$

V. Results

A. As-Is 1 Results

The Results for As-Is 1 in 60 minutes for different Container Throughput and varying number of AGVs and Reach Stackers can be seen in Table II

It must be noted that the simulation focused solely on container handling from barge to stack, excluding barge travel time. To account for realism, an additional 30 minutes was added to the average container processing time. Calculations revealed a 23-minute barge travel time for a 5-kilometer trip at the maximum allowable inland waterway speed of 13 kilometers per hour. Additional time for acceleration, deceleration, and docking on both sides justifies rounding the travel time to 30 minutes. The results demonstrate that barge travel time often constitutes a significant portion of the total container handling time, in some cases nearly double the time spent on land. Quay crane unloading contributes a large portion to the overall average time per container for storage.

The research examines the impact of AGV quantity on container delivery times. While all configurations exhibited a rise in delivery time with more AGVs, the rate of increase appears to be moderated by a higher number of reach stackers. This suggests that while simply adding more AGVs is not a sufficient solution to bottlenecks, it can have a less detrimental effect when complemented by an increased reach stacker presence.

TABLE II
THE RESULTS FOR AS-IS 1

Average Container Transport Time (mins, with Barge Travel of 30 minutes approximately)					
	Throughput				
AGVs | RSs	**10**	**15**	**20**	**25**	**30**
10					
10	47.76	52.03	58.11	55.85	63.65
15	48.52	52.51	56.81	64.14	68.63
20	47.41	51.73	56.5	61.51	65.28
15					
10	47.92	58.48	56.93	68.7	70.47
15	48.24	52.9	59.2	60.03	65.13
20	48.28	54.71	60.15	64.7	68.32
20					
10	53.21	50.73	56.23	62.97	70.41
15	49.25	55.59	62.5	64.13	65.77
20	47.39	51.18	55.27	63.12	68.81
25					
10	48.62	58.1	59.47	64	64.4
15	48.48	55.5	59.45	57.42	65.17
20	47.98	56.49	56.37	61.54	65.94
30					
10	47	55.91	52.96	61.56	67.09
15	47.52	57.57	55.74	59.69	66.95
20	48.1	52.93	54.18	63.37	70.69
35					
10	48.96	51.61	56.72	60.4	68.55
15	49.57	56.1	61.75	59.52	68.17
20	53.4	60.25	58.29	59.09	68.76

B. To-Be 1 Results

The results of To-Be 1 in 60 minutes for different Container Throughput and varying number of AAGVs and Reach Stackers can be found in Table III. The simulation results investigate the impact of varying numbers of Reach Stackers on Automated Guided Vehicles (AAGVs) in a container handling operation. The findings demonstrate that AAGVs function best when complemented by an appropriate number

TABLE III
THE RESULTS FOR TO-BE 1

Average Container Transport Time (mins)					
AAGVs | RS	**Throughput**				
	10	**15**	**20**	**25**	**30**
10					
10	35.70				
15	35.00				
20	35.99				
15					
10	35.17	39.05			
15	35.05	37.52			
20	35.63	36.88			
20					
10	34.71	40.61	42.48		
15	36.58	37.23	44.26		
20	35.39	39.39	41.81		
25					
10	33.30	38.47	38.00	44.94	
15	33.32	36.09	43.01	47.54	
20	33.98	36.45	41.60	45.86	
30					
10	35.06	41.39	40.26	49.34	48.15
15	36.13	38.86	47.45	48.90	
20	33.54	40.12	42.33	51.33	49.42
35					
10	34.71	39.87	46.25	50.23	46.45
15	34.48	40.55	41.56	43.56	46.46
20	35.87	39.50	43.11	50.83	49.17

of Reach Stackers, highlighting their potential to significantly improve overall efficiency in container movement operations.

The research investigated the effectiveness of Automated Guided Vehicles (AGVs) in a container terminal with high traffic. The results demonstrate that AGVs outperform the traditional method of using Reach Stackers. While simulations showed potential congestion with a high number of AGVs, this is mitigated in real-world scenarios where arrival times are naturally spaced out. Additionally, the 60-minute simulation timeframe limited the ability to model a second trip for all AGVs, as they can complete only one round trip within that timeframe.

C. As-Is 2 Results

TABLE IV
THE RESULTS FOR AS-IS 2

Average Container Transport Time (mins, with Barge Travel of 30 minutes approximately)					
AGVs	**Throughput**				
	10	**15**	**20**	**25**	**30**
10	39.82	41.57	43.16	44.92	46.61
15	40.35	41.1	43.65	45.3	47.2
20	39.93	41.33	43.75	45.57	47.43
25	40.03	41.61	43.33	44.87	46.93
30	40.07	41.23	43.24	45.07	47.34
35	40.49	41.95	43.85	45.36	47.13

Table IV shows the results for As-Is 2, which involves AGV operations with Quay Cranes, barges and RTGs.

The research investigated the impact of throughput and the number of Automated Guided Vehicles (AGVs) on container transport time within a shipyard. Findings demonstrate a positive correlation between throughput and average transport time, signifying that increased container volumes lead to congestion and extended wait times for resources like AGVs and cranes. Interestingly, the effect of adding more AGVs is not always linear. While additional AGVs generally improve efficiency, specific yard layouts can restrict their movement, limiting the benefit. Furthermore, an influx of AGVs can exacerbate bottlenecks at fixed resources like cranes, negating the advantages of extra vehicles.

These results highlight the intricate relationship between AGV quantity, throughput, and transport time. While strategically increasing AGVs can enhance efficiency, yard design, bottleneck management, and external factors like barge wait times significantly influence overall transport time.

As stated before, Amphibious AGVs, with their ability to navigate both land and water, can potentially address these limitations. Their operational flexibility could overcome layout restrictions and provide alternative routes, thereby reducing congestion and improving overall throughput.

D. To-Be 2 results

TABLE V
THE RESULTS FOR TO-BE 2

Average Container Transport Time (mins)					
AAGVs	**Throughput**				
	10	**15**	**20**	**25**	**30**
10	26.72				
15	26.39	28.19			
20	26.76	27.16	28.50		
25	26.60	28.22	28.85	29.27	
30	25.76	27.41	27.93	28.45	28.99
35	26.09	26.92	27.99	28.74	30.41

Table V shows the results for the To-Be 2 scenario, investigating how efficient AAGVs are in moving containers between terminals without quay cranes.

The findings demonstrate that increasing the number of AAGVs leads to a decrease in transport time, alleviating congestion and expediting container flow. This effect is particularly pronounced at lower throughput levels. However, the benefit diminishes with a further increase in AAGVs, suggesting a potential saturation point. These results highlight the potential of AAGVs as an efficient solution for container transportation within terminals, particularly when considering their throughput and existing equipment configurations.

VI. COMPARISONS

A. As-Is 1 compared to To-Be 1

The results visualize the performance of As-Is 1 against To-Be 1 for different throughput. The throughput refers to the number of containers that have been successfully moved. For all throughput evaluated, AAGVs demonstrate a clear

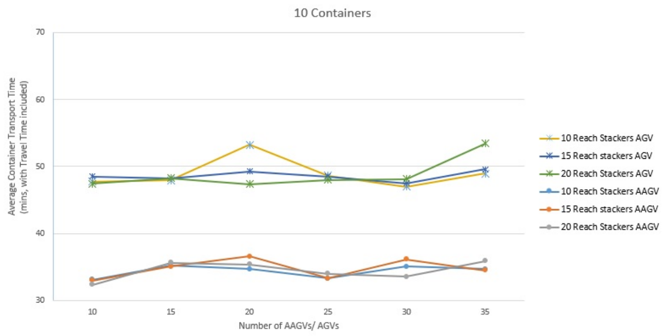

Fig. 12. Throughput of 10 Containers

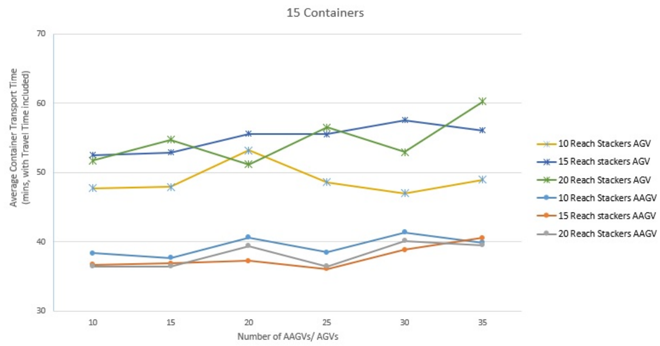

Fig. 13. Throughput of 15 Containers

Fig. 14. Throughput of 20 Containers

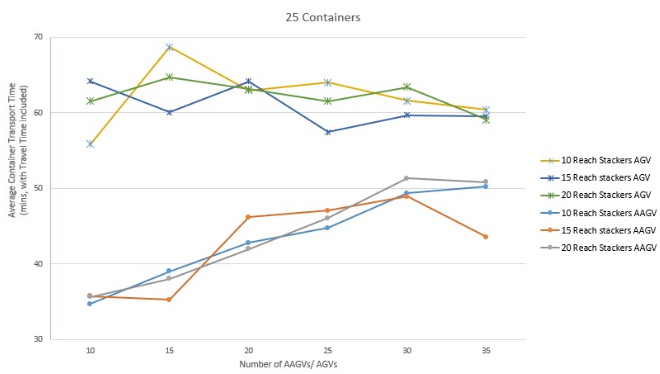

Fig. 15. Throughput of 25 Containers

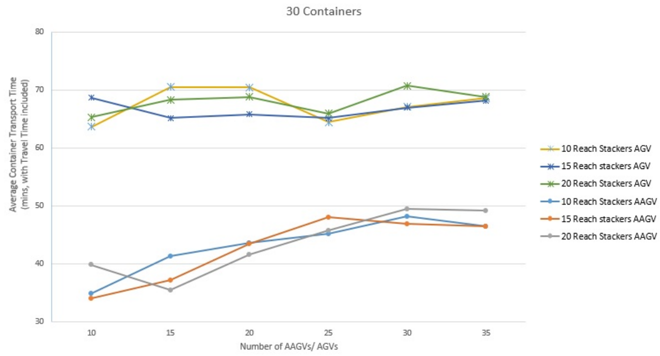

Fig. 16. Throughput of 30 Containers

advantage over AGVs in terms of average container transport time.

One key factor contributing to this efficiency is the elimination of barge unloading. AGVs rely on barges to deliver containers to the port, adding an extra step to the transportation process. AAGVs, on the other hand, can bypass this step by travelling directly to the container storage area, significantly reducing the overall transport time.

The graphs also reveal that increasing the number of AAGVs leads to faster delivery times. This is likely due to the increased capacity and parallelism in container movement offered by additional AAGVs. With more AAGVs, all containers can potentially be delivered in fewer trips, further enhancing efficiency.

In conclusion, these results demonstrate that AAGVs outperform AGVs in container transportation within a port. The ability to directly travel to the container storage area and the scalability of AAGVs through increased deployment contribute significantly to this advantage.

B. As-Is 2 compared to To-Be 2

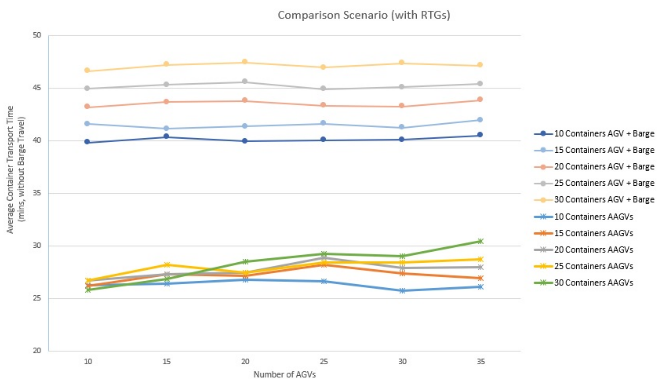

Fig. 17. Comparison for all throughputs of As-Is 2 vs To-Be 2

This section provides a comaprison between the two datasets, As-Is 2 and To-Be 2, which represent the average container transport time for various throughput levels ranging from 10 to 30 containers per hour. Throughput refers to the number of items processed or produced in a given time period.

The results demonstrate that AAGVs consistently outperform AGVs in terms of average container transport time across all throughput levels. For instance, at a throughput of 15 containers per hour, the average transport time using AAGVs is significantly lower compared to AGVs. This improvement can be attributed to the unique capabilities of AAGVs. Unlike AGVs that rely on Quay Cranes for container exchange at the quay, AAGVs can directly access the RTG crane, eliminating an entire step in the process. Additionally, AAGVs bypass congestion issues typically encountered with barges at the quay, further reducing transport time. It is worth noting that barge travel time, which has been taken as 30 minutes, can increase substantially due to barge congestion, especially when quay cranes are unavailable. These factors combined contribute to the overall superiority of AAGVs in terms of container transport efficiency.

VII. Conclusions

A. Conclusions and Discussions

The results conclusively demonstrate that AAGVs outperform the traditional method in all throughput ranges tested (10-30 containers within 60 minutes). This advantage stems from AAGVs eliminating the time-consuming process of unloading containers from barges using QCs. Traditional AGV operations require QCs to unload containers from barges, adding a significant time burden to the overall transport process. AAGVs, however, can travel directly between the source and sink terminals, eliminating barge travel time and the associated inefficiencies of using QCs.

The As-Is scenario partially mitigates the inefficiencies of barge unloading by increasing the number of AGVs or Reach Stackers (RS) used for unloading at the terminal. This approach can improve the average container transport time by reducing congestion during unloading. However, the To-Be scenario consistently outperforms As-Is due to the complete elimination of barge unloading. Even when increasing the number of AAGVs in To-Be leads to longer wait times for unloading by RS due to competition, AAGVs still achieve significantly better results compared to As-Is. This is because the time saved by eliminating barge unloading outweighs any congestion caused by more AAGVs competing for a limited number of RS.

Overall, the research convincingly demonstrates that AAGVs are a more efficient solution for container transportation within terminals compared to traditional AGVs with barges. AAGVs eliminate the need for barge unloading and potentially reduce travel distances, leading to faster overall transport times and improved throughput. These findings offer compelling evidence for the implementation of AAGVs in container terminal operations to achieve significant efficiency gains.

B. Assumptions and Limitations

The simulation time horizon is limited to one hour due to software constraints in all libraries except the Process Modeling Library within AnyLogic [13] [40]. This limitation is acknowledged and may influence the accuracy of results for systems operating over extended periods [13]. However, the research emphasizes the validity of the model for the simulated hour. Arena software was not chosen as an alternative due to limitations on the number of entities it can handle, which is not a suitable constraint for this specific model [13].

The simulation considers a travel distance of 5 kilometers on water. This distance encompasses routes between Euromax, ECT Delta, and Delta II Container Terminals in the Port of Rotterdam. It also incorporates other terminals across various global ports, including those in DP World, Dubai, and Port of Saigon, Vietnam, making the model non-port specific.

Current battery capacity and charging data for existing AGVs deployed by ECT, the company controlling both Euromax and Delta Terminals, are not applicable due to their diesel-electric nature [15]. While the Port of Singapore utilizes electric AGVs, their system relies on battery charging instead of swapping [14].

The simulation considers AGVs and AAGVs carrying the maximum permissible weight of a 40-foot container. Consequently, the simulations will likely underestimate battery consumption and vehicle range.

Both scenarios within the simulation assume the closest possible travel distances to the stack location. This translates to assuming the closest available unloading Quay Cranes and ramps to the designated stack.

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