Utilizing Amphibious AGVs to Optimize Container Transshipment for Deep Sea and Hinterland Operations

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ABSTRACT

Transshipment is a key component of modern-day shipping logistics. Container supply chains rely on transhipment hubs to access remote locations. With globalisation driving growth in container trade, maritime congestion is rising at container terminals in ports worldwide. This is expected to worsen as demand continues to grow. This research explores novel maritime equipment designs that can contribute to solving problems in the trans-shipment chain. One such idea is that of the Amphibious Automated Guided Vehicle, an innovative concept that travels on both land and sea. Envisioned as a tool to minimise the rehandling of containers, the Amphibious AGV forms the heart of the new changes that this research proposes for the future of trans-shipment. Complementing swifter trans-shipment, the research also proposes complementary design concepts such as floating terminals to add more flexibility for container ships and Amphibious AGVs applied to exchange containers offshore. To validate these ideas, an agent-based modelling methodology was used and replicated in the environment of the Hong Kong- Pearl River Delta. This work, therefore, opens up an intriguing future scope for maritime transshipment that is both sustainable and adaptable while also discussing limitations and concerns that need to be carefully considered.

KEY WORDS

Marine Design, Transshipment network, Floating Terminals, Amphibious AGV, Agent-Based Modeling

INTRODUCTION

Globalisation has sprung up a huge surge in international trade. With the increase in international trade, container trade has also seen a substantial increase in the last few years. With container ships getting bigger, both inland and deep sea terminals are seeing massive volumes of container flow daily. Consequently, hinterland transportation networks have become extremely important for trade and accessibility worldwide. In this era of globalization, an increasing number of inland cities are playing pivotal roles in global trade by supplying electronics, essential goods, and even food items. However, with this growth, deep sea terminals that are often the gateways for inland container traffic become congested with the influx of multiple barges. In the ports of Rotterdam and Antwerp, terminals that often only see 1 ultra-large container ship a day would see 23 barges dock by the terminal (Shobayo and Van Hassel, 2019)

This number amplifies to 120 barges in busier ports like Hong Kong (Seatrade Maritime News, 2015). This contributes to arrival/departure problems, berth planning issues, and quay crane allocation problems in ports (Tang et al, 2022). Often, terminals are forced to use deep-sea berths to unload waiting container barges, preventing bigger ships from docking. Congestion in many other regions of the world, such as the United States, has taken a different turn, with the Port of Los Angeles

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and Savannah seeing queues of up to 100 vessels, of which 70 of them were container vessels (Bu et al, 2023). Ports in the United States saw a massive increase in dwell times by 27.4% in 2021 compared to 2016. Similarly, in the Port of Rotterdam and Antwerp, only 41% of barges arrived/departed within a two-hour window that is usually reserved for barges From a policy side, congestion has caused tensions between barge operators and deep sea terminal operators since the former and latter do not share any contractual relationship (van der Horst et al, 2019), therefore not obligated to pay berth fees while spending 1/3rd of their operational time at deep sea terminals (Konings, 2007).

Compounding the issue, when the world's two busiest waterways, namely the Rhine and Yangtze rivers, were compared, their different upstream and downstream dynamics warrant solutions that are globally applicable to solve congestion (Notteboom et al, 2020). In the context of barges and inland waterways, congestion is also caused by multiple trips originating from the same inland port, which is a direct consequence of low container call sizes. Port of Rotterdam and Antwerp have seen this problem escalate at their deep sea terminals with call sizes as low as 6 TEU per barge trip with an average of just 33 TEU per deep sea terminal during a barge trip (Konings, 2007). This has meant that despite a priority for deep sea ships, some deep water berths are forced to block 3000 TEU+ ships to unload barges (Shobayo, 2023). This has also mounted to the congestion in container terminals with repetitive barge trips. Historically, this has called for better coordination and information exchange between deep-sea terminals and hinterland barge operators, but such alliances are not in place, and expect to take a long time before anything materialises (Wiegmans et al, 2018) When the issue is analyzed from a global perspective, the urgency to solve the problem of congestion is underlined by the fact that seaport/terminal inefficiency in handling container shipments will lead to higher maritime transport costs, which will eventually influence the prices paid by consumers for goods due to container holding costs (Sanchez et al, 2003). In its worst manifestation, COVID-19 showed how these prices could worsen when holding containers raised shipping costs 10-15 times in 2021 (Freightos, 2023). For instance, in 2021, freight rates for shipping a 40ft container from the USA to China skyrocketed to $20,600 (Regular cost- $1400). While congestion is never expected to impact trade as COVID-19 did, inefficiency in the supply chain can compound existing delays. Maritime congestion, therefore, sees terminal inefficiency as one of its leading causes. With the enormous growth in container trade and more markets and inland ports being breached, congestion at deep-sea terminals is imminent. This would essentially segue well into exploring terminal and port expansion through land reclamation, but this has many inherent issues. Singapore, one of the most prominent ports in the international shipping line, expanded in 2014 to increase the number of deepwater berths to 15, aiming to boost container throughput to 50 million in the coming years. However, this was not without its drawbacks, as the expansion severely impacted the ecological welfare of nature reserves despite preventive measures (Lian et al, 2015). This warrants a solution that is also sustainable. From a social sense, taking the example of the Port of Hong Kong, the terminals, which see 120 barges/day, are unable to expand due to the impending housing crisis in Hong Kong, which has threatened to close some terminals to create space for housing complexes and settlements (Chong and Li, 2020). Congestion in such circumstances will only worsen with fewer avenues of expansion. This has knock-on effects on daily schedules with worsening berth management issues. Shifting hub ports like Hong Kong to another place or creating new hubs is not viable in the maritime industry as various inland waterway ports are directly linked to these hubs. Some examples include Hong Kong- Pearl River Delta, Antwerp/Rotterdam- Rhine, and Shanghai- Yangtze. However it is not only the lack of expansion space affecting terminals, congestion is both a consequence and a cause of inefficient container handling operations that are seen today which is a constraint of technology and manpower. While ports have become more autonomous and have achieved the pinnacle of technology with the introduction of AGVs, automated quay, and yard vessels, it has still not solved vital issues such as rehandling of containers where a lot of time is lost even today (Caserta et al, 2011). Most containers lose time transiting between different types of vehicles, both in port and on water. A container transfer between two terminals would need the use of an AGV+Barge (Schroër et al, 2014), or the use of a truck which would have to travel 20+ km on land when the terminal is just 2km across water (Ghiridharan, 2023). Both transfer methods lead to delays in handling incoming and outgoing container consignments from partner terminals or inland entities, leading to higher dwell/waiting times for deep sea ships and especially barges, which generally look for quicker turnaround times (Chen and Schonfeld, 2010), given their low call sizes. This is also a domino effect, with rehandling often leading to container relocation problems in stacks/yards. Looking at the bigger picture to understand the cascading phenomenon, ship delays due to congestion have seen an increase in rehandlings by 44% in worse-case scenarios, and it gets worse with growing demand call sizes and container reshuffles aggravating maritime congestion (Gharehgozli et al, 2017).

Deep Sea- Hinterland transportation, therefore, has multiple challenges. It has to grow sustainably while addressing congestion, efficient inter-terminal and inland transport, and minimize or eliminate land reclamation while opening new avenues for expansion. With global trade set to grow by 70% in 2030 (Gibson, 2021), container handling at both deep-sea terminals

and hinterland must be efficient to enable seamless trade windows for international deep-sea vessels and domestic barges. The trade targets also bolster the need for new perspectives in container shipping for the future. Thus, this paper describes and analyzes the implementation of marine design concepts that can provide a novel outlook for deep sea to hinterland transportation.

According to the literature review, we identified four areas that would need new perspectives. These include: i) the minimization of container rehandling, ii) addressing low call sizes of barges, iii) identifying alternate avenues for expansion, and iv) an integrated network design and methodology to implement this novel trans-shipment idea. Most of the research carried out so far has emphasized on optimizing existing networks through various analytical and lean approaches to address bottlenecks(akin to point iv). However, as seen in the introduction and problem analysis, it is clear that certain design concepts are directly responsible for increasing container handling and barge congestion. This is where novel design approaches and methodologies are needed to enhance the performance of major container transshipment networks.

Therefore the goal of this work is to introduce such novel designs addressing each of the four points listed above and applying it to a real-world container transshipment network namely the Hong Kong- Pearl River Delta with the aim to reduce barge congestion, maintain stable container throughput and container transport time while also enabling future avenues for growth in such ports.This work aims to present preliminary design concepts that can enable a framework to address the four burning issues of this research.

The structure of this paper is organized as follows: Section **Related Work** introduces the state-of-the-art, providing a foundation for the research. This is followed by a detailed presentation of the methodology in Section **Methodology**, where we outline the authors' proposed approach for addressing the transshipment problem, encompassing both the theoretical design and practical implementation aspects. Subsequently, Section **Case Study** describes the validation of the proposed transshipment solution through a meticulously conducted case study. The findings from this case study are thoroughly examined in Section **Results**, where the effectiveness of the new transshipment method is evaluated. Finally, Section **Conclusions** concludes the paper, offering key insights derived from the research and suggesting directions for future work in this area.

RELATED WORK

This section is dedicated to providing a comprehensive overview of the existing literature and prior work that has significantly shaped the direction of our study. Much of the research in the maritime domain has traditionally been conducted with a focus either on design aspects or optimization techniques. However, instances where both design and optimization methods are integrated are notably rare. This gap highlights the unique contribution of our work, as we aim to synthesize these two approaches to address the challenges in the maritime field more effectively.

Barge Congestion Challenges- Addressing Call Size Variability: the congestion of barges at deep-sea terminals and along inland waterways presents a significant challenge, arising from a blend of operational and policy-related issues. This subsection explores the variability in call sizes across different ports, such as Hong Kong, and discusses the economic advantages of barge transport. It highlights the efficiency and cost benefits of barges compared to other modes of transport, emphasizing the global shift towards increased hinterland transport. The congestion of barges at deep-sea terminals and along the inland waterway has generally been caused due to a combination of operational and policy issues. One of the recent works aimed at solving barge congestion in part uses an agent-based modelling approach (Shobayo and Van Hassel, 2019) and makes important suggestions on how a mandate/contract needs to be agreed upon for a minimum number of containers that a barge calls at a terminal. The work suggests 30 TEU for the environment of Rotterdam and Antwerp as a minimum call size. The effects of this would be reduced port calls, and therefore reduced congestion. An earlier work which focused on opportunities to handle denser barges in the future (Konings, 2007) also corroborated the idea of having a minimum agreed-upon call size. This figure, however, is not universal with the port of Hong Kong recording call size anywhere between 50 TEU (Seatrade Maritime News, 2015) TO 120 TEU (Post, 1994) with 120 barges a day. The motivation to use a higher (and minimum agreed upon call size) is also complemented by research which has shown that barge transport costs as low as 12.6 Euros per 1000 Ton kilometers when compared to trucks and trains that cost 4 times as high (Gharehgozli and Zaerpour, 2018). Similarly, even regarding mileage, barge transport records 576 miles/ton/gallon compared to 413 in trains and 155 in trucks (Bu et al, 2023).

Ports worldwide are also increasing the proportion of hinterland transport given its cost and fuel benefits, with Rotterdam and Antwerp increasing the share to 45% by 2030 (Gumuskaya et al., 2020). Higher call sizes, in that sense, would benefit both barge companies and terminal operators in reducing trips. Congestion, when seen from a sustainable expansion point of view, brings numerous possibilities. A general deep sea terminal has provisions for deep sea ships, feeders, and barges.

Innovative Terminal Solutions to Combat Congestion: innovations such as dedicated handling spaces and the barge hub concept are explored here. These solutions aim to efficiently reconfigure terminal space, promoting larger call sizes and potentially reducing congestion, while also addressing their scalability and feasibility challenges. This section covers the development of integrated terminal ship transfer systems and other direct trans-shipment methods. Such advancements aim to streamline operations, reduce the use of unnecessary vehicles, and offer cost-effective alternatives for terminal expansion. Research has also explored dedicated handling spaces for barges and feeders, with the barge hub being a prominent example of reconfiguring existing terminal space without unnecessary land reclamation (Pielage et al., 2007) (Konings et al., 2013). A barge hub would be an intermediate terminal that extends hinterland services by shifting the centre of congestion from deep sea terminals to an area accessible by hinterland actors. This concept also encourages larger call sizes to flow in at once drastically reducing barge frequency. A major drawback of this shown in research (Nicolet et al., 2023) is that barge hubs work predominantly for small cargo volumes given that expansion would result in similar problems to deep-sea terminals and could cause similar levels of congestion. Location often would also become a contentious point if even feeders and deep sea ships had to be handled, reducing versatility (Konings, 2007). The Barge hub would still need investment in the yard, vehicles, and straddle carriers. A more flexible concept has been seen in floating terminals, which have been explored in various sustainable and modular forms. Initial concepts include repurposing post-panamax vessels with on-board harbour cranes for loading and unloading containers (Baird and Rother, 2013). The quay of 300 m would be long enough to support up to 3 standard rhine barges or two feeder ships and would cost 1/3rd of a regular terminal. Despite its cost benefits and stability certification, such a concept would not be able to accommodate as many quay cranes as needed and would lose time in loading, unloading, and transfer, thereby contributing to higher waiting times and congestion. When connecting this idea with container rehandling concepts are needed to reduce this rehandling, desirably through direct transfer trans-shipment between ships, minimising storage for repositioning (Shen and Zhang, 2015). These have been manifested in a 2020 work that discussed exploratory concepts for floating terminals (Jovanova et al., 2022). Simulated in the Port of Genoa, the floating extensions were modular and used carrier cranes that could simultaneously transfer containers overhead from one vessel to another. This would essentially reduce rehandling and the number of ground vehicles and space in the process. The drawback here was that the lack of yard space meant that even temporary storage was not possible. However, a work within the same timeline by Johannes March proposed an integrated terminal ship transfer system (March, 2020). While this is not a floating terminal out and out, the benefits of direct trans-shipment were shown using a similar over-the-head crane that spanned across an ultra-large container vessel, a feeder/barge, and also part of the quay/yard. This concept eliminates unnecessary vehicles and simplifies container access points from respective ships/yards. The research also claims a 50-80% reduction in overall investment and is an important consideration for alternate container expansion approaches. However, hub and spoke limitations and approaches concerning hinterland hubs also need to be considered regardless of floating terminal versatility as depicted in works done on Port of Antwerp and Rotterdam (Caris et al., 2011; Konings et al., 2013).

Rehandling of Containers during Inter-Terminal Transport to Reduce Congestion: technological innovations, including waterborne AGVs and the Amphibious AGV, are discussed for their potential to transform inter-terminal transfers and reduce container handling points, illustrating a shift towards autonomous and efficient maritime logistics operations. The port feeder barge concept is examined here, highlighting its potential to improve inter-terminal transport efficiency through faster loading and unloading processes. The potential resistance from traditional terminal operators to this innovation is also discussed. Addressing an identified problem of inter-terminal transport through trucks, another important idea in research that looks to solve container rehandling, call size issues, and congestion is the Port feeder barge idea (Malchow, 2020). This is essentially a crane-on-barge concept with a capacity of 168 TEU, aimed at serving small inland barges with swift loading, unloading and instant transfer. The port feeder barge has the potential to shorten multiple inter-terminal transfers on water (from 20km to 2km (Ghiridharan, 2023)) and reduce the overall time spent for barges within the port. While this idea is promising to solve congestion, as pointed out in another research (Nicolet et al., 2023), deep-sea terminal and hinterland operators could resist the involvement of a third party for stevedore operations. Eliminating the hassle of operators, the waterborne AGV was developed with a vision to enable swift inter-terminal transfer and transshipment. Envisioned to be operated by deep sea terminals, the waterborne AGV is essentially a 2 TEU AGV that traverses on water instead of land (Zheng et al., 2017). The waterborne AGV uses azipod thrusters for propulsion and is currently in the prototyping phase at TU Delft. The waterborne AGV is

promising, given its autonomous nature and the extensive research in inter-terminal transport. Complementing its significance, waterborne AGVs have also been simulated in cooperative control using a fleet of WAGVs either as a swarm or platoon in Port of Rotterdam conditions, displaying its versatility (Chen et al., 2019). Given the Maasvlakte's expansive layout, literature has also corroborated with Waterborne AGV's efficiency over trucks in reducing time, distance, and emissions for container transfers (Zheng et al., 2016). However, container rehandling remains an issue. Recalling previous literature accounts and sections, just as how an AGV or Truck + Barge is needed to move containers between terminals, similarly the waterborne AGV would still be involved in a switch with another truck or ground AGV. The handling points in the system would remain the same and in case of any ship delays, as seen earlier (Gharehgozli et al., 2017), handling times could compound by 44% or worse. Furthermore, this adds to the high number of trucks and AGVs that the terminal already has to operate, aggravating land and water-based congestion. The handling point can only be eliminated or reduced if a concept combines land and water handling capabilities. That is where the Amphibious AGV(AAGV) comes into the picture, a nascent yet significant concept in the broader terminal operations picture. The AAGV is again another 2 TEU vehicle that can travel on both land and water. Envisaged as an instrument to reduce container handling points in the supply chain, the AAGV was first designed as a general transport vehicle in 2019 (Kleefstra, 2019). It was subsequently redesigned by a TU Delft project team featuring the primary author of this research paper. The AAGV in preliminary findings (Abhishek Rajaram, 2023; Ghiridharan, 2023) produced a 21% saving in transfer times between container terminals. In both the aforementioned recent works, the AAGV reduced handling points, reducing barge/feeder waiting times and opening avenues for versatile implementation in tandem with concepts such as floating terminals.

Simulation Techniques for Congestion Analysis: this section delves into the use of simulation techniques, such as discrete event simulation and agent-based modeling, in analyzing maritime congestion and evaluating the effectiveness of proposed solutions. Recent advancements in addressing barge congestion have leveraged agent-based modelling techniques. Studies have effectively used agent-based modelling to address call size issues by implementing a minimum call size for barges at terminals, with recommendations for specific sizes in ports like Rotterdam and Antwerp, to alleviate congestion. When seen from an implementation point of view, maritime networks often follow either hub and spoke theories,point-to-point theories, or a combination of both (Tagawa et al., 2021). From a simulation standpoint, various approaches have been discussed to present the barge congestion situation accurately. One is by sequentially planning events, and this is discrete event simulation in research; this has been successful in modelling waterways (Bu et al., 2023), berth planning (Legato and Mazza, 2001) and also container yard management (Kotachi et al., 2016). However, this type of simulation is not capable of doing parallel processing, which would otherwise be possible in an agent-based modelling approach. Agent-based modelling (ABM) approach is an approach where every entity has autonomy while interacting with other entities. These entities are the agents in the simulation. For example, suppose a barge, Quay Crane, and Container terminal are considered agents. In that case, these agents have their functions, such as loading, unloading, and container inventory management, while they have separate interactive functions, such as loading and then leaving. ABM has found its relevance in various areas of container shipping, namely in frameworks for reducing congestion (Shobayo and Van Hassel, 2019), container terminal productivity (Mazloumi and van Hassel, 2021), and most importantly, in both inter-terminal transport (Iqbal, 2015) and interland (Feng et al., 2015).

A review of existing research and best practices has shed light on how to tackle the complexities of transshipment between deep sea and hinterland terminals. This exploration revealed four crucial areas demanding attention: i) minimizing the number of times containers are picked up, moved, and put down is essential. Streamlining container movement within terminals is key to achieving efficient operations; ii) traditional methods of expanding container terminals may not suffice. Exploring innovative solutions is crucial to accommodate the ever-growing volume of cargo; iii) currently, barges might not be filling to capacity, leading to inefficiencies. Optimizing barge loading schedules and sizes is essential for a smooth flow of goods.; iv) implementing a novel transshipment network requires a comprehensive strategy. This includes carefully planning and managing the system to ensure its effectiveness. This narrative approach uses figurative language and storytelling elements to make the content more engaging and easier to understand. It highlights the challenges in a way that is clear and memorable.

METHODOLOGY

The methodology of this work is divided into four distinct phases. The first phase targets the rehandling of containers. This is considered an important link, given that rehandling can only be addressed using a different transporter design. Subse-

quently, the next phase targets alternate avenues for expansion with the same design description. The third phase will focus on addressing existing barges' low call size situation. Since this is not a conceptual or cosmetic design change but merely an increase in call size, this will not be explained in detail. The final phase of the methodology describes a comprehensive design of the transport systems network implemented with a simulation approach. This methodology will then be validated through simulations in a real port environment that connects the deep sea and hinterland.

Phase 1 - Address Rehandling of Containers

Amphibious AGV Design

The review of the state of the art has helped identify key problem areas such as rehandling of containers between truck and barge, and longer and unnecessary routes for inter-terminal transfers. Several promising concepts were studied, namely waterborne AGVs, Port Feeder Barges, and Amphibious AGVs. Port feeder Barges suffer from operator compatibility issues (Nicolet et al., 2023). While waterborne AGVs were promising in their design and research availability, it became clear that rehandling issues still appear despite the reduction in inter-terminal transfer time and distance (Zheng et al., 2017). As the related work section states, Amphibious AGV is a container AGV that can traverse on land and water. This was specifically designed to address container re-handling problems and reduce inter-terminal distance. The Amphibious AGV went through various design cycles with three concepts being considered. This included a standard AGV chassis modification as the first idea, with hovercraft and catamaran designs also being considered. After being evaluated on a multi-criteria analysis of stability, complexity, manoeuvrability, efficiency, and cost, the standard AGV design was chosen owing to its design and dimensional compliance with current container AGVs on the market. As depicted, the design of the Amphibious AGV has been adapted specifically to handle geographical disparities. Changes in this include creating space for the water propulsion system. Since this is envisioned as a sustainable vehicle, the propulsion is all electric. Therefore, space is also made for the battery pack placed in the centre of the main chassis. This is shown in the form of boxes in Figure 2. The battery pack is estimated at 600 kWh. The battery pack itself is made up of 42 modules of 6.3 kWh each. These are stacked in three separate blocks of 12,12 and 18 modules, amounting to 710 kWh. The chassis itself measures 16.6 m (length) x 3 m (width) x 1.8 m (height). This allows enough space for mounting a fully loaded 40-foot container (or two 20-foot containers) and space in front and rear to accommodate the pump jet system, marked in red in Figure 2. The pumps are also flanked by 4 electric motors at the wheels for ground propulsion The Amphibious AGV also has more angled edges than regular ground AGVs. This makes it hydrodynamic, and the edges serve as a breakwater against waves should it encounter waves in port waters. The original design of the Amphibious AGV also had 4 holes to incorporate a SAE 316 stainless steel-based locking system to connect with other Amphibious AGV. However, this system has been disbanded for this work since such contraptions on water could create more instability. To enable floatation on water, the Amphibious AGV also has pontoons which will be delineated later. Given that the Amphibious AGV will also be in contact with water, choosing non-corrosive and water-resistant materials was important. While stainless steel would have been the best choice, due to cost concerns carbon steel was chosen for the body of the Amphibious AGV given that it offers similar performance levels as stainless steel. The pontoons have to be of high strength and flexibility. Taking inspiration from hovercraft designs, the pontoons are made of nylon base cloth, with the outer layer being made of natural rubber and neoprene. These are strong enough to resist the internal air pressure and buoyant force.
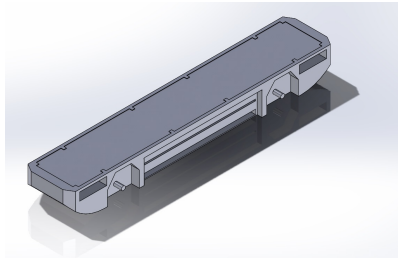
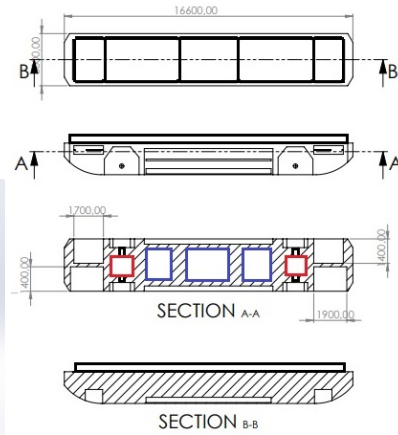**Figure 1:** AAGV Body Exterior

Figure 2: AAGV Body Interior

The land mode of the Amphibious AGV has been depicted in Figure 3. In this scenario, it is clear that the pontoons can be retracted because they would not be needed on land. Only the electric motors would be at work in land mode, drawing power from the battery pack. The Amphibious AGV was designed with the assumption that they would travel on ramps to enter or exit water. There will be a point between land and water where land and water-based propulsion and powertrains are used to enter water from land or vice-versa. The AAGV in water mode has been depicted in Figure 4. In this mode, the floatation pontoons are activated and marked in yellow in the figures. As mentioned earlier, the AAGV will engage both land and water-based propulsion systems while transitioning from the ramp to water. Subsequently, it will switch to completely water-based pump jet propulsion. The locking mechanism while still present can be used for locking with quays of container terminals but this is optional and does not affect the functionality of the Amphibious AGV.
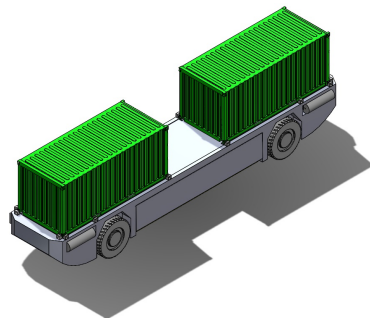

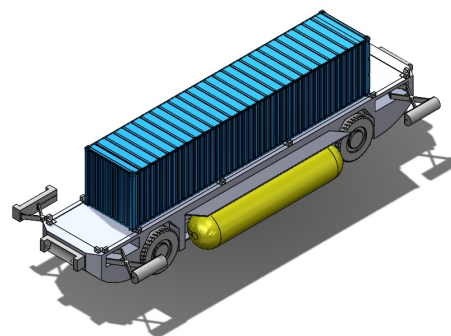**Figure 3:** Land Mode- Isometric View

Figure 4: Water Mode of The AAGV

The amphibious AGV consists of salient mechanisms that stabilize it on water and lay frameworks for future dual powertrain concepts. The idea of pontoons on the AAGV was deemed necessary due to the low centre of gravity of the Amphibious AGV. This is caused due to the 5000Kg battery pack and 7000Kg propulsion. pump and powertrain systems installed.The Amphibious AGV was designed considering short-haul transfer between terminals on water and within, land. The above specifications on power were computed considering a slope of 3 degrees, wind speed of 20 m/s, a maximum operating speed of 12 Km/hr and acceleration of 1 m/s to support a maximum load of 75 Tonnes. Using these considerations, a maximum power rating of 457 kW is obtained for terrain with the slope. It is prudent to note that the ramps used for entry and exit of AAGV from land to water or vice versa are set to 3 degrees. In regular flat terrain conditions, the Amphibious AGV only requires 331 kW of power to transport 75 tonnes. In terms of energy consumption, a container AGV moves a few hundred metres to some km per day. Given the functionality of the Amphibious AGV, each cycle of operation is assumed at 25km over 8 hours after which the battery is swapped. The battery capacity is therefore calculated to be 710kWh. The same Amphibious AGV's

batteries will be swapped when empty and a standard swap takes between 6-7 minutes as mentioned in industry (Konecranes, 2023) and literature (Schmidt et al, 2015). Therefore 3 shifts of an Amphibious AGV is achievable with 75km of daily range. Summary of major power-train specifications are given in Table 1.

The water propulsion system will consist of 2 Schottel SPJ 30 C pump jets (Odetti et al, 2019) that can give a combined output of 200 kW. While a maximum of 250 kW was computed for a top speed of 8 knots, it must also be realised that if the admiralty formula (Giernalczyk et al, 2010) is considered, a lower velocity of 6 knots would deem 200 kW as sufficient power to propel 75000 Kg of load. These calculations have been done considering a pressure of 135 PSI at 85% volumetric efficiency. The speed considerations of the Amphibious AGV(initially developed for Port of Rotterdam) are based on their speed limits imposed by the Port of Rotterdam (Centre, 2014). With a near 70% of travel distance slated to be on water, the pumps would consume 495kWh of energy during an 8hr operational period. This is the full load capacity of the AAGV of which 54000 Kg is from the fully loaded containers which can be either a single 40 ft container (29000 Kg) or two 20 ft containers (54000 Kg). The remaining masses are comprised of the Amphibious AGV chassis (8000Kg), the electric drives and motors (8000 Kg), water-based propulsion system (4000 Kg) and the pontoon-based support structures (1000 Kg). On an operational level, the amphibious AGV is assumed to function 24 hours a (Liu et al, 2001) for 315 days a year since some days may also be used for servicing and maintaining the AAGV. This amounts to 7500 operational hours in a given year.

The stability aspect of the Amphibious AGV on water was not tested primarily but computed with logical assumptions. The Amphibious AGV when fully loaded with 2 TEU would weigh 75000 Kg and the design is akin to that of Inland barges which generally have fuller hulls(block coefficient of over 0.8). The Amphibious AGV features a fuller hull as well and places stability over maneuverability given the linear range of routes and guideways on land and water. The Amphibious AGV is also underlined by the fact that when fully loaded 75% of the body will be under water while 25% remain above. To enable this buoyancy, pontoons are inflated before the Amphibious AGV enters the water. With a requirement for 25% buoyancy, the pontoons should provide an upthrust of 185 kN(against a downward force of 735kN). The calculated volume of both pontoons are 24.505m^3 with a radius of 0.736m and a 7.2m pontoon length. The pontoons will be filled with air using Grundfos NB 150-315 pumps(Grundfos, 2024)capable of pumping at a flow rate of 447.8m^3/hr. This implies that the pontoons will be filled in 1.65 minutes. The pumps are rated at 37kW and at a maximum flow rate, each inflation/deflation would draw an energy of 2.035kWh for both pontoons which is 0.3% of the total battery capacity. It must also be noted that inflation holds more precedence over deflation as most port roads have space to accommodate Amphibious AGVs with fully inflated pontoons in the event of low battery. The pontoons also have 4 equally sized air-tight chambers, which implies that in the event of a puncture and water infilitration, only one out of the four pontoon segments would be impacted and the Amphibious AGV can return to safety. The Amphibious AGV also has space for ballast tanks placed over the battery with dimensions of 7.5m x 2.4 m x 1m translating to a capacity of 18000 Litres of Water which can be adjusted corresponding to on-board payloads or even a pontoon puncture as cited by the reviewers.

Table 1: Powertrain Specifications

Specifications	Values
Battery Voltage	720 V
Motor Power Rating(without slope)	331000 W
Motor Power Rating(with slope)	457000 W
Motor Maximum Loading Capacity	75000 Kg
Total Loading on Vehicles	54000 Kg
Distance Covered in a day (3 Shifts)	75 Km
Max Speed on Land	12 Km/hr
Operational Hours per day/AAGV (3 Shifts)	24 hours
Working days in a year	315 days
Operating Hours in a year	7500 hours
Travel in a year	23625 Km

While the author and previous works did not dive into the control system aspect of the Amphibious AGV, the Amphibious AGV is envisioned to function both by itself and in a coordinated control manner akin to the vessel train formation (Chen

et al., 2019) and cooperative control (Chen et al., 2020). The subsequent part of this research in phase 4 will discuss the agent-based modelling implementation that links terminals, containers, and transporters such as barges and feeders) with the Amphibious AGV's schedule. This is linked with routing systems that direct the Amphibious AGV to the concerned berth on water/yard position on land. This will fully utilize the Amphibious AGV's capabilities while also trying to ensure that it runs full-load trips on both journeys in the port conditions.From a stability point of view, ballast tank water levels can potentially be managed by a Model Predictive Control system (Negenborn et al., 2009) that uses a cost function that minimizes instability by maintaining appropriate tank levels.

The Amphibious AAGV will use ramps to enter and exit container terminals. These ramps resemble roll-on/roll-off ramps used in car carriers and ferries. The Amphibious AGV has been designed to handle slopes of 3 degrees at peak speeds The optimum speed assumed for roll-on roll-off slopes is 9km/hr based on literature (Di Ilio et al., 2021). These will be passive ramps installed at quays of container terminals to enable a smooth transition between entry and exit of the Amphibious AGV. Depending on the quay heights, the ramps can vary in length. For instance, in the author's earlier(Abhishek Rajaram, 2023) work, when the Port of Rotterdam was considered a testing ground, the ramp was 95 m length x 5 m width at barge terminals. In comparison, deep sea terminals with higher quays (12m and above because of draught) had ramp dimensions of 270 m length x 5 m width. Both were at an inclination of 3 degrees slope. Other accessibility details also include a travel delay of 40-100 seconds. The pontoon takes 1.65 minutes to deflate and inflate and this is initiated on the way to the ramp(S.A.S, 2018). This accounted only in the form of a setup/verification time used to check if pontoons are fully inflated and at required pressure(10 PSI) Depending on the length of the ramp, it is expected that the AAGV will spend 1.5 min to 2.5 min on the ramp when taken on a triangular distribution (Park et al., 2023). These assumptions and calculations will also be a part of the phase 4 implementation and validation section. When implemented, the Amphibious AGV will reduce the rehandling point since it can link the yardside and quayside of container terminals with other terminals by accessing both land and water modes and transit via the ramp. This means that any container to be transported to a nearby terminal can merely be loaded from the yard/ship, then take the water route and enter the other terminal. This prevents the need for the truck+barge mechanism or even the longer route of inter-terminal transfer generally taken by trucks. An added aim of the Amphibious AGV is to prevent additional barge and truck fleets in the process, which can also make the chain more sustainable while complementing existing barge networks.

Phase 2 - Alternative Means of Terminal Expansion

With saturation in terminal handling space, it has become clear that alternate but sustainable sources of expansion are needed to complement current deep-sea terminals. One such solution is the floating terminal, which provides a lot of flexibility regarding its modularity and location. The floating terminal will essentially provide the ability to split the feeder and deep-sea vessel traffic. With constraints in space, a floating modular terminal becomes the only choice that can alleviate congestion while providing more growth opportunities for existing container terminals worldwide. The Amphibious AGV becomes a crucial element in the chain since it is the only vehicle capable of transferring short packages of containers between an on-shore and offshore entity. This is the intersection point where, previously a combination of AGV and barge would have been needed but is now possible with just an Amphibious AGV. While this comes at the cost of some small-vehicle congestion, dedicated route corridors in the future will make it possible for large container ships and barges to not be affected. This is also where a modular floating terminal is needed to handle a versatile set of vehicles. The factors that warranted the need for a novel floating terminal design are lack of yard space in existing ideas (Jovanova et al., 2022) and lack of flexibility and efficiency in terms of loading and unloading (Baird and Rother, 2013). In concepts such as the port feeder barge, there is an issue of operator compatibility with current deep sea terminal and hinterland operators. It is prudent to mention that this research also considered several other concepts, such as barge hubs to handle traffic (Pielage et al., 2007). Still, it was deemed problematic because despite having dedicated space for barges, the barge hub would lack flexibility, especially in terms of location. As seen in the state-of-art section, distance plays a huge role in setting up a barge hub which is not a problem in the case of a floating terminal which can be modular and built anywhere. This also makes the research future-proof. A floating terminal would also require fewer ground resources in terms of vehicles.

From the study of major container hub ports such as the Port of Rotterdam, Port of Antwerp, and Port of Hong Kong, deep sea terminals are primarily congested with not only barge traffic but also feeder traffic. In all three ports where feeders

occupy deep sea berths by default, a feeder requires about 2-3 quay cranes (Meulenkamp, 2023) to load and unload containers. This means that freeing up two feeder berths would free up 4-6 quay cranes, typically needed for a deep sea vessel (Evers and De Feijter, 2004). To maximize the output of existing deep-sea terminals, the authors believe it will be prudent to assign deep-sea terminals to handle only deep-sea ships while the external floating terminal handles both feeder ships and super barges along with the Amphibious AGV. The design of the floating terminal is presented in Figure 5. The proposed design of the floating terminal has a 1km long quay with a yard that is 80 m wide. The terminal houses 10 rail-mounted gantry cranes with simultaneous transfer and exchange capabilities on both sides. of the bridge and over-reach. The crane used is akin to those used between rail barges and yard-side equipment. Therefore, the specifications and handling capabilities are based on the Liebherr Rail mounted gantry crane (Liebherr, 2024). The cranes are also equipped with twin spreaders, which enable two containers to be loaded, unloaded and transferred across in one go given the lifting capacity of 65 tonnes. The berths for the floating terminal design can be configured in different ways. A sample has been presented in Figure 5. Three rail-mounted gantry cranes have been enabled for feeder/feeder-max vessels with capacities between 800-3000 TEU depending on size and destination. The presence of twin spreaders will speed up feeder ships' loading and unloading process. Three such feeder ships can be accommodated at once in the floating terminal. Super barges which were introduced in the last phase will use two such rail-mounted gantry cranes to load and unload containers (Meulenkamp, 2023). Three berths have also been assigned for the super barge. The remaining 5 empty slots in the floating terminal will be occupied by Amphibious AGVs as marked in Figure 5. The Amphibious AGV will represent the impactful link between the floating and deep sea terminals for hinterland-bound containers and inter-terminal transfer. Regarding other terminal features, the floating terminal is designed to function without any vehicles and automated stacker cranes. The overhead rail-mounted gantry cranes will serve both yards and vessels, each crane can handle 30-50 moves/hour when modelled on a triangular distribution (Bartošek and Marek, 2013). When this is taken over 350 days across 10 cranes, the terminal can handle up to a maximum of 4.2 million TEU year-round. If the twin spreader is considered, the RMG crane will be operated at minimum speed for safety. However, it can still output 5.04 million TEU at maximum theoretical capacity. Regarding yard space, it has been designed to stack containers 90 length-wise, 25 width-wise, and 6 height-wise to give a total container storage capacity of 13500 TEU at once.

Figure 5: The Floating Terminal Design Configuration

The floating terminal will be located close to the deep sea terminal to handle feeder and barge traffic. Feeder ships generally carry containers destined for both inter-terminal transport and hinterland. The deep sea ships which arrive at the respective deep sea terminals also carry a mix of hinterland-bound and inter-terminal-bound containers. Considering the modal split of major ports such as Rotterdam, Antwerp and Hong Kong (Gumuskaya et al., 2020; Marine Department, Hong Kong, 2022), it is estimated that 30% of all containers coming into ports are transported by barges through inland waterways while the remaining 70% are comprised of inter- terminal/export transshipment containers. The research in general is only concerned

about the 30% containers transferred through the inland waterways. Once transporters such as super barges, feeders and Amphibious AGVs arrive at the floating terminal, the containers are sorted based on destination after which they are directly transferred overhead to the relevant transporter which could be either of the aforementioned. This is why the transporters dock only at berths which are parallel to the transporter to which the container needs to be transferred. For instance, in Figure 5, from the left, we see that the feeder is parallel to two Amphibious AGVs on the first berth. It can be assumed that the container from the feeder has to be transferred to the Amphibious AGV. After the direct container transfer, the transporters leave for the concerned destinations: Amphibious AGV to the deep-sea terminal, super barge to inland ports and feeder departs to the home port.

Phase 3 - Addressing Low Call Sizes

A predominant reason for the barge congestion today is the extremely low call sizes barges currently resort to. As seen in literature (van der Horst et al., 2019; Shobayo and Van Hassel, 2019), call sizes at deep sea terminals currently range from as low as 6 TEU to 48 TEU with an average of 33 TEU. The irregularities in call size result in less efficient use of berth space and time since many vessels with higher call sizes might be in the queue. This also includes deep-sea vessels despite priority for deep-sea vessels. This would put forth a case for higher call sizes and experience from Antwerp, urging barge operators to follow a standard minimum. Still, higher call sizes have yielded good results, with barge calls falling by 40%, decreasing congestion at DP World Antwerp Gateway (Buitendijk, 2019). Analysing the prevalence of common destinations in major waterways such as the Rhine Delta (Konings, 2007) and the Pearl River Delta, it makes more sense to have higher call sizes per barge trip to ensure lesser congestion along these waterways. These would be transported to the major inland ports. But the absence of such transporters thus far has made it hard to carry higher amounts of containers. However, a sustainable container ship concept has emerged in the form of COSCO's electric ship, which was introduced in 2023. This electric vessel has a total container capacity of 700 TEU currently plying across the waterways of the 1000km long Yangtze river (Lepic, 2023). This inland vessel is 119.8 m long and 23 m wide, falling in between the large Rhine Class Va and large Rhine Class Vb in terms of dimensions, implying that this vessel will fit within existing barge berth dimensions while having a notably higher capacity than current barges (Program, 2019). This vessel has a dead weight of 10,000 tonnes and is powered by two 900 kW propulsion engines. This electric ship has 36 portable container-sized batteries that hold a capacity of 50,000 kWh and are replaced accordingly at various ports of call along the inland waterways. This research will use this inland vessel concept and henceforth refer to it as "Super Barge" owing to its higher overall capacity. The call sizes for this super barge are set at 400-700 TEU, which is approximately 10 times higher than current call sizes. These again will be shipped to the main ports along the inland waterways, which can be distributed to destinations by truck or smaller barges. This would essentially reduce the congestion of barges at the main deep-sea terminal with the denser capacity configurations of 400-700 TEU. The COSCO electric container ship/Super Barge is also sustainable with projected CO_2 reductions of 32 metric Tonnes per 24 hours of operation (Lepic, 2023).

Phase 4 - Transport Network Systems Design

The methodology's final phase involves redesigning the transport systems network and a means to simulate and implement the networks as depicted in Figure 6. For this, an agent-based modelling is used. The predominant reason for this choice is that this simulation allows major entities in the system to have autonomy while interacting with other major entities. Discrete event simulation is a sequential simulation process which has also been often used for modelling container terminal operations. However, simulation process elements such as simultaneous berth planning and export/import container management warrant parallel processing, which can only be accomplished by agent-based modelling. This also allows for hierarchy in the system. But most importantly agent-based modelling opens up many research opportunities in integrated control for the future given its prevalence. The agent-based modelling system categorises all major elements into three agents: i) Ports and Terminals, ii) Containers, and iii) Transporters. These elements will possess their function besides the interaction with the other agents. To better understand these agents, they can either be a single agent (like a standalone container terminal) or a population of agents (like trucks, ships, or even multiple hinterland terminals). These will be mentioned below.
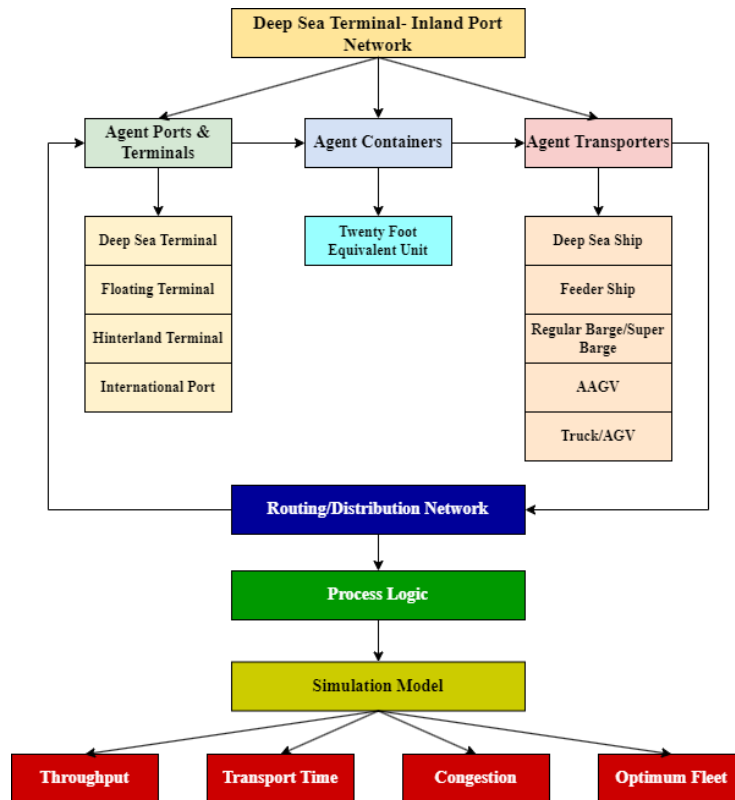
Figure 6: The agent-based modelling simulation of the deep sea terminal and inland network

1. **Agent Ports and Terminals**: this agent comprises international ports, deep sea terminals, floating terminals, and hinterland terminals. Depending on import, or export, this agent serves as the origin, destination or transit/transshipment hub for all containers in the system. Except for hinterland/inland ports, all the other terminals function as single agents. The international ports feature terminals themselves but will be classified as a single agent in this research. These are the origin points for containers in the system and they are picked by feeders and deep-sea ships. Deep sea terminals are intermediary points that function as transshipment hubs. They are a single agent and receive deep sea ships and feeders with containers. Hinterland terminals or ports are the final destination of these containers. In this research hinterland ports have been considered across various locations hence they function as a population of agents. The floating terminal is also a single agent and the new addition to the redesigned transshipment network. The floating terminal agent is also an intermediary transshipment hub complementing the deep sea terminal and handles transporters such as feeders, Amphibious AGVs, and super barges.

2. **Agent Containers**: these are a population of agents that originate from international ports and terminate at inland ports. This research considers standard twenty-foot equivalent units for classification and calculation purposes.

3. **Agent Transporters**: transporters refer to carriers of containers between various ports and terminals. Under this agent, existing concepts such as deep sea ships, feeders, barges, and trucks and the Amphibious AGV concept will form a crucial part of the proposed transshipment networks. All transporters are the population of agents. The Deep Sea Ships form the starting point of the entire process. These are considered vessels with a capacity of 3000 TEU and more, with the biggest capable of carrying 24000 TEU. Generally, they have a draught of 14m or more, hence the name deep sea. Deep sea Ships are also those ships that travel predominantly between major transhipment hub ports owing to the magnitude of containers they handle. They therefore require 6 quay cranes to unload containers (Bartošek and Marek, 2013). The second major actor responsible for bringing in containers are feeder/feedermax ships which have capacities in the range of 800-3000 TEU and travel to both hub ports and inland ports given their draught is less than 14m(Ogunsola, 2022).In most inland and deep sea terminals, barges arriving usually have call sizes ranging between 12 and 50 TEU with an average of 33 TEU(van der Horst et al, 2019). This research considers the upper bound of

50 TEU as the call size, and these are referred to as regular barges in this work henceforth. One of the gaps identified in the literature was the congestion consequences of using small container call sizes while transporting from deep sea terminals to the hinterland. The Super Barge is therefore an exploratory barge concept that addresses barge congestion by carrying larger call sizes of containers from deep-sea terminals to the hinterland. This concept is akin to the 700 TEU capacity electric container ship employed by COSCO in the waterways of Shanghai(Mandra, 2023). This research considers the call sizes from 400-700 TEU per barge trip. The Amphibious AGV envisaged to reduce the rehandling of containers forms the final piece of the puzzle, having the capability to travel on both land and water (Ghiridharan, 2023; Eijk et al, 2023). The Amphibious AGV will replace trucks/AGVs which are also modelled as the population of agents.

This multi-agent network of the aforementioned agents helps define the container transport environment from the international port to the deep sea terminals to the hinterland. This network is then paired with a routing and distribution network which distributes containers as a function of distance, which implies that the closer the destination is, the higher the number of trips to that destination and hence the higher container throughput. A process logic is then used to link all the agents and the routing networks. The process logic defines the container loading, unloading, and transfer sequence to subsequent destinations. This repeated throughout multiple change points. For instance, the benchmark involves entities like international ports, deep-sea terminals, and hinterland terminals therefore this process of loading, unloading, and transfer is seen in all the entities. This is then fed to a simulation model which processes the system's key performance indicators: congestion, container throughput, container transfer time and fleet trade-off. While the first three KPIs directly result from the agent-based modelling simulation, the fleet optimization is done with the help of a genetic algorithm (Yang et al, 2023) that works on the parameters, the objective and constraints shown in Table 2. This optimization aims to find the optimum transporter fleet size for the given utilization, which is set at 85%, considered a standard in literature for container equipment (Koo et al, 2004).

Table 2: Optimization Parameter, Variables, and Constraints

Objective	Maximize Utilization, U
Variables	
Total Transporters	$N = [1, \infty)$
Transporters Used	$T = [1, \infty)$
Utilization, U	T/N
Parameter	
Container Agent	Parameter as in ABM
Transporter Agent	Parameter as in ABM
Terminals Agent	Parameters as in ABM
Constraints	
Utilization	T/N <0.85
Total Transporters	N>0
Transporters Used	T>0
Output	
Transporters Used	Optimum T

This agent-based modelling implementation will now be applied to the current transshipment scenario, or the benchmark network design. Subsequently, the new transshipment scenario will also use this agent-based modelling methodology. The benchmark and new transshipment chain results will be compared to see if maritime congestion has been reduced.

Benchmark Network Design

The current transshipment network design is a hub and spoke design that has been followed for a substantial period of container shipping history (Langen and Van der Horst, 2008). An overview of the network with the concerned transporters, ports and terminals, and most importantly the interaction between the entities is shown in Figure 7. To summarise the agents, the

transporter agents involve the deep sea ship, feeders and container trucks. The ports and terminal agents involve international ports(example- Port Klang, Malaysia), deep sea terminals (example- Port of Hong Kong) and hinterland ports(example- the Pearl River Delta ports). Feeders/Feedermax (800-3000 TEU) and Deep Sea Ships(3000-24000 TEU) bring containers from international ports to deep-sea terminals in the home country. Deep sea ships and feeder ships bring in call sizes on an average of 2000 TEU and 1000 TEU per port, respectively (Shobayo and Van Hassel, 2019). These feeders and deep sea ships dock at the deep sea berths and unload their containers via quay cranes, after which they are sorted for inter-terminal transfer and hinterland-bound containers. The hinterland-bound containers are loaded onto container trucks, which transport the container to the barge berths at the deep sea terminal. This translates to ground congestion of trucks and waiting congestion of barges at berths in deep-sea terminals. The containers from trucks are subsequently loaded to regular barges via barge cranes. For the benchmark per current operation, the average call size of each barge is set at 50 TEU (Seatrade Maritime News, 2015; van der Horst et al., 2019). The barges then transport these containers to inland ports/terminals. A few details to be noted here are that in port waters and till the inland, barge speeds are set at 13 km/hr (Centre, 2014), the operational truck speed is set at 20 km/hr (Duisburg, 2018) with 30-50 moves/hour assumed for quay/barge cranes (Bartošek and Marek, 2013).
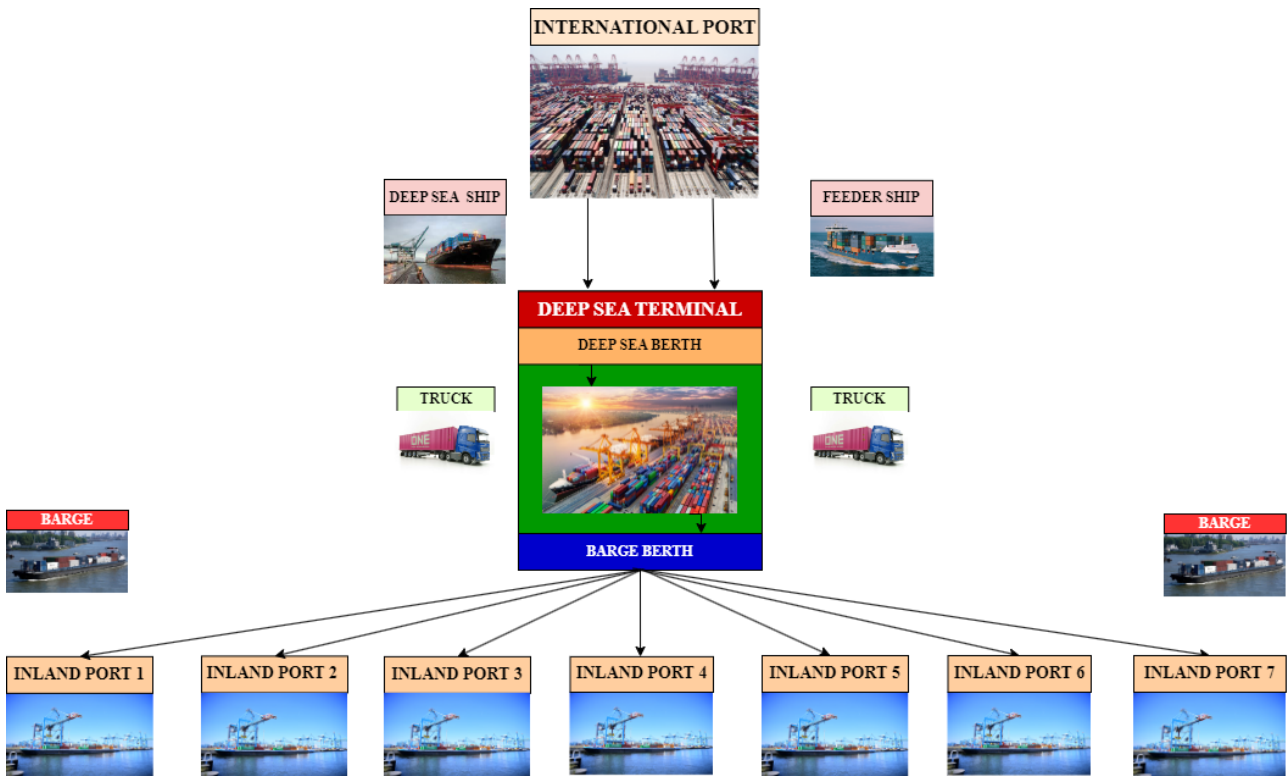

Figure 7: Current Transshipment Network- Benchmark

The New Transshipment Chain Solution

The new transshipment chain solution is also a hub and spoke approach implemented with the same agent-based modelling methodology as done for the benchmark. An overview of the network with respective transporters, ports, and terminals and their interaction is presented in Figure 8. For this network, the transporter agents involve deep sea ships, feeder ships, super barges, and amphibious AGVs. The ports and terminal agents involve international ports, deep sea terminals, floating terminals and hinterland ports. The process for the new transshipment scenario varies from the benchmark, especially concerning transporter and terminal interaction. As in the current scenario, both feeders and deep sea ships are loaded with containers from international ports (for example, Port Klang, Malaysia). However, after this, the process differs. To shift feeder traffic from deep sea terminals, the feeders from the international port dock at the floating terminal while the deep sea ships directly

dock at the deep sea terminal. The Amphibious AGVs now spring into action. The hinterland-bound containers present in the deep sea ship are transported from the deep sea terminal to the floating terminal via the Amphibious AGVs. The feeder docked currently at the floating terminal has a mix of hinterland-bound and inter-terminal transfer containers. The hinterland-bound containers stay at the floating terminal while the Amphibious AGVs take back the inter-terminal-bound containers on their return journey to the deep sea terminal. Upon their return, the Amphibious AGVs take inter-terminal containers to the relevant deep-sea berth or transfer them back to the yard. The hinterland-bound containers in the floating terminal are directly transferred to super barges that also dock at the floating terminal. These super barges take in call sizes of 400-700 TEU and transport them to hinterland ports (for example- Pearl River Delta ports). A subtle difference that is readily noticeable is the fact that in this new method, the Amphibious AGVs will have full load on most of the journeys to the floating terminal and the return back to the deep sea terminal. In the benchmark, this is a problem because trucks are guaranteed to be full only one way of the journey (during berth transfer). The Amphibious AGV's speed will be set at 12 km/hr, while the other parameters remain the same as the benchmark.
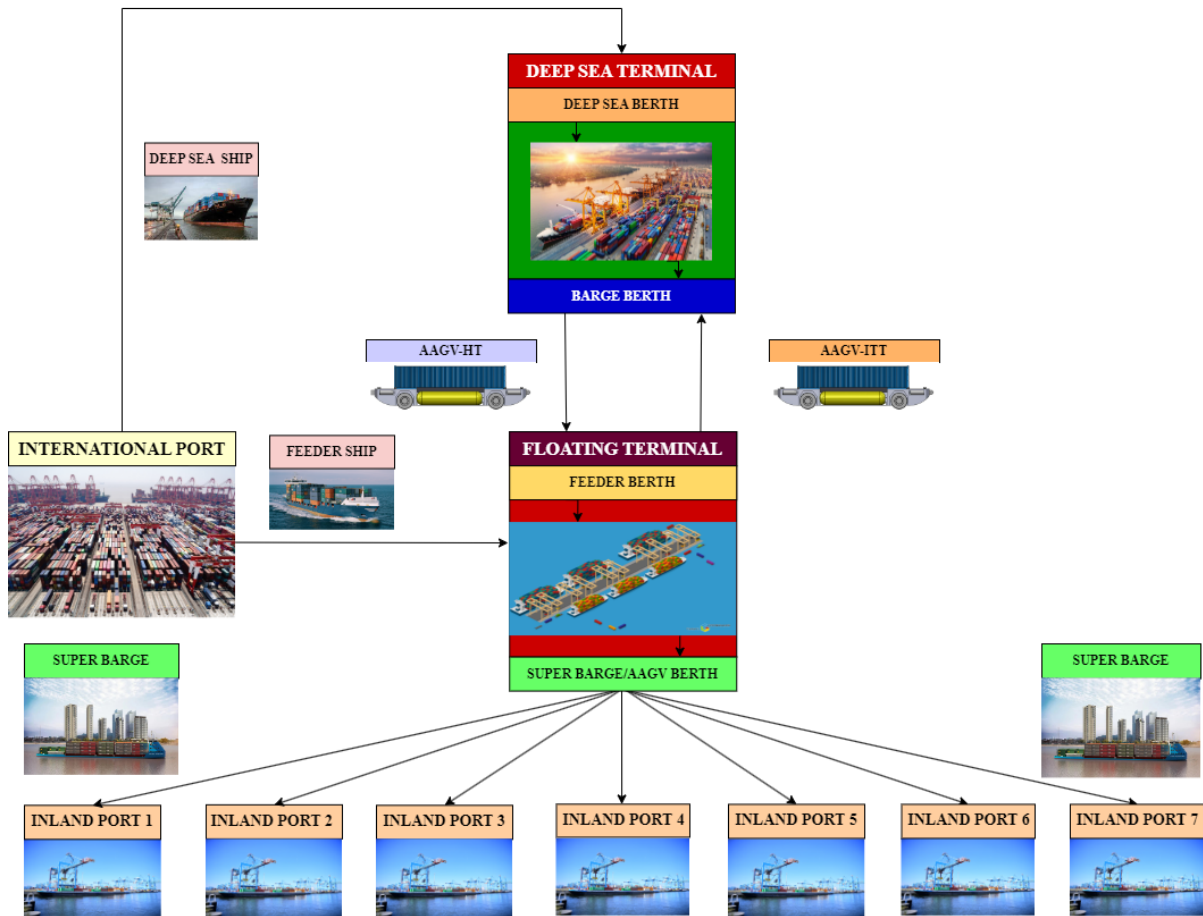

Figure 8: The New Transshipment Chain Solution

CASE STUDY

A case study is performed on the Port of Hong Kong and the hinterland of China's Pearl River Delta to validate the proposed transshipment network and simulate its performance. The Pearl River Delta is one of the largest inland waterway networks in the world, with an extensive range of industries from electronics and garments to plastics flanking the banks of the waterway. Due to this industrial productivity and the presence of multiple clusters of tech parks, the Pearl River Delta is also known as the world's factory or more recently the world's design studio of the world (Fuller, 2017). In terms of economic value,

the Pearl River Delta has a GDP of \$1.2 Trillion forming 10% of China's GDP despite accounting for only 1% of China's territory. Of the 14000 Km stretch, 5000 km connects the southwest region through the extensive inland waterway network of barges (Wang and Li, 2012). The main trans-shipment ports here are Hong Kong, Guangzhou, and Shenzhen. Hong Kong stands out as a vital trans-shipment hub due to its robust connections with ports southward, including Port Klang in Malaysia and the Port of Singapore, and northward to the Port of Busan in South Korea and the Port of Taiwan. The Pearl River Delta, comprising nine major cities, contributes 18% to the nation's output and forms 73% of Hong Kong's inward trans-shipment. Despite a drop in Inland Waterway Transport (IWT) from 26% to 5% during 1980-2000, barge transport has rebounded, now holding 10% of the market. Calls for expansion in barge handling and trans-shipment services are increasing, driven by rising demand and sustainability needs, alongside local pressure to address the housing crisis. Recently, this crisis has threatened to close down a part of Kwai Tsing Terminals to build settlements (Chong and Li, 2020). This is where new transshipment solutions can help.

Figure 9: The Pearl River Delta (We Build Value, 2017)   **Figure 10:** Floating Terminal & Berths (Google, 2024)

Hong Kong Ports

The Hong Kong port is located in the South China Sea and comprises a river and deep water ports. The deep water port, commonly known as the Kwai Tsing Terminals, receives an average of 36000 TEU Per Day (Marine Department, Hong Kong, 2022). There are a total of 9 container terminals that are capable of handling 24 million TEU annually. Due to the COVID-19 pandemic, traffic at Hong Kong port declined to 12.869 million TEU in 2022 (Marine Department, Hong Kong, 2022). For this research, HIT and HIT-COSCO terminals with an annual throughput of 8.03 million TEU will be considered. They operate Container Terminal 9S(Left of image, berth in green), and Container Terminals 4, 6, 7 and 8 which are all marked in green in Figure 10. These also represent the 7 deep sea berths. The barge berths spread across terminals 4 and 6 are shown in red. Terminals 4 and 6 combined house 9 such barge berths (Hutchison Ports Trust, 2023). HIT and COSCO handled a peak of almost 6500 TEU per day in 2016, with 120 barges making footfall daily (Seatrade Maritime News, 2015). Looking at the current split between trans-shipment and PRD containers, the HIT-COSCO terminals receive 22000 TEU from international ports such as Singapore, Port Klang, Port of Busan and also from the west such as Colombo, Rotterdam and Port of Los Angeles (Bu et al., 2023; Marine Department, Hong Kong, 2022). This corroborates with the 70-30 split as derived in Phase 2. This translates to 6500 TEU headed to the Pearl River Delta and 15,500 TEU headed to other international ports. Apart from the 120 barges that make footfall, 15-18 (average -17) vessels dock at the deep sea berths daily. These mix feeder/feeder max vessels, panamax and ultra-large container ships (ULCS). The floating terminal is located in the region marked in yellow. This will use the large-scale floating terminal design (Figure 5), which has a 1 km quay with a theoretical

handling capacity of 2.52 million - 4.2 million TEU annually (5.04 million TEU with twin spreader). The berth configurations will be exactly used as shown in Figure 10. Among the 17 ships that dock at HIT-COSCO for benchmark case, 11 are feeder or feedermax vessels. The feeder/feeder max vessel traffic can be shifted to the floating terminal by the new transshipment chain methodology. Three RMG cranes per feeder max vessel will be used to unload and load containers. Owing to the length of these ships, realistically 3 feedermax ships (marked in pale pink in Figure 10), 3 Super Barges(marked in orange) and 5 Amphibious AGVs (marked in blue) can be accommodated at once in the floating terminal. It is also important to mention that despite the presence of the floating terminal, it will always be the deep sea terminal with the higher annual throughput. This is done to retain its competitiveness. Therefore the split of 22000 TEU between deep-sea terminals and floating terminals are tested in two configurations. The first is (14000 TEU at HIT-COSCO and 8000 TEU at the Floating Terminal) and second configuration is (12000 TEU at HIT-COSCO and 10000 TEU at the Floating Terminal).

Inland Ports in Pearl River Delta

The Pearl River Delta has 2000 inland ports within the region. Seven major import and export inland ports have been chosen for this research: Sanshui, Foshan, Jiangmeng, Shekou, Yantian, Zhongshan, and Humen. The ports are shown in Figure 9. These are ports quite prominent in the automotive, electronics and manufacturing industries given that Shenzhen and the Pearl River Delta region are hubs for mobile and communications OEMs. Currently, barges with call sizes of 50 TEU carry consignments from the Port of Hong Kong to the Pearl River Delta. This will be simulated in the benchmark network analysis. It is envisioned that when the new transshipment chain solution is employed, super barges will carry call sizes ranging from 400-700 TEU to the ports in the Pearl River Delta. The barges in the benchmark will depart from the barge berths marked in red from the HIT-COSCO deep sea terminals. Similarly, super barges will depart from the floating terminal to the Pearl River Delta for the new transshipment chain. The AAGVs will rotate between the deep sea and floating terminals, transporting containers for hinterland and other terminal transfers.

RESULTS

The Hong Kong-Pearl River Delta simulation presented a very intriguing set of results. The results are presented in Figure 11. The benchmark case from the simulation records 121 barges docking in at Hong Kong's HIT-COSCO terminal to transport 6500 TEU to the Pearl River Delta. This information corroborates with the terminal data of 120 barges a day (Seatrade Maritime News, 2015). As anticipated this causes an average congestion of 13 barges per berth per day which is disadvantageous given that the HIT-COSCO terminal is forced to use 2 barge quay cranes to unload barges when usually only one quay crane is used. When we shift the focus to the new transshipment scenario, it becomes clear that in both configurations of container split, there is a congestion of only 14 super barges per day. This is a direct result of the difference in call sizes of the respective barges. In the benchmark, the regular barges load or unload call sizes are 50 TEU, while the super barges in the new transshipment scenario take anywhere between 400-700 TEU (consider an average of 550 TEU) per barge trip. This makes it easier to have only two super barges visit each of the major ports in the Pearl River Delta daily instead of having up to 20 separate regular barges visit the hinterland ports in the benchmark case. This work also considered ground congestion as an important metric, and here it can be seen that in the benchmark, there are about 1788 daily truck visits to the berths to deliver containers to and from barge berths to/from deep sea berths/container yard compared to the 2104 and 2511 Amphibious AGV visits to the floating terminal. When the Amphibious AGV congestion is compared, it is clear that the Amphibious AGV has a higher frequency of visits given that it has to transport containers not only to the floating terminal but also on the return journey back to the deep sea terminal or the container yard. This also implies that the Amphibious AGV runs full load on at least 50% - 75% of the journeys (50% in the 12000 DST:10000 FT case, 75% in the 14000 DST:8000 FT case). This is not the case for trucks which run full on only one leg of the journey while transporting containers from the deep sea berths to barge berths. The trade-off is that the Amphibious AGV offers more productivity at the cost of slightly more added congestion. Furthermore, it must be realised that the Amphibious AGV is trying to replace the functions usually done in combination with a barge and a truck. When we analyse the fleet of both the benchmark and the new transshipment scenario in a graph 11, the fleet size of the new solution is 53% lower than the benchmark comprising 14 super barges and 70 AAGVs. This contrasts with the 126 regular barges and 54 trucks in the current solution. A large maritime fleet size and congestion scale have been reduced

by about 80%. The Amphibious AGVs have a larger fleet size than trucks but complete much longer round trip journeys (9km) than an average 2km back and forth berth transfer journey. This makes the Amphibious AGV more competitive per kilometre compared to trucks and justifies the increase in fleet. Also, to reiterate the Amphibous AGV is essentially covering for functions of both the truck and the regular barge. The new transhipment solution also has advantages when it comes to transporting containers to the hinterland. The benchmark posts a transfer rate of 2247 TEU/day to the Pearl River Delta while the new transshipment solution sees a marked 27%-30% improvement in throughput rate (2869 and 2953 TEU/Day) for both configurations. Complementing the throughput rate, the hinterland transport time also sees a 21%-23% improvement in the overall time recorded to move containers to the Pearl River Delta. While both the Amphibious AGV and super barge leg raised advantages over the conventional truck and regular barge, it was noticed that the biggest difference came in the AAGV transfer times which were 30% faster than that of trucks which transfer between deep sea and barge berths. This justifies the increase in the fleet of Amphibious AGVs over trucks. There were also marginal improvements in super barge transfer times compared to regular barges. One positive knock-on effect of implementing the new transshipment solution is that it frees substantial berth space. Since the floating terminal uses three cranes to unload a feeder/feeder max ship, at least 6 feeders can be accommodated over a day. This would essentially free space for two ultra-large container ship berths (18000+ TEU) requiring 6+ quay cranes. This translates to potentially handling 730 new ultra-large deep-sea ships year-round. The opportunities however do not end there. The barge berths at HIT-COSCO originally present in the benchmark also stand unused thanks to the new transshipment solution. These berths can also be repurposed to occupy feeder ships or a Panamax ship (5000TEU) (Ogunsola, 2022). This would mean that potentially 2 ultra-large container ship berths and 3 feeder berths have been identified as possibilities for expansion within HIT-COSCO's existing canvas. If all berths are used at full capacity as mentioned it would push up HIT-COSCO's handling capacity from the current 8.03 million TEU to 12.41 million TEU which represents a 54% increase in container handling capabilities. This makes the solution future-proof. The results also provided other crucial insights that have not been directly depicted in the graph. A pattern noticed here is that Amphibious AGVs become more effective when demand is higher. In the 14000-8000 case, maximum one-way demand is 5560 TEU (4270 TEU on way back) while in 12000-10000 case the max one-way demand is 6950 TEU (3660 TEU on way back). The AAGV performs the best in the latter. The super barges are used with call sizes from 400-700 TEU. Large call sizes can often be very uncertain owing to common delays that occur at points of origin. Therefore, this research deemed it important to experiment with call sizes for super barges ranging from 400-700 TEU. A short graphical analysis was done to find the optimum point for throughput, call size and congestion and here, a maximum throughput of 2927 TEU/Day was obtained at a congestion of 12 barges a day and a call size of around 600 TEU. For context, this result falls within the range seen in the average results for throughput (2869-2953 TEU/Day) and similar congestion for barges (12 v 14 a day). Similarly, when simulations with 400 TEU call sizes were done, a congestion of 17 barges a day was obtained.
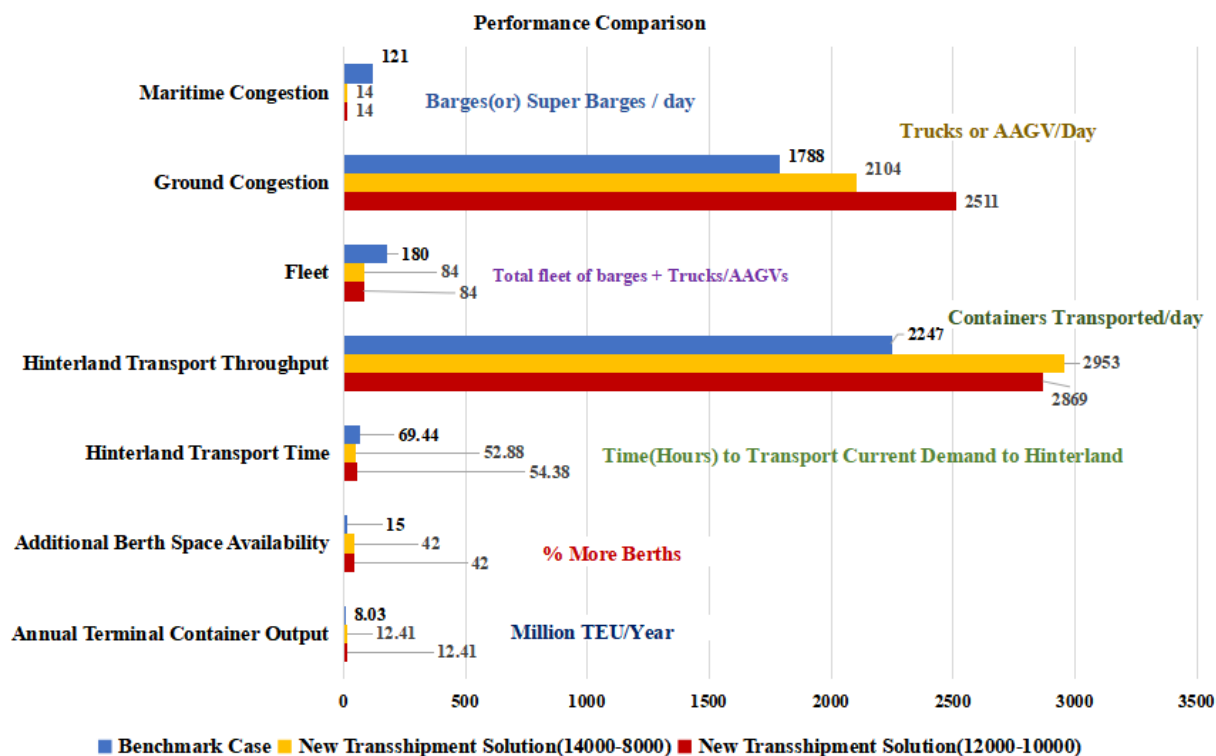
Figure 11: Performance Comparison

CONCLUSIONS

Trans-shipment forms a significant part of the services sector today and enables greater accessibility of industries and businesses located deep inside a country. This is also supported by the fact that the maritime industry takes care of 80% of the international trade volume. With increased trade, bigger ships, limited expansion space for ports, and growing congestion, there is an urgent need to develop future-proof solutions. Therefore this research was initiated to formulate new design and network solutions for the container shipping industry to facilitate efficient deep-sea to hinterland trans-shipment. A breakthrough in this research was introducing and using an Amphibious AGV for inter-terminal transportation. Being a 2 TEU vehicle, the Amphibious AGV provides the capacity of regular AGVs and trucks while providing the flexibility to travel on both land and water. This research also investigated the effectiveness of modular floating terminals as an alternate means of expansion, given the unsustainability of land reclamation. The author proposed a novel terminal design with a capacity of 4.2 million TEU annually. The design proposed a direct over-the-head instant transfer of containers from one transporter to the other, saving yard space and waiting time. To validate the problems faced today in trans-shipment, the Port of Hong Kong and the hinterland ports of the Pearl River Delta were chosen as the ground for the simulation. Using an agent-based modelling simulation on AnyLogic, it was clear that congestion was a serious issue with nearly 120 barges making footfall at HIT-COSCO terminals in Hong Kong, competing for just 9 berths. Essentially these barges were still using quay cranes generally used for deep-sea ships. This represented problems of congestion, saturation in handling capabilities, and other problems such as acute berth planning issues and quay crane allocation. With these constraints in mind, a new trans-shipment network solution involving the Amphibious AGV and the floating terminal was developed to boost handling capabilities by 50% as well as show how instrumental concepts like Amphibious AGV are in enhancing inter-terminal and hinterland transport. A salient feature of this new proposed network was also the use of a Super Barge, which took on higher container call sizes per trip to the tune of 400-700 TEU to reduce overall barge congestion by 80%. Under the new network, the feeder traffic was shifted from deep sea terminals to floating terminals enabling the berths to be occupied by extra deep sea ships. The simulations showed a container throughput increase from the current 8 million TEU to 12.41 million TEU when changes

were implemented. The takeaway from this research is that novel design solutions can indeed be found to address the current growth crisis. From a fleet transportation design perspective, novel network approaches have been implemented to address shortcomings of the status quo. Amphibious AGVs and floating terminals can potentially deliver more applications, such as liquid and dry bulk commodities. Amphibious AGVs were also envisioned to be sustainable and powertrain control is at the forefront with amphibious powertrains being relatively new. On a business level, Amphibious AGVs also have the potential to be effective for small and micro industries located on the hinterland and call for its investigation. The authors also believe that in the coming years, this work will be critically looked at to encourage impactful concepts like Amphibious AGVs and floating terminals to be introduced for the benefit of hinterland transportation that could eventually lower the prices of commodities that we use every day. From a design perspective, this work has proposed a preliminary concept that shows the potential of such an Amphibious AGV contraption is possible within a similar as canvas regular ground container AGVs. Future studies can move in the direction of certifying its stability and interaction with other equipment in the port.

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