Appendix A

Amphibious AGV

This Appendix contains the report of the project "Amphibious Hive-Minded AGV", which was developed as a part of a mandatory requirement for the course "ME44110: Integrated Design Project for Multi-Machine Systems" handled by Dr. Jovana Jovanova & Ir. Wouter van den Bos at TU Delft. The project titled "Amphibious Hive-Minded AGV" was authored by Quincy Colsen, Vijit Samuel Datta, Casper van Eijk, Vijay Sathya Ghiridharan, Benjamin Groenhart, Jouke Hompes, Abhishek Rajaram and Suryaa Vadachennimalai Selvaraj [11].

Report starts from the next page.

Amphibious Hive-Minded AGV

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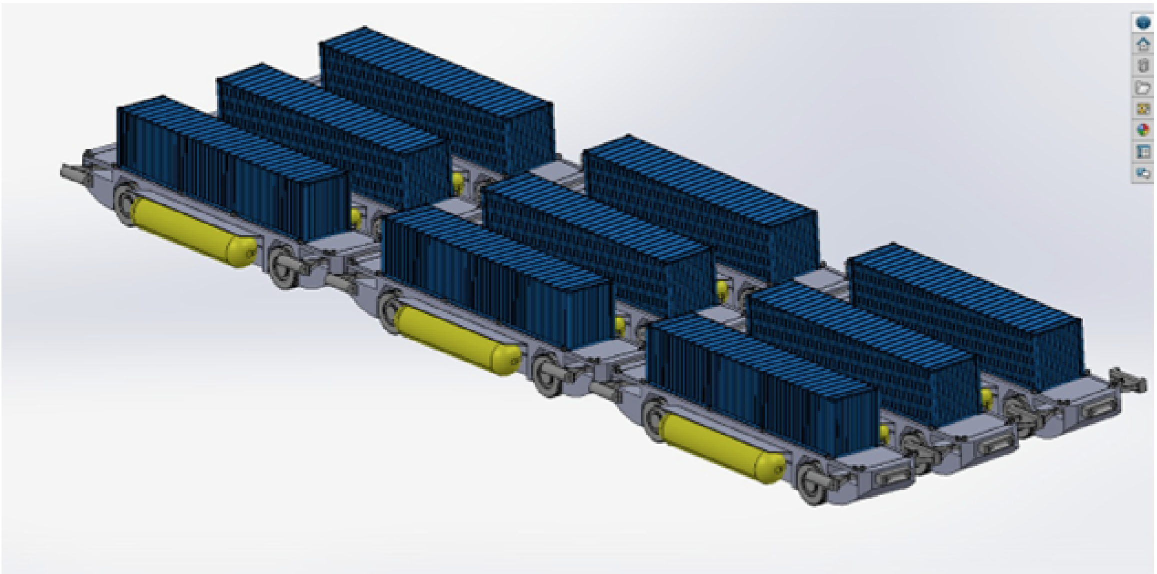

Abstract

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

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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

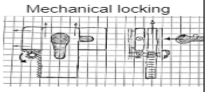
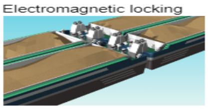
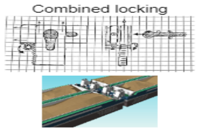
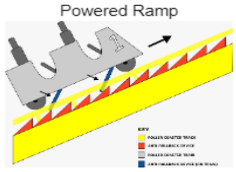
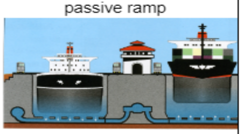
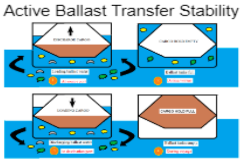
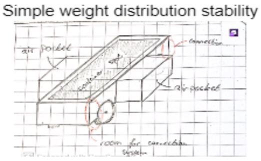
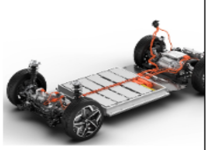
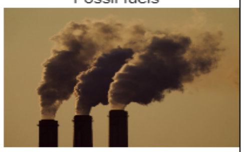
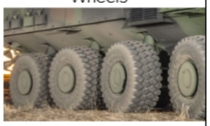
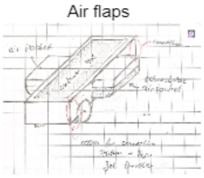
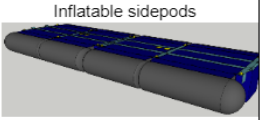
The requirements stated in the previous part demand a number of different subsystems. First of all, the AGV will be amphibious and thus will have to be able to traverse in water. Some form of propulsion for this is needed as the land traversing system will not be sufficient. Secondly, the system should 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.

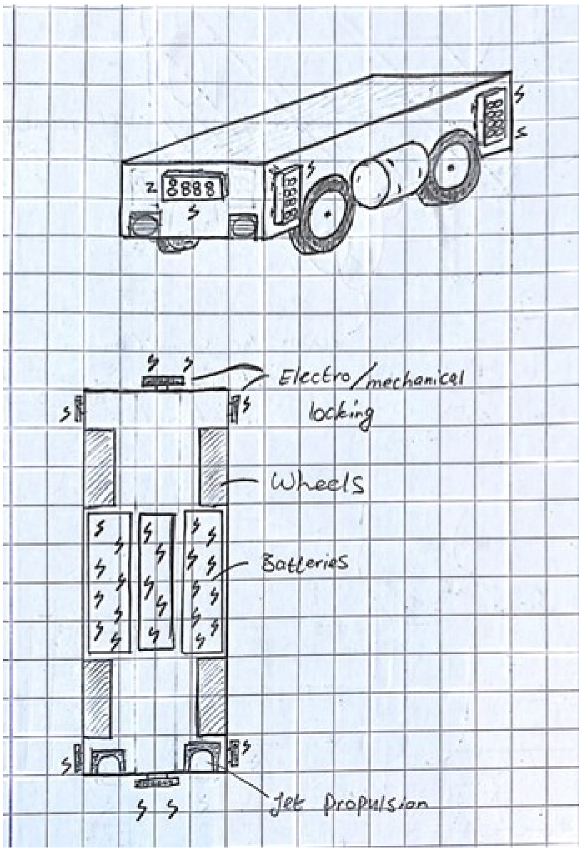


Figure 1: Concept 1

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.

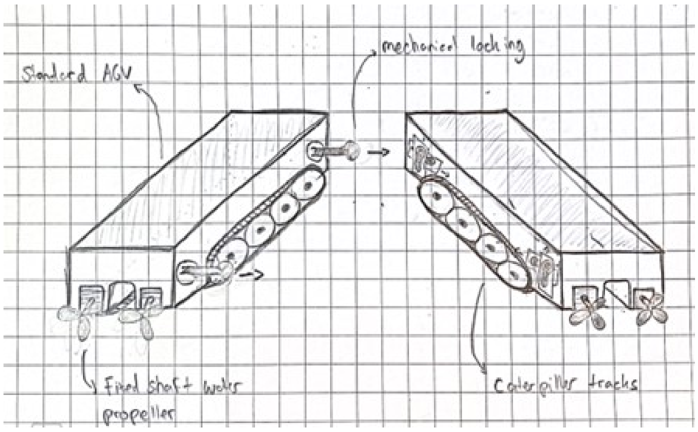


Figure 2: Concept 2

Concept 3

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

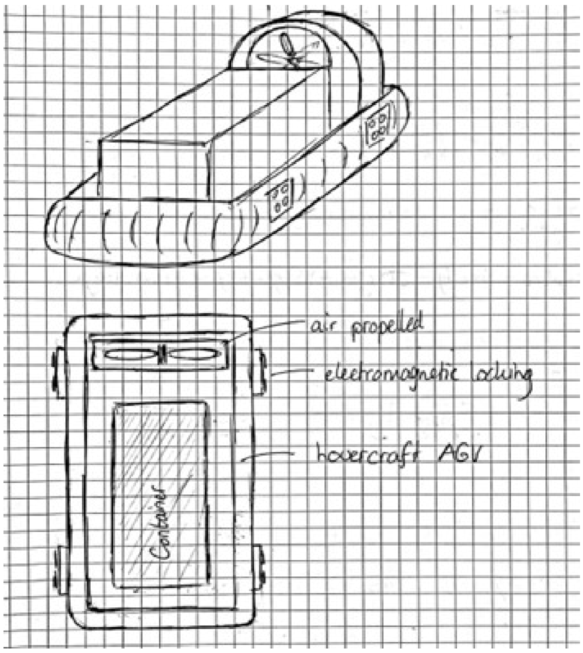


Figure 3: Concept 3

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.

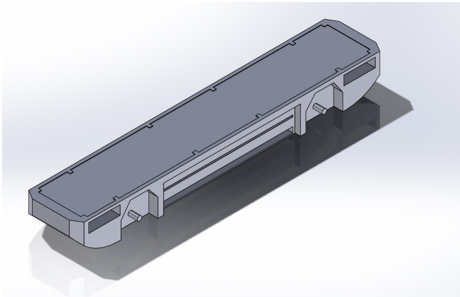


Figure 4: AAGV body outside

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.

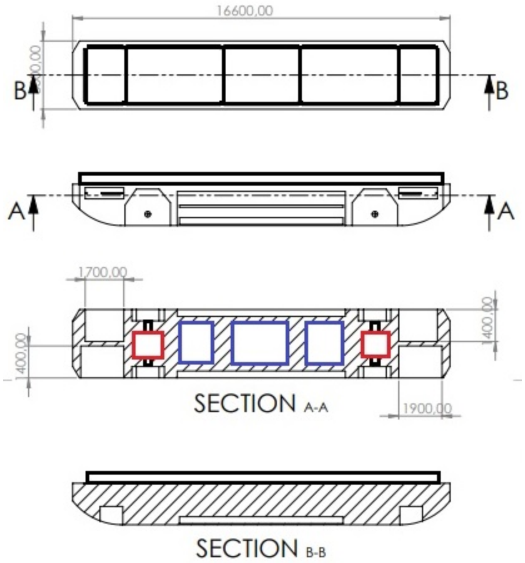


Figure 5: AAGV body inside

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

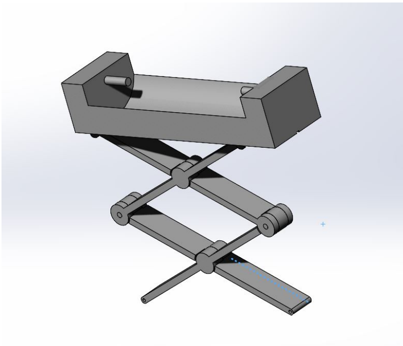


Figure 7: Female part

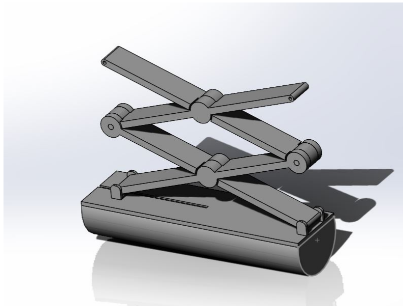


Figure 8: Male part

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.

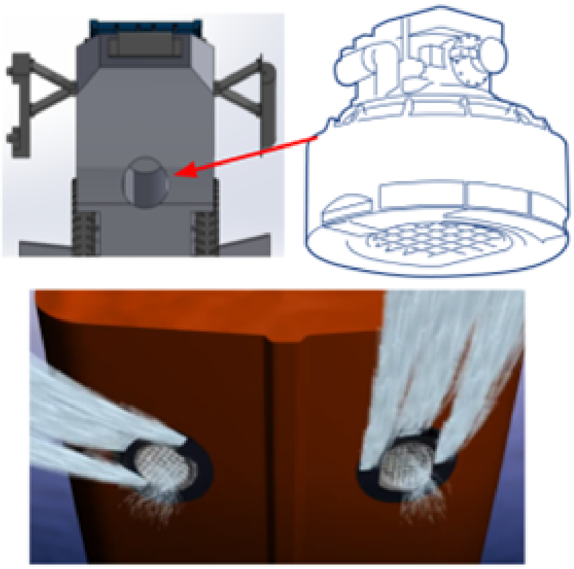


Figure 9: Jet pump

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.

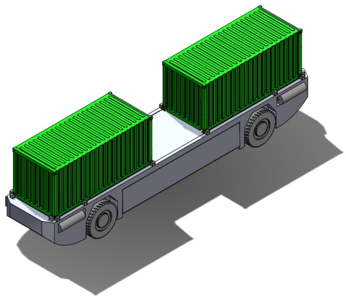


Figure 10: Isometric

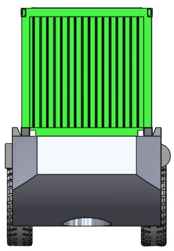


Figure 11: Front

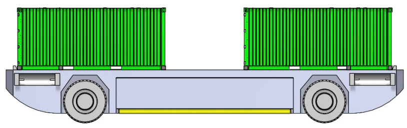


Figure 12: Side

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.

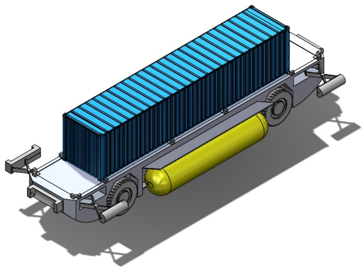


Figure 13: Isometric

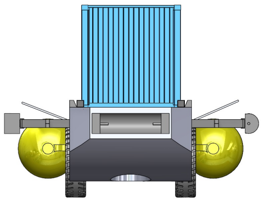


Figure 14: Front

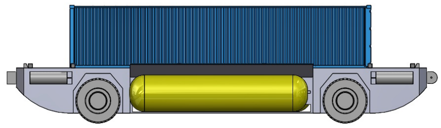


Figure 15: Side

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.

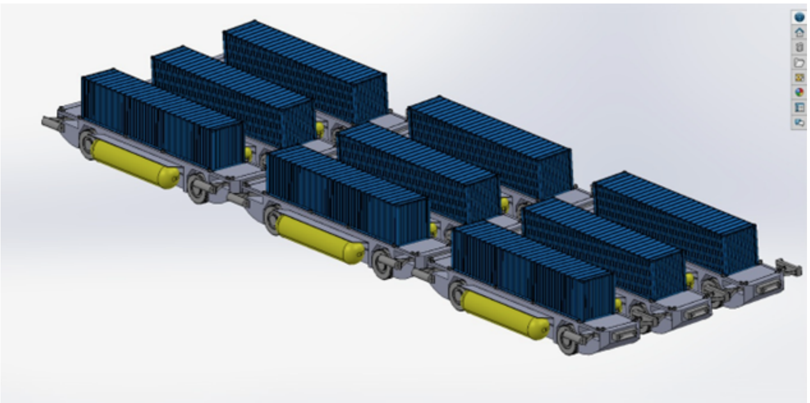


Figure 16: AAGV grid formation

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.

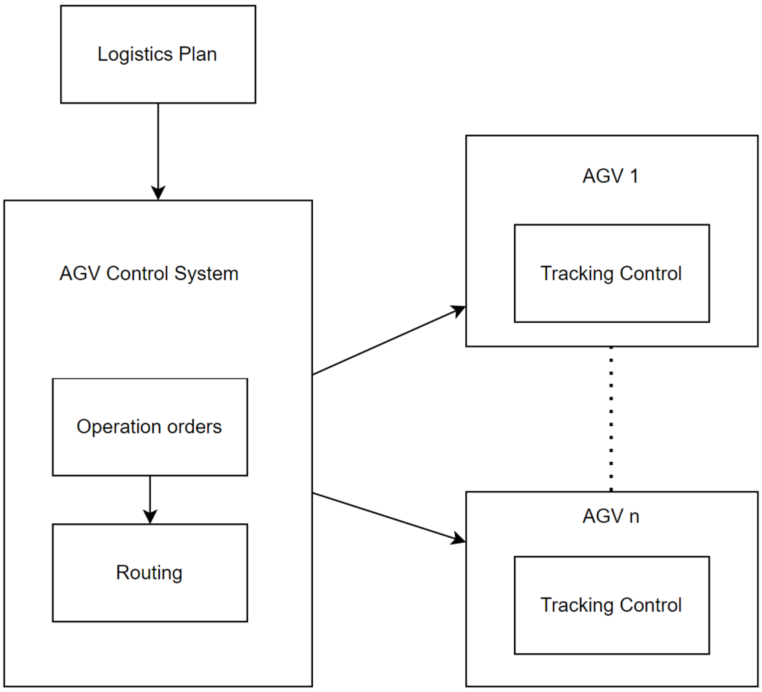


Figure 17: Control system architecture

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

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

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

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

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

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

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

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

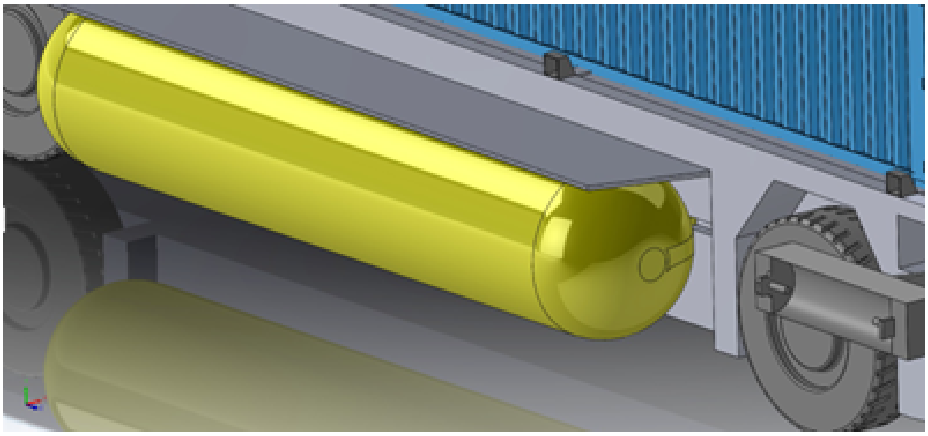


Figure 18: Air pocket

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]

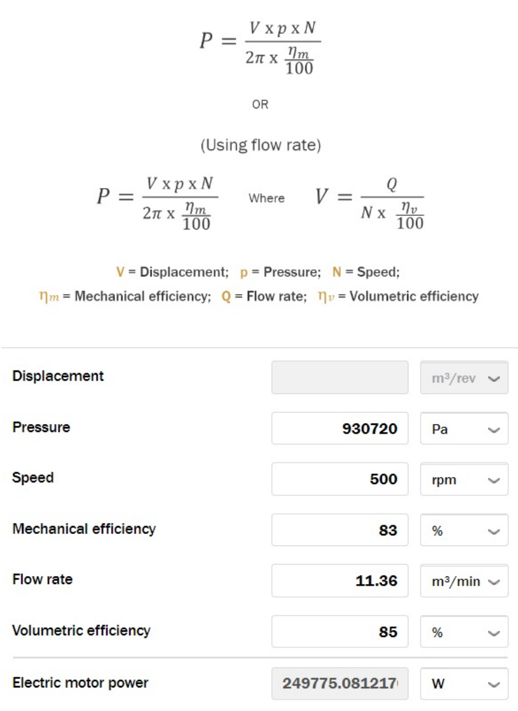


Figure 19: Motor power calculation

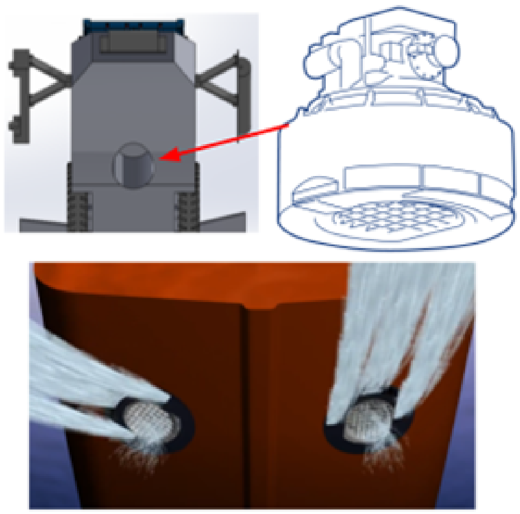


Figure 20: Jet pump

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

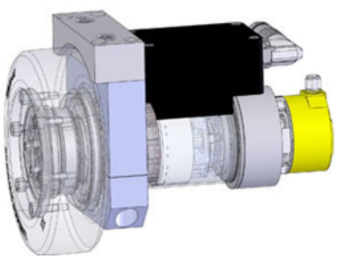
$$CUMULATIVEFORCE = AAGVMass * f_{rolling} + F_{wind} + F_{roll} + F_{slope} = 91.7kN$$

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

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]

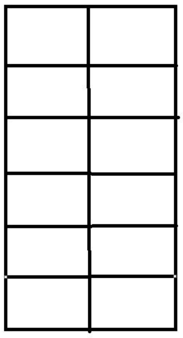
4.4.1 Battery Charging

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

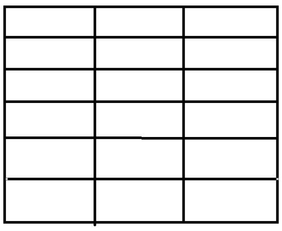
The batteries of the AGV are split into three different modules so we can allocate space for the stability systems such as pontoons to be stored. Furthermore retrieving the battery becomes easier with the use of lighter cranes. An added advantage is that the system would not need all three batteries 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:

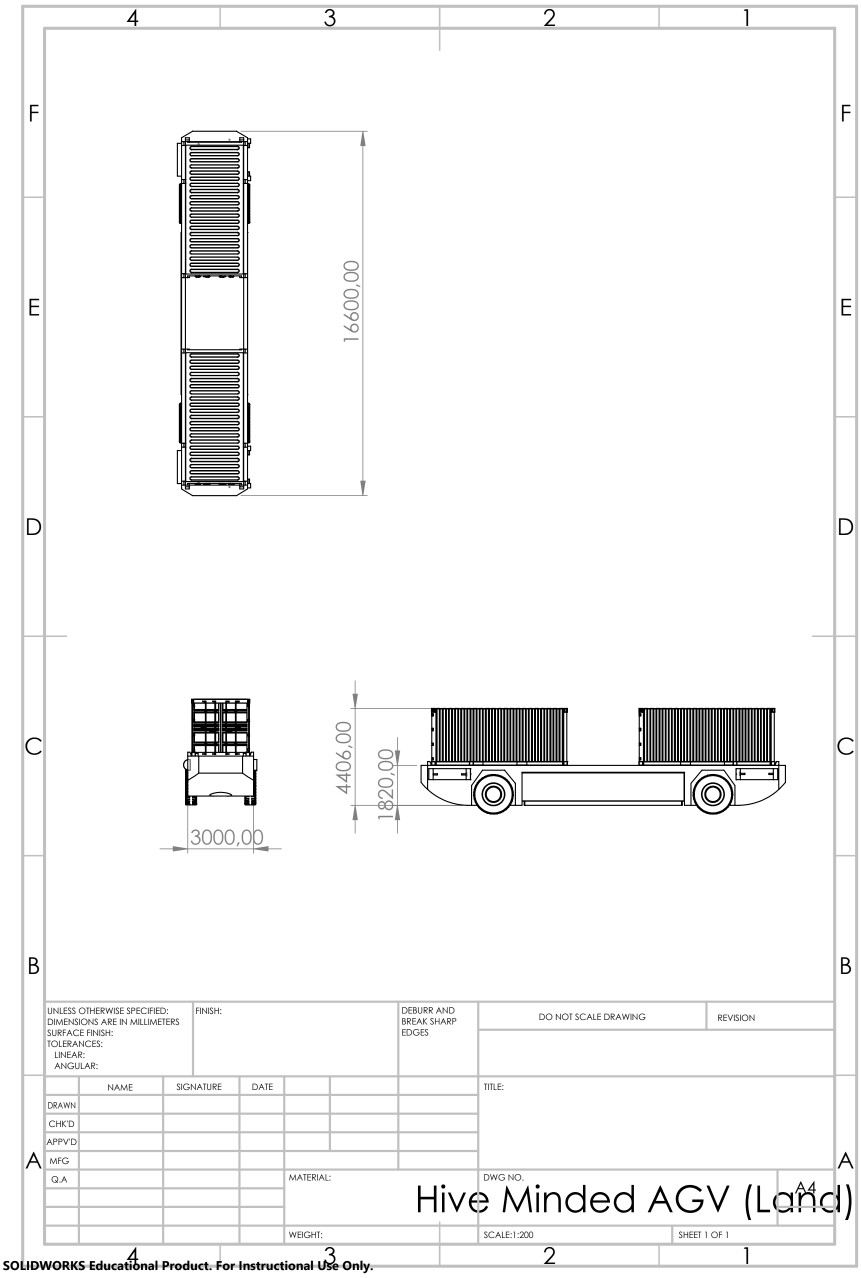


Figure 21: Drawing Land mode

Dimensions of the Water mode:

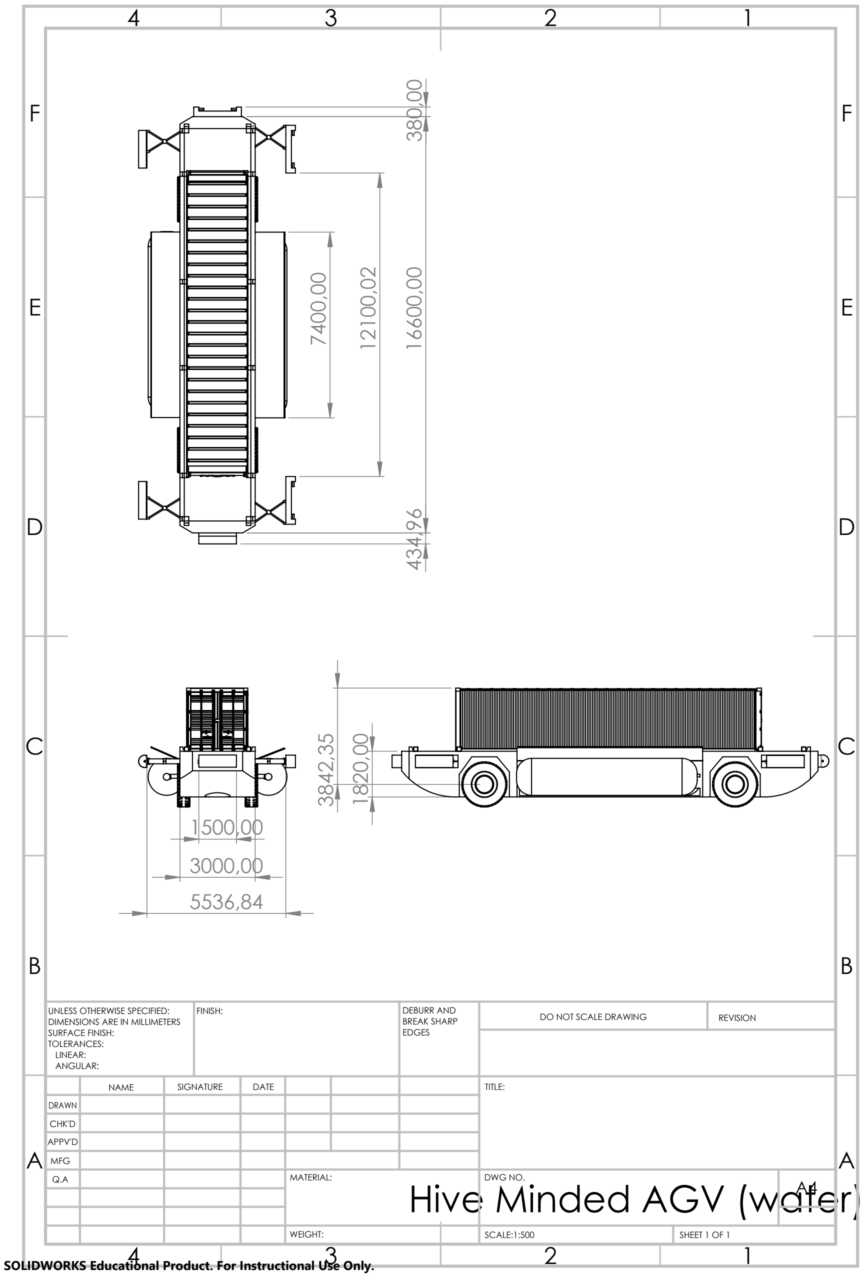


Figure 22: Drawing Water mode

Dimensions of the Grid formation:

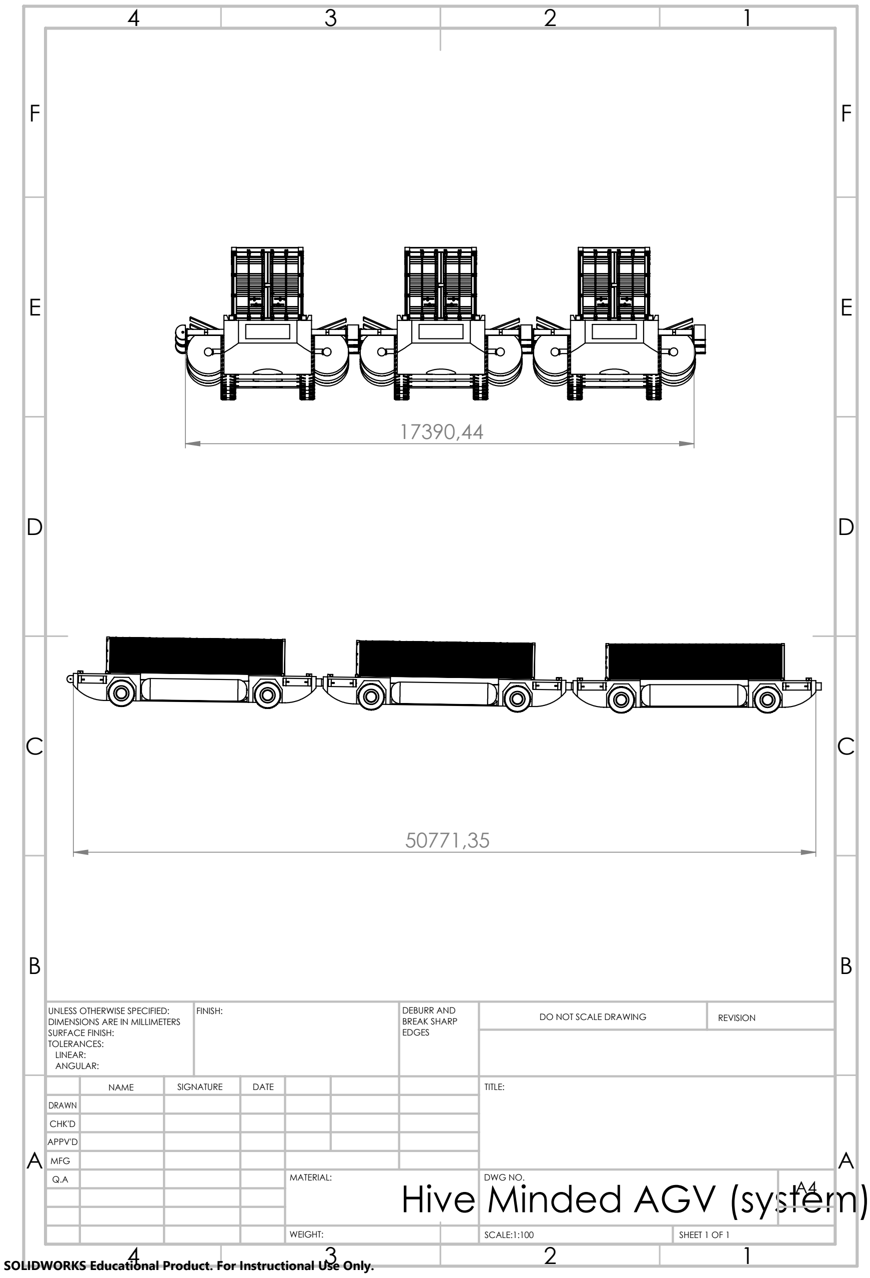


Figure 23: Drawing Grid formation

Dimensions of the Locking mechanism:

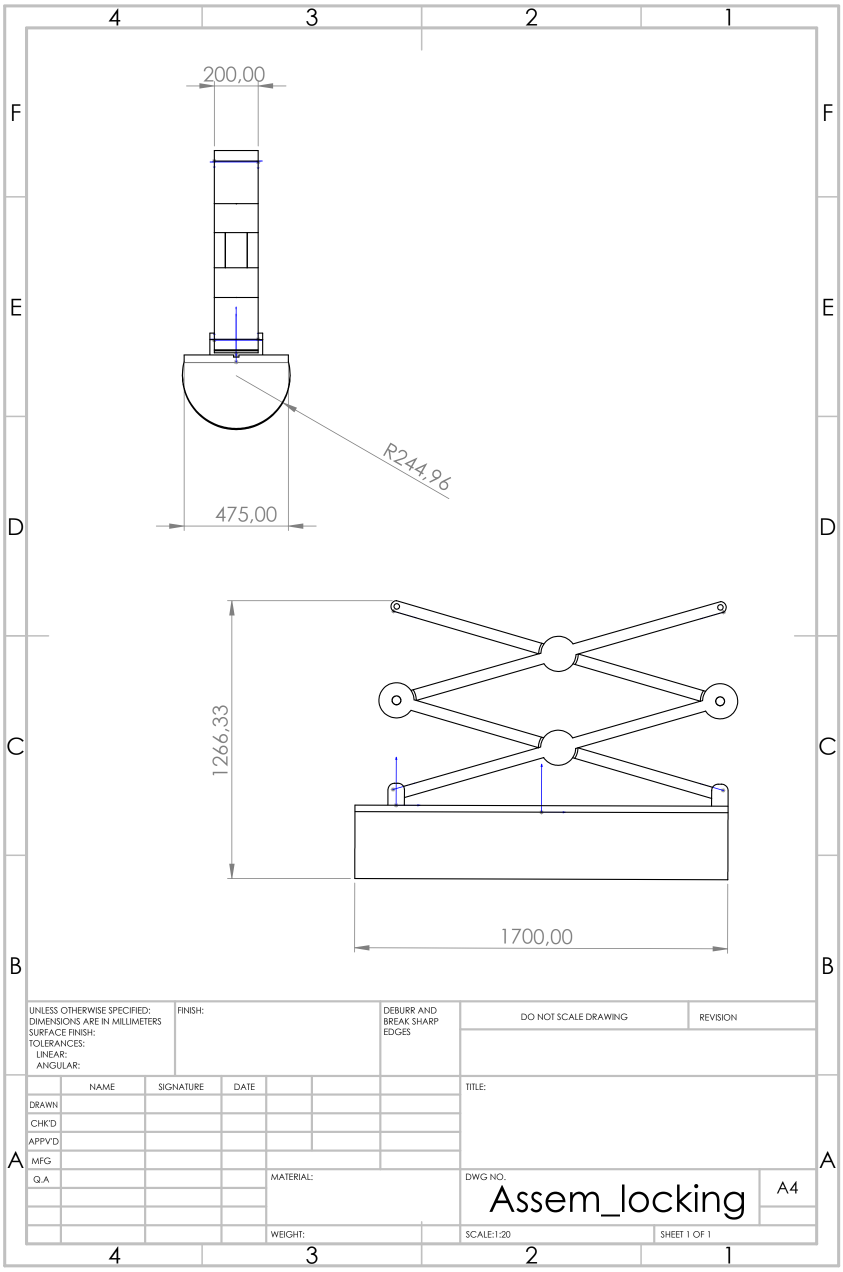


Figure 24: Drawing Locking mechanism

References

[1] SiemensGamesa,How it all comes together at sea: installing an offshore wind farm, https://www.youtube.com/watch?v=mDvS7tizetg&feature=youtu.be, 2020, Retrieved on November 17, 2020

[2] Pump Jets calculation, https://trelleborg.com/apps/hydrauliccylinder/?lang=en

[3] Battery Capacity calculations, https://https://pspowers.com/battery-capacity-calculator-for-electric-vehicle/

[4] https:aef-performace, Hovercraft skirts, //aef-performance.com/hovercraft-skirts/: :text=Materials%20used%20for%20the%20Navy's,Rubber%2C%20depending%20on%20the%20component

Appendix B

Simulation Model

This Appendix consists of the route data used as a input for Simulation arranged equipment wise.

B.1 Simulation Model - Route Input

B.1.1 Truck

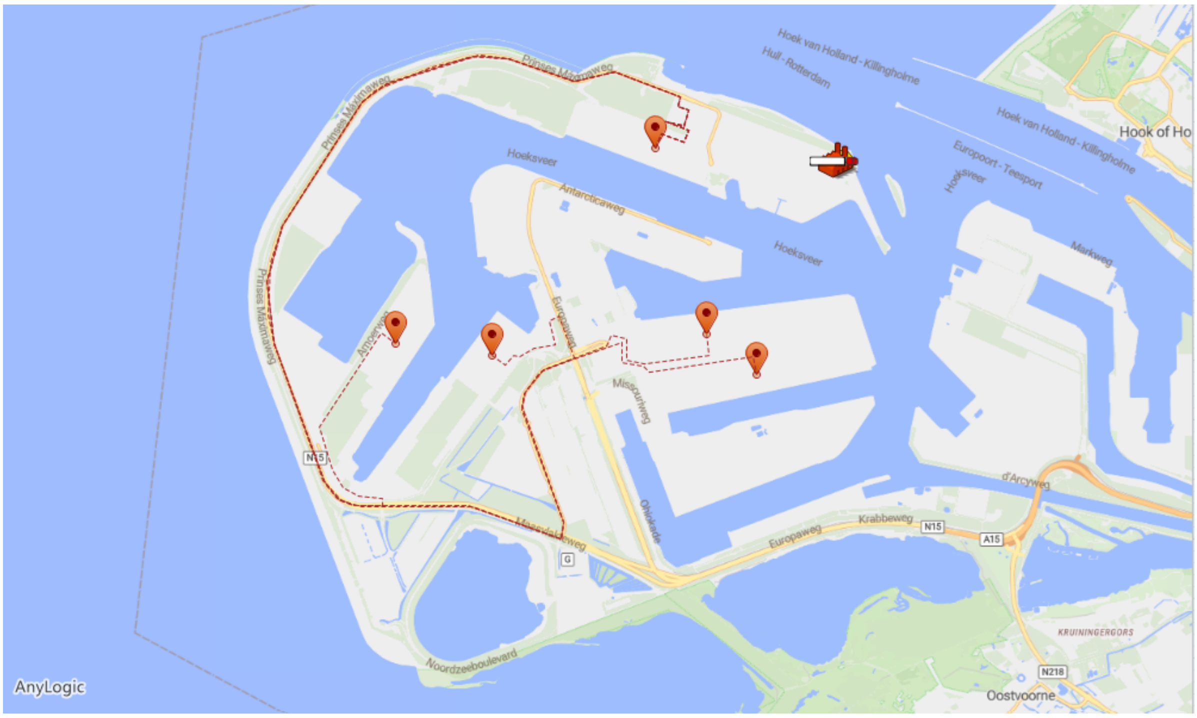


Figure B.1: Container Transport on Truck between the Yard Areas

B.1.2 Barge

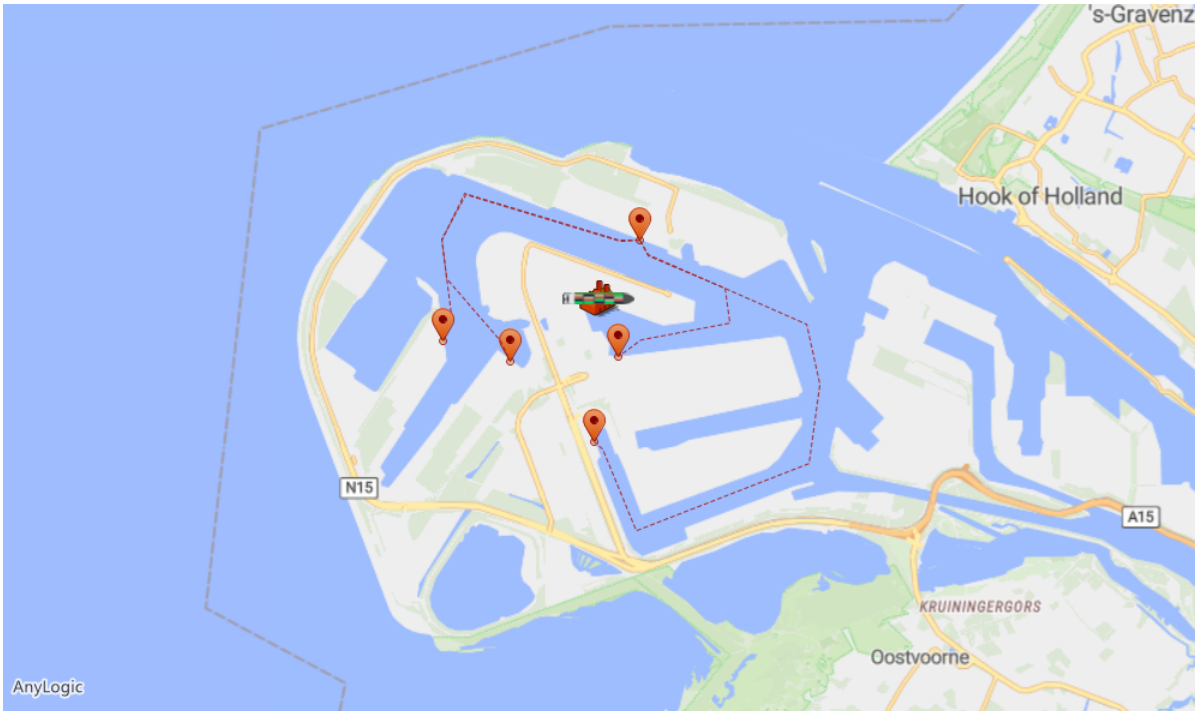


Figure B.2: Container Transport on Barge between the Quay Areas

B.1.3 AAGV

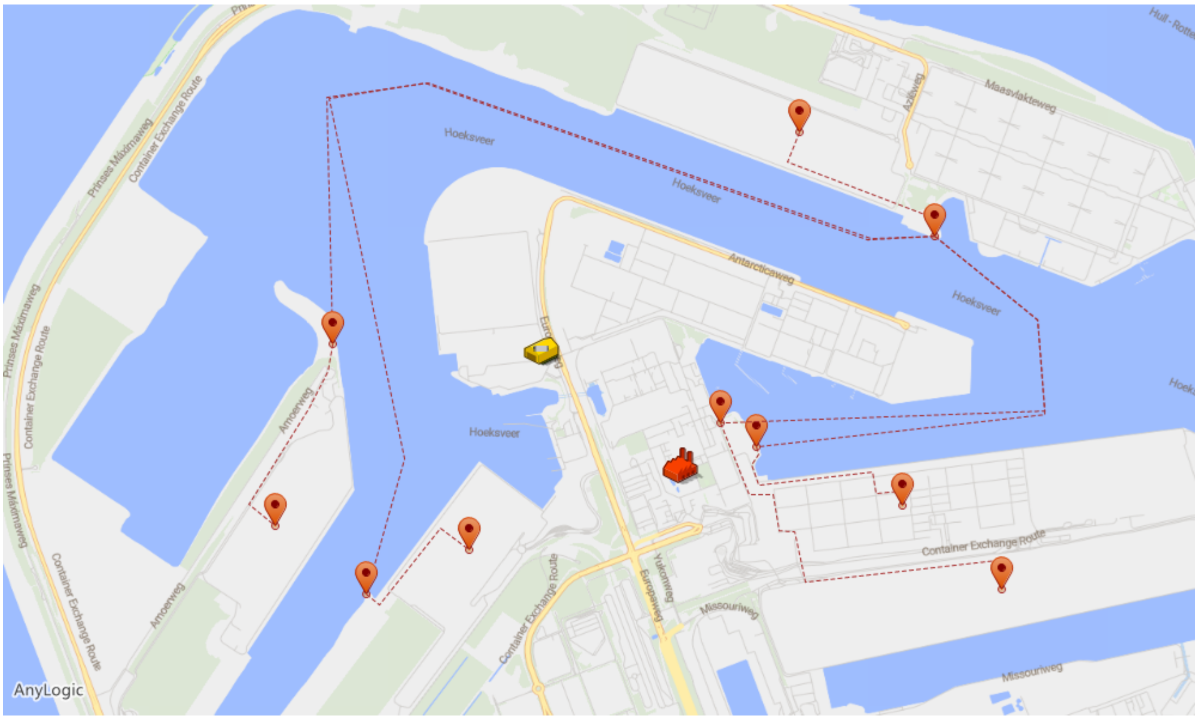


Figure B.3: Container Transport on AAGV between the Yard Areas

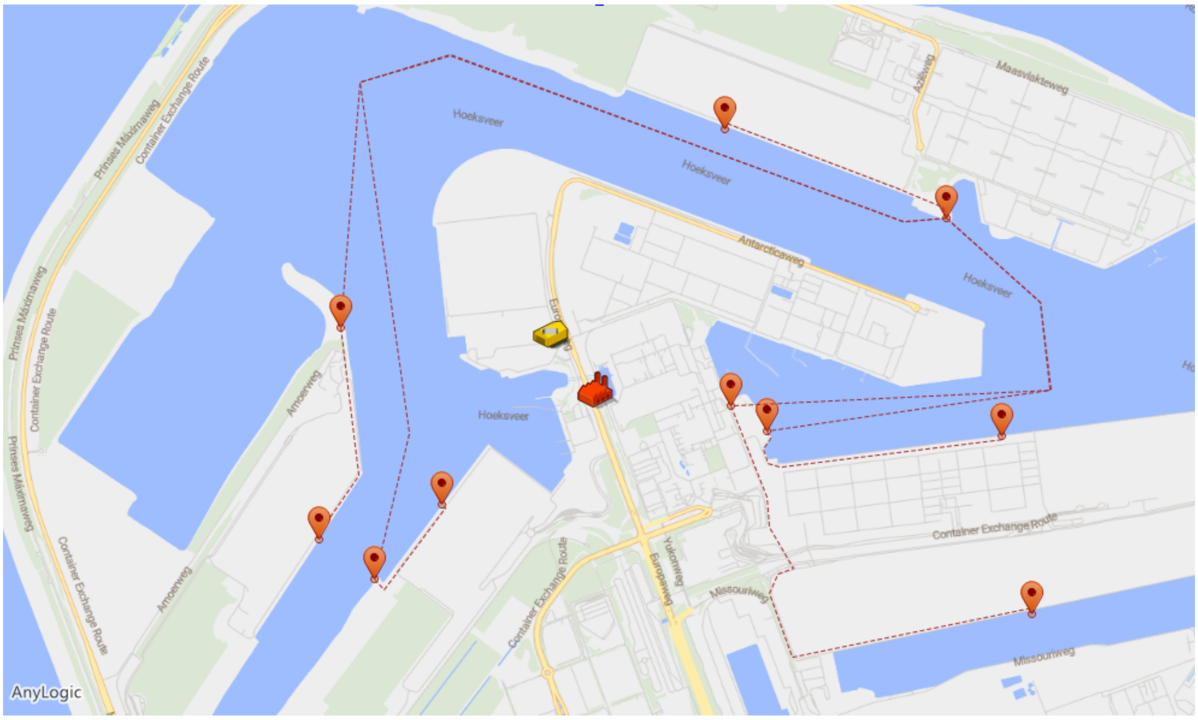


Figure B.4: Container Transport on AAGV between the Quay Areas

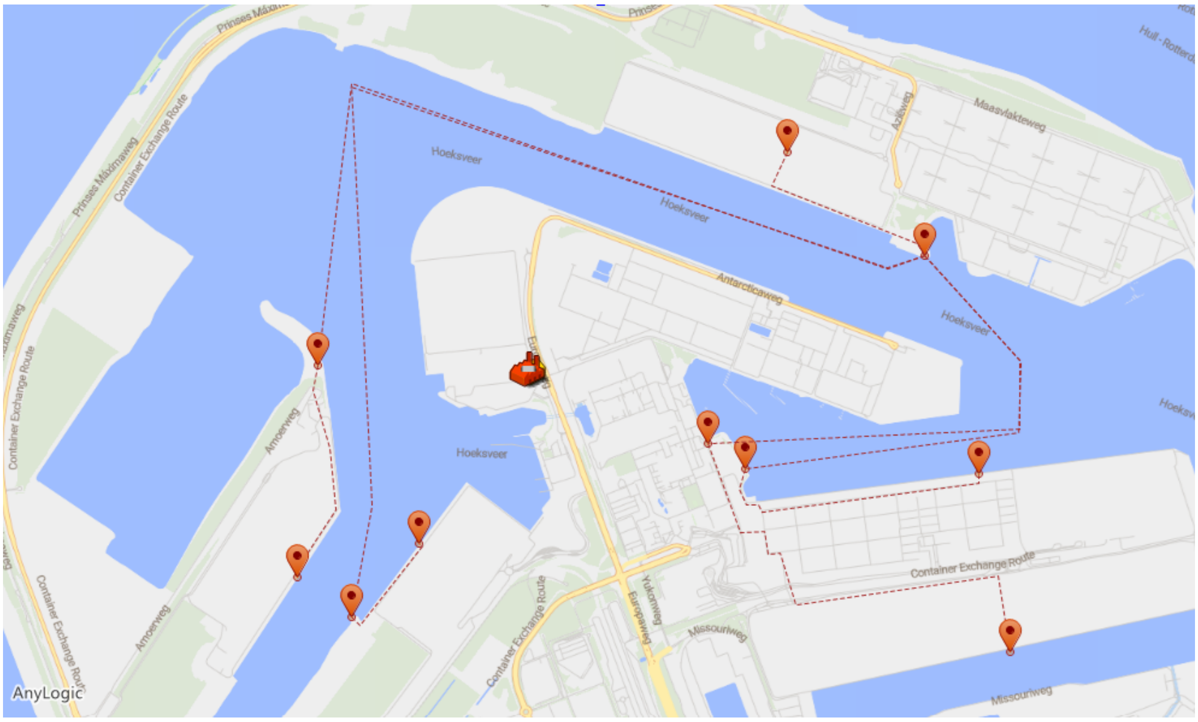


Figure B.5: Container Transport on AAGV between the Yard Area of ECT Euromax and the Quay Areas of other terminals

Figure B.6: Container Transport on AAGV between the Quay Area of ECT Euromax and the Yard Areas of other terminals

B.1.4 AGV

AGVs are used as supplementary handling equipment to complete the logistic chain. All AGV routes are based on the intra terminal routes for AGV as depicted in figures 4.8, 4.10, 4.9, 4.11 and 4.12.

Appendix C

Simulation Results

This Appendix has all the information regarding the simulation outputs and how that data was processed to obtain results. The simulation output is shown for the first case and similar process models are applied for other cases. These are sorted case wise with route analysis and then followed up by a overall route analysis and sensitivity analysis.

C.1 Case SS: Yard To Yard

C.1.1 Model Output

Truck

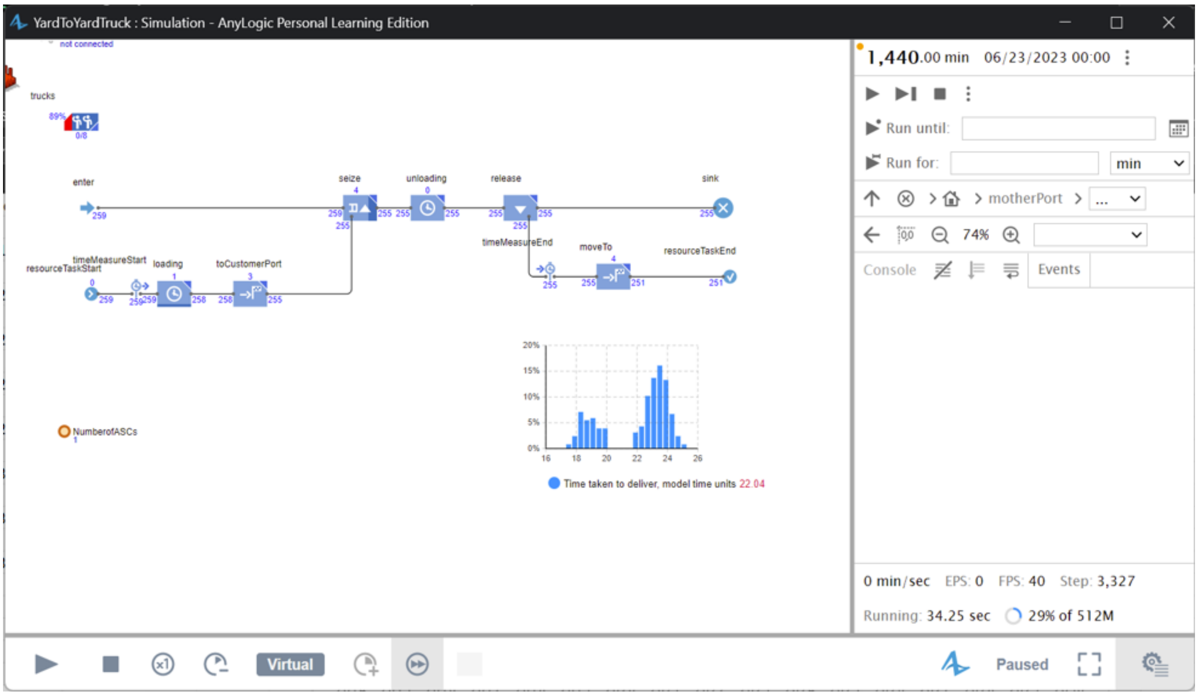


Figure C.1: Case SS Truck

Barge

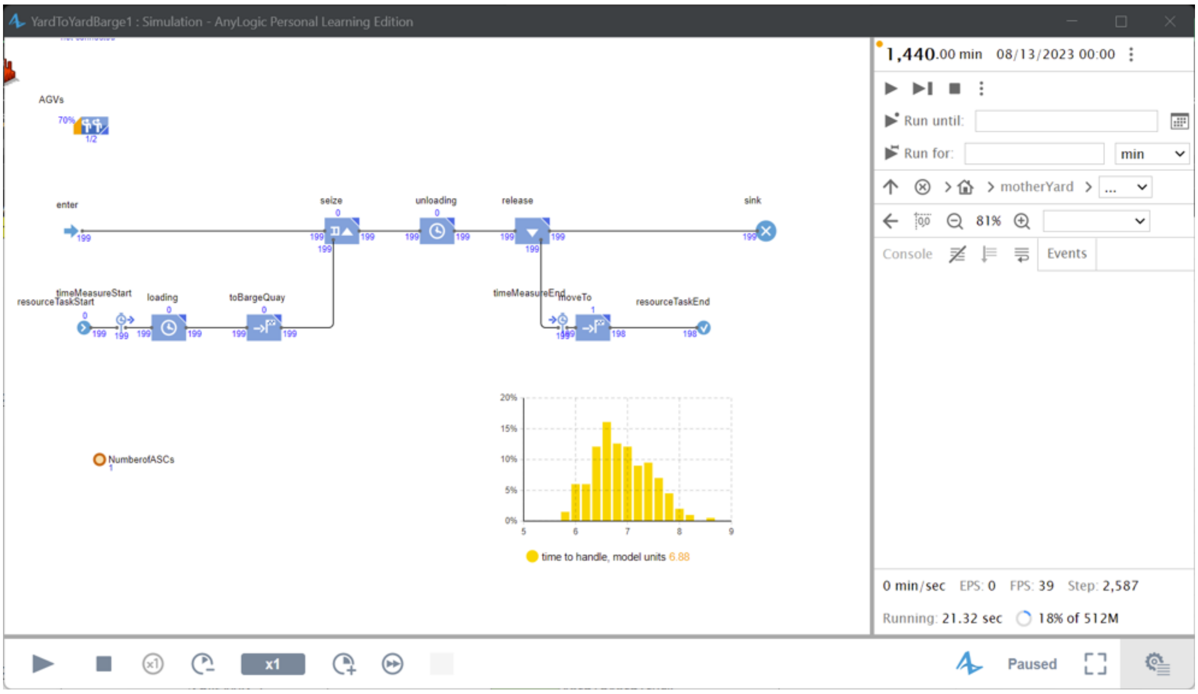


Figure C.2: Case SS Barge A

Figure C.3: Case SS Barge B

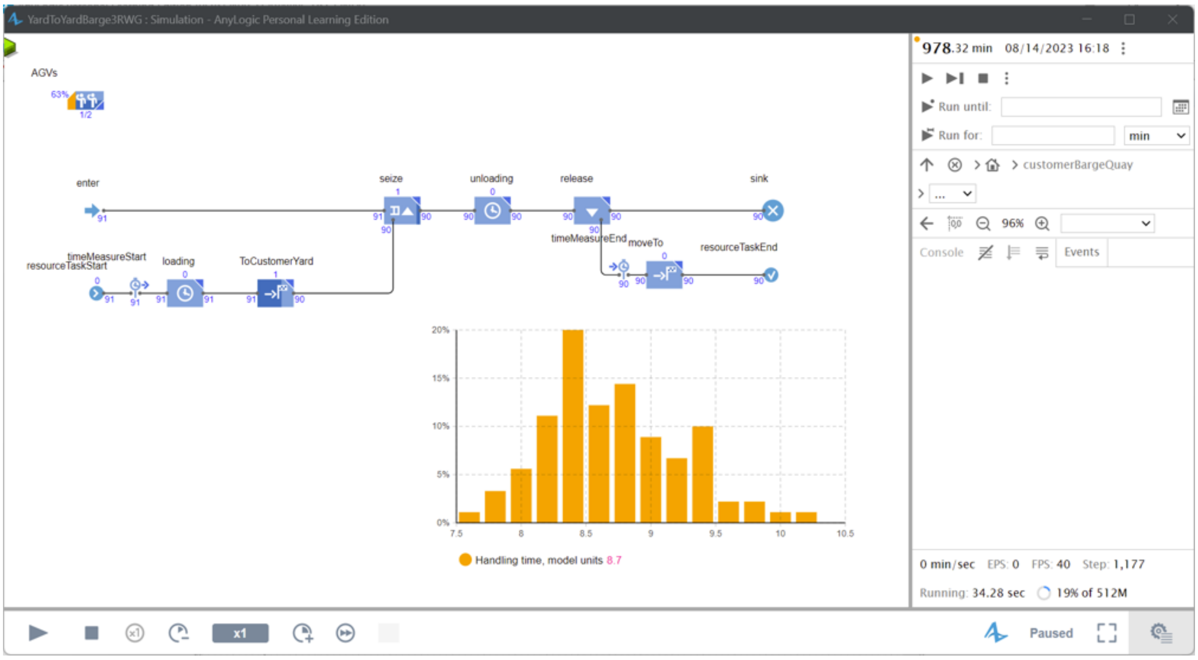


Figure C.4: Case SS Barge C1

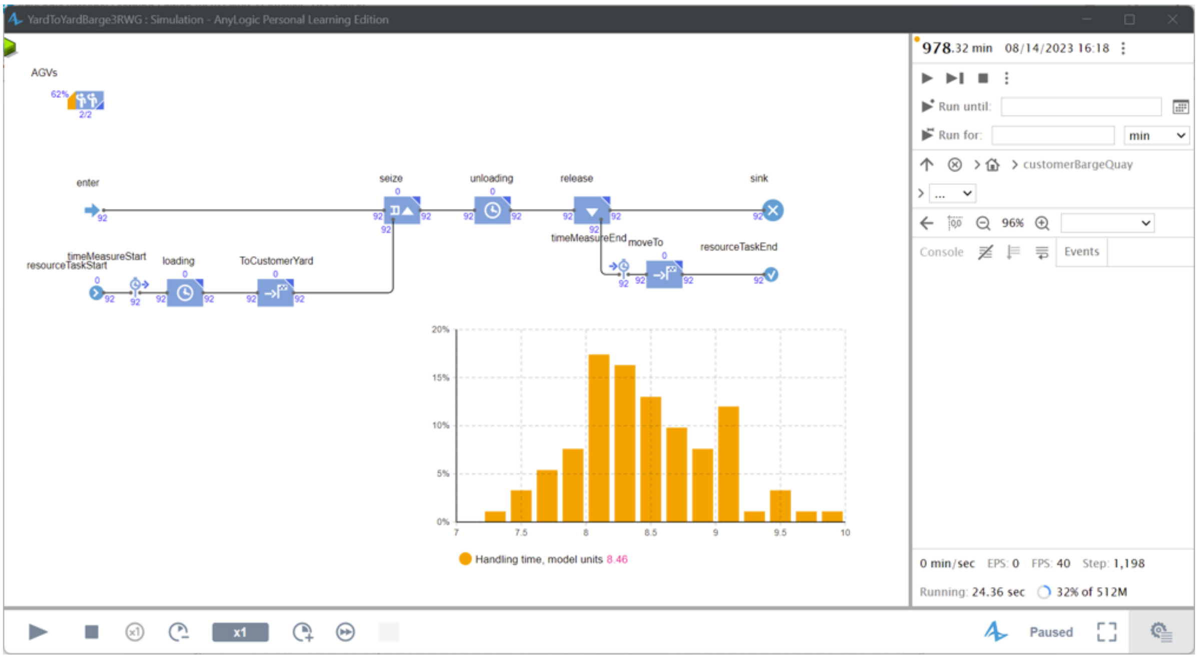


Figure C.5: Case SS Barge C2

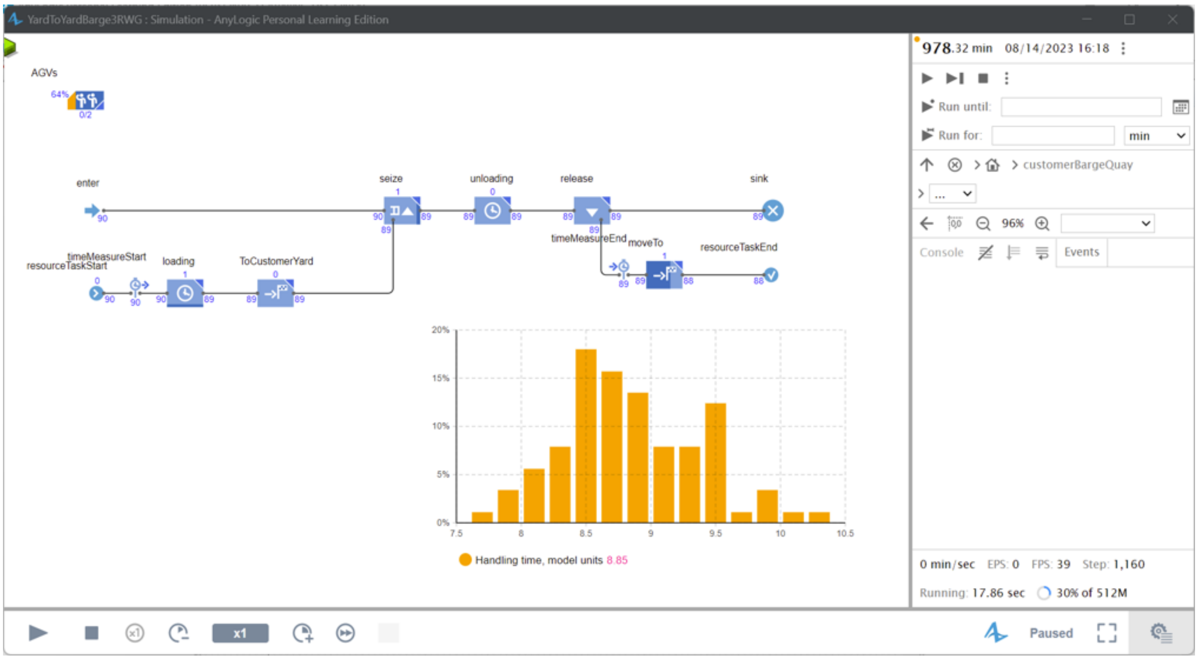


Figure C.6: Case SS Barge C3

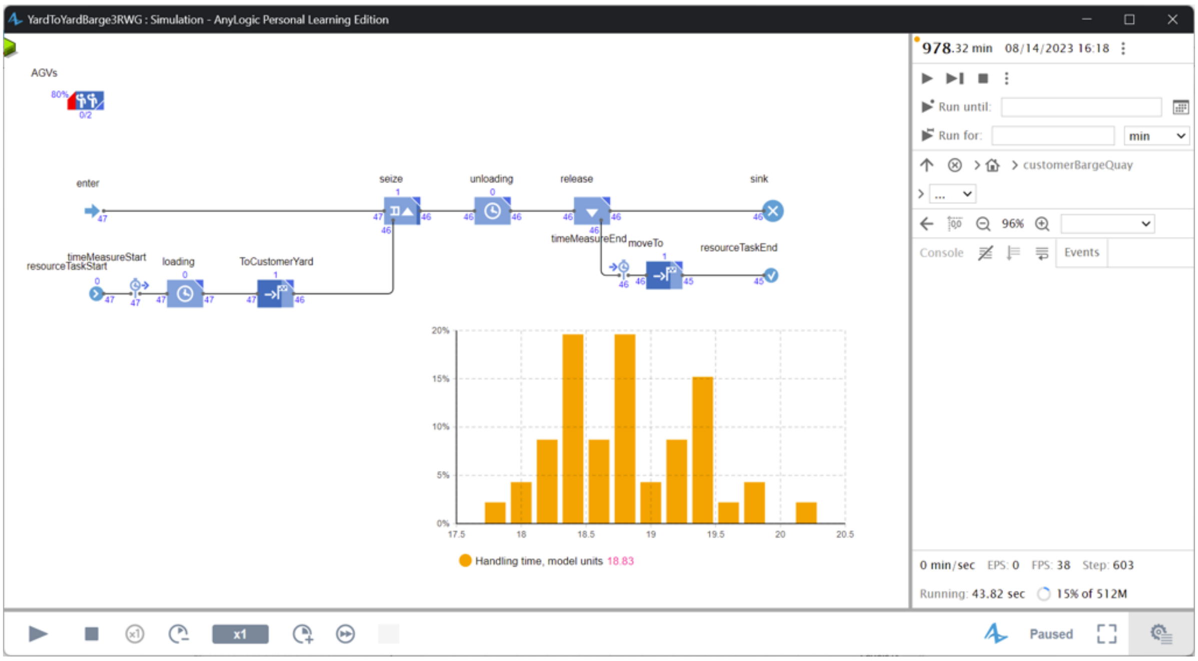


Figure C.7: Case SS Barge C4

AAGV

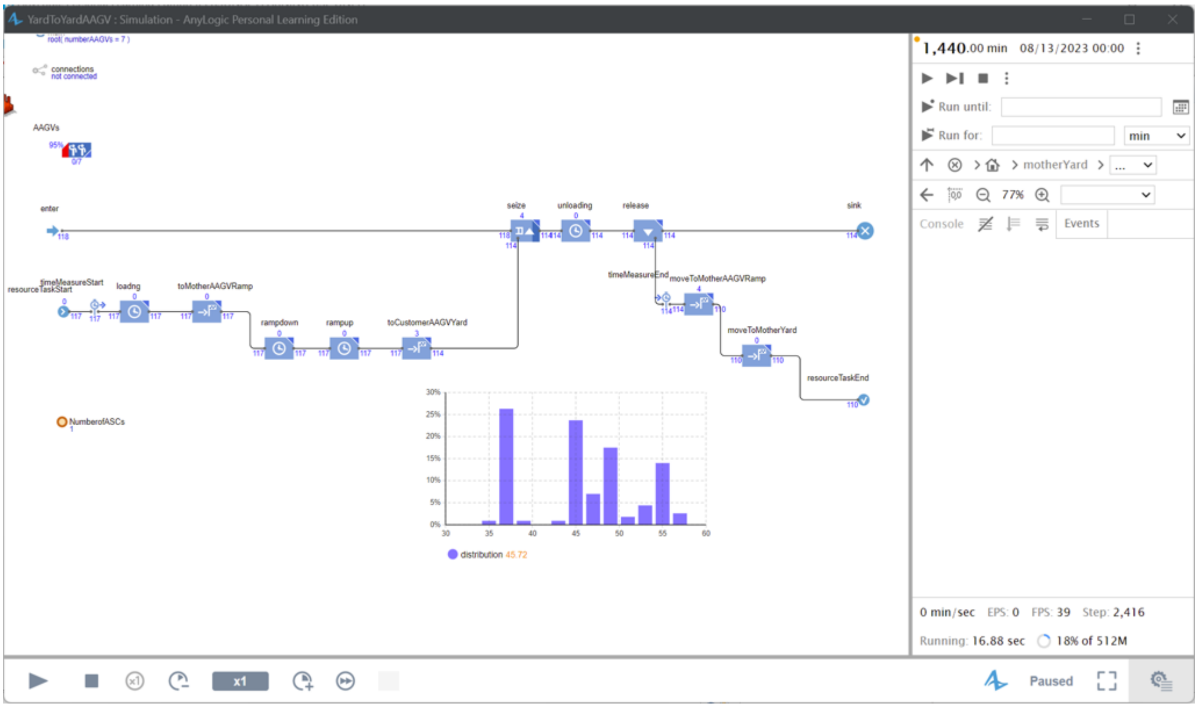


Figure C.8: Case SS AAGV

C.1.2 Results

Table C.1: Case SS Data

	Truck	Barge(100% Capacity)							AAGV
		AGV	Barge	AGV					
Overall Container Input	3761	3761	3582	675	675	675	675	3761
Container Input	259	199	1200	91	92	90	47	118
No. of Cranes for loading	14	18	3	3	3	3	3	31
No. of Cranes for unloading	14	3	3	7	7	7	14	31
Average Time per vehicle (Minutes)	22,04	6,88	454,8	8,7	8,46	8,85	18,83	45,72
Throughput(TEU/hr)	297,5	298,5	226,08	77,28	78,99	76,42	78,99	294,5
Fleet Size	112	36	15	14	14	14	28	217
Container Output	255	199	900	90	92	89	46	114
RunTime(Minutes)	1440	1440	1433,12	978,32	978,32	978,32	978,32	1440
Barge Input			36					
Barge Output			9					
Number of Parallel Processes Required	14	18	3	7	7	7	14	31
Overall Container Output	3570	3582	2700	630	644	623	644	3534

Table C.2: Case SS Results

Mode	Average Time per container (minutes)	Throughput (TEU/hr)	Re-Handling Points	Total Fleet Size	Fulfillment rate (%)
Truck	22,04	297,5	2	112	94,92
AAGV	45,72	294,5	2	217	93,96
Barge	472,89	211,75	4	121	67,56

C.1.3 Route Analysis

Model Output

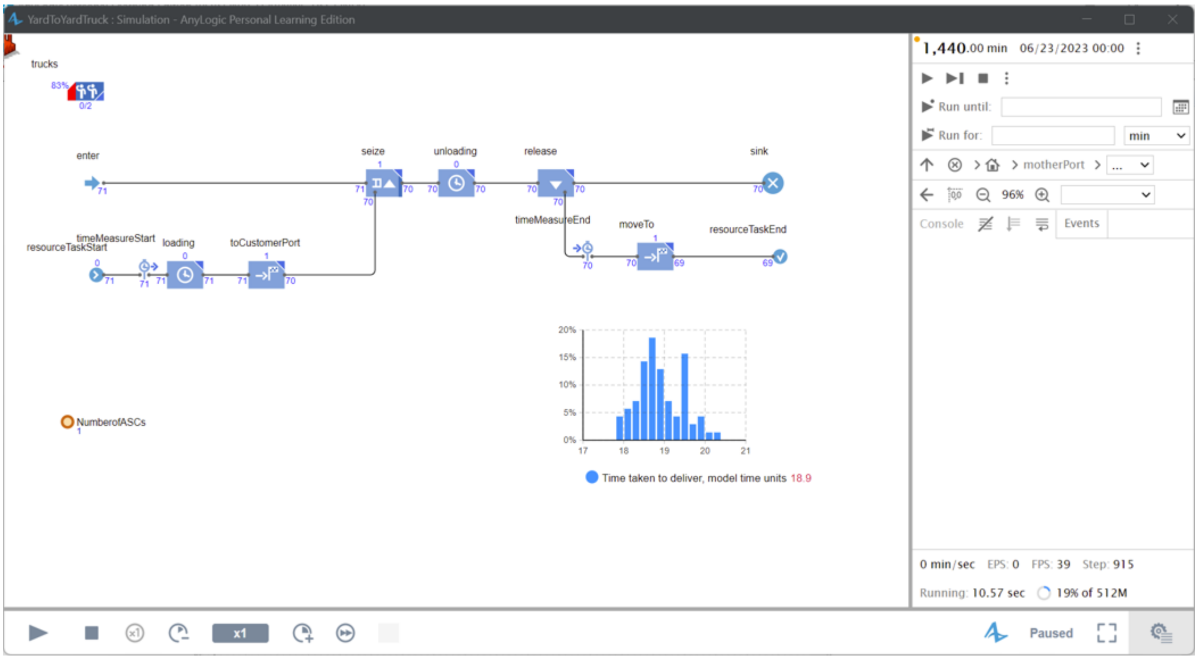


Figure C.9: Route Case SS Truck 1

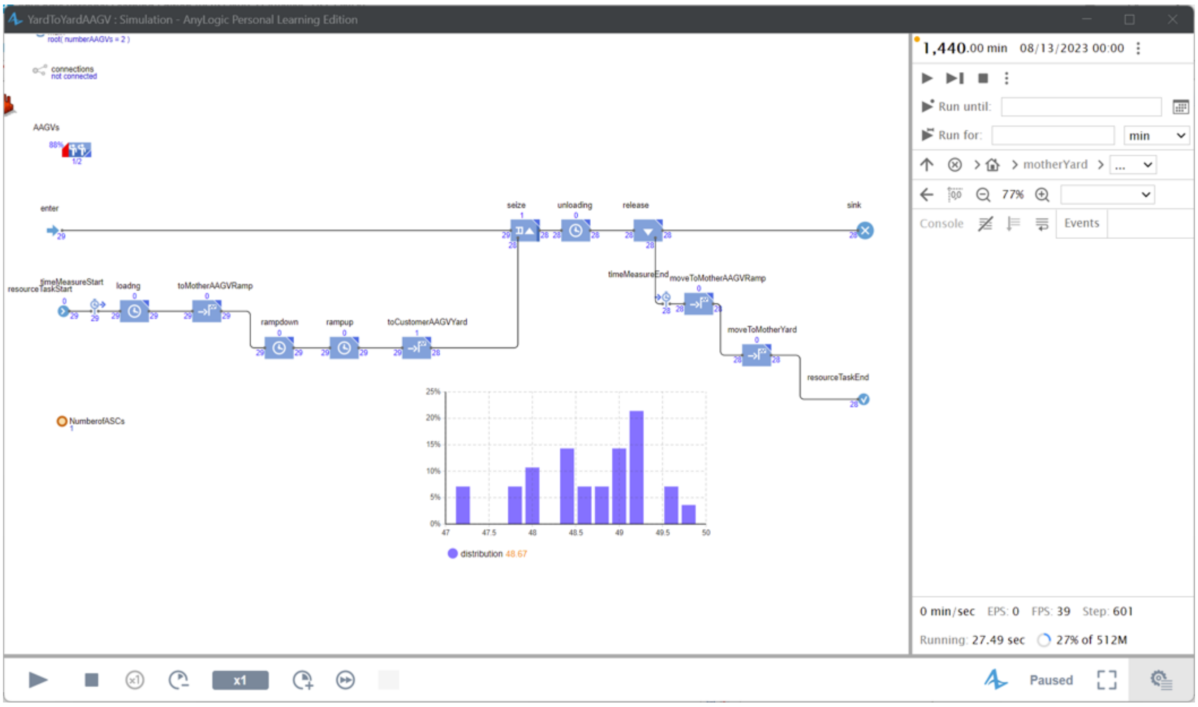


Figure C.10: Route Case SS AAGV 1

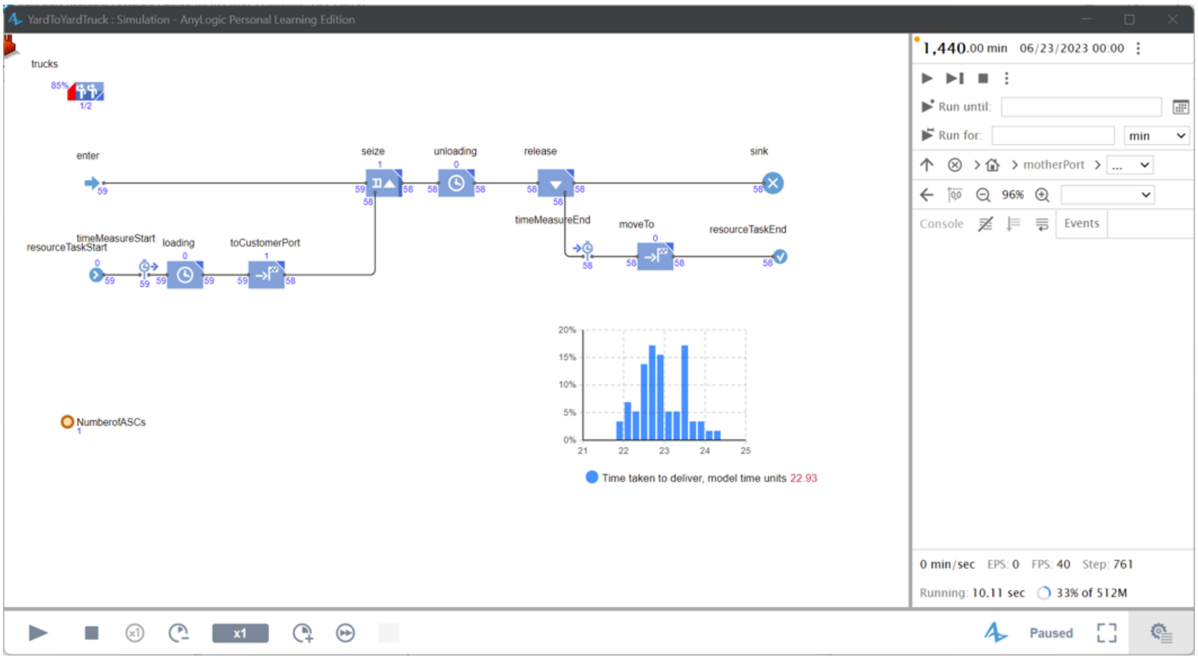


Figure C.11: Route Case SS Truck 2

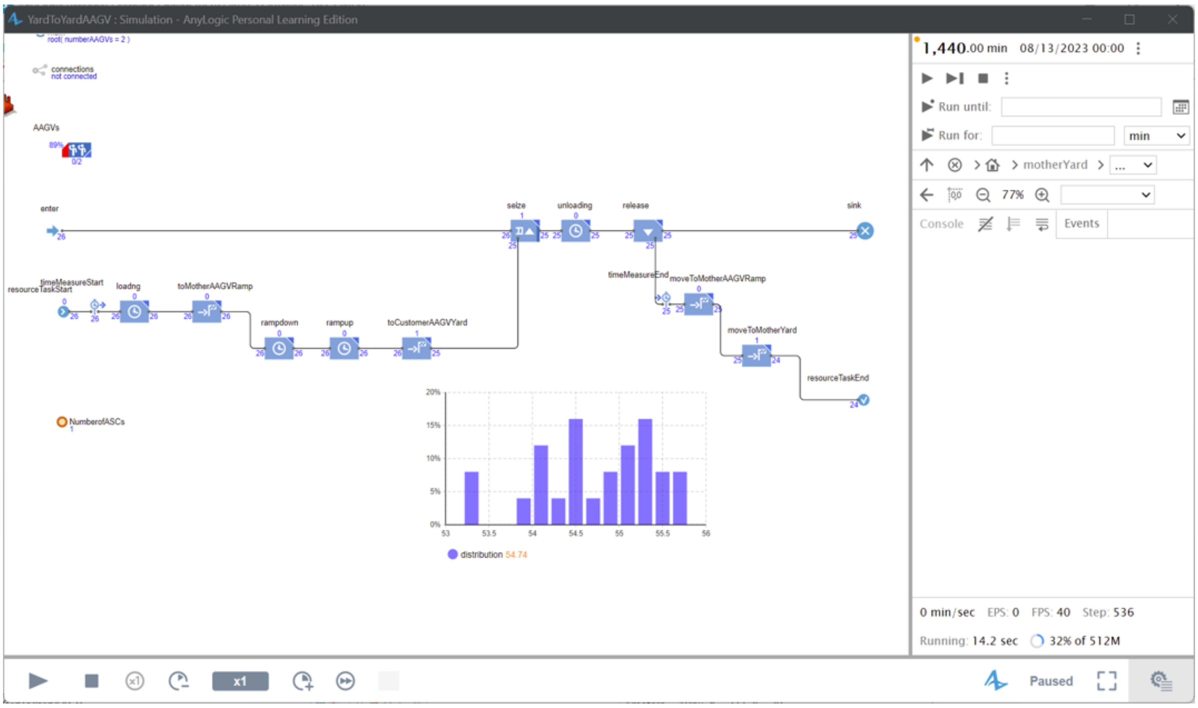


Figure C.12: Route Case SS AAGV 2

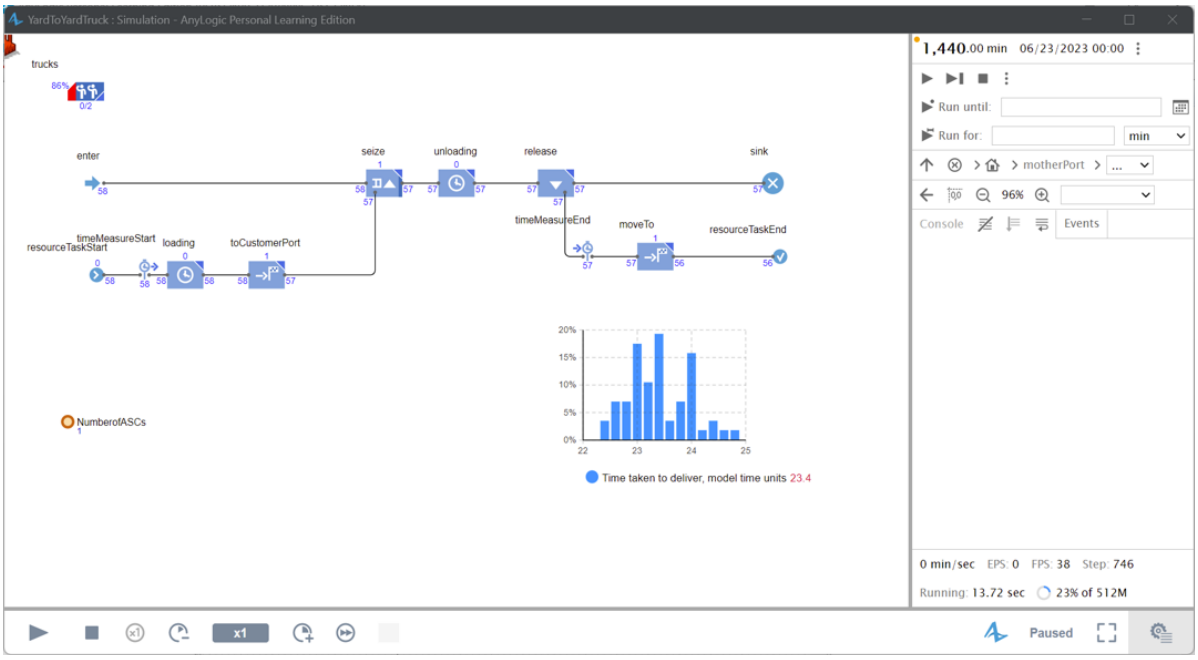


Figure C.13: Route Case SS Truck 3

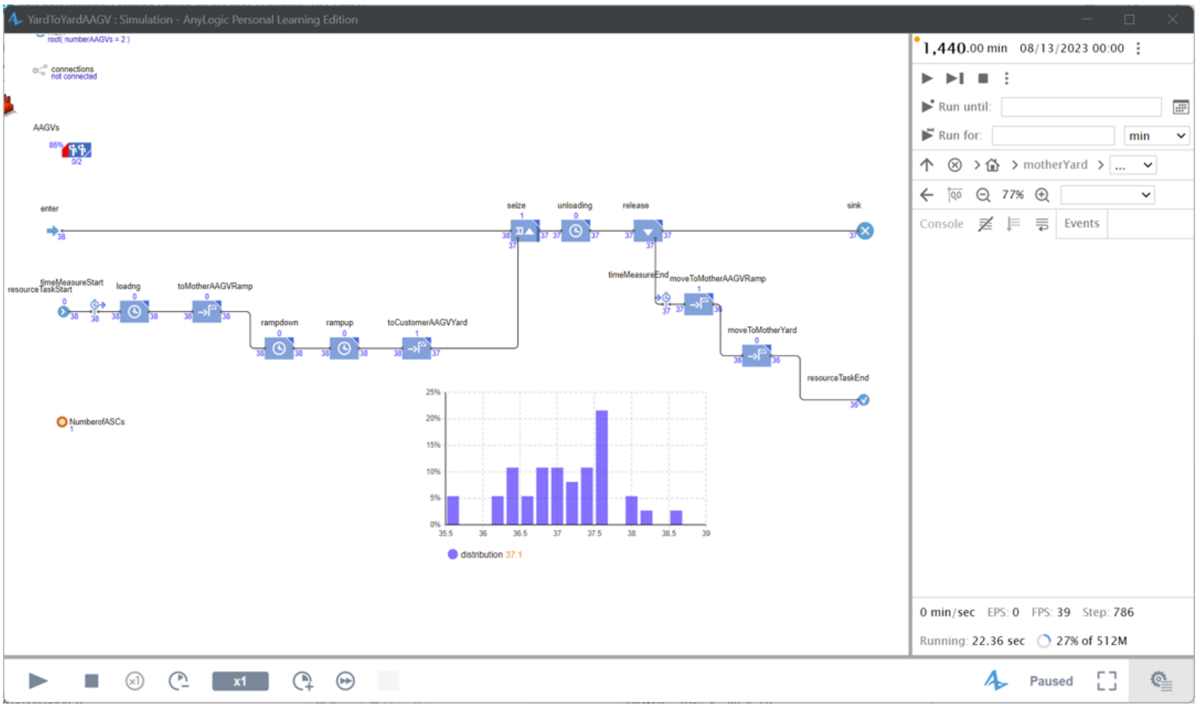


Figure C.14: Route Case SS AAGV 3

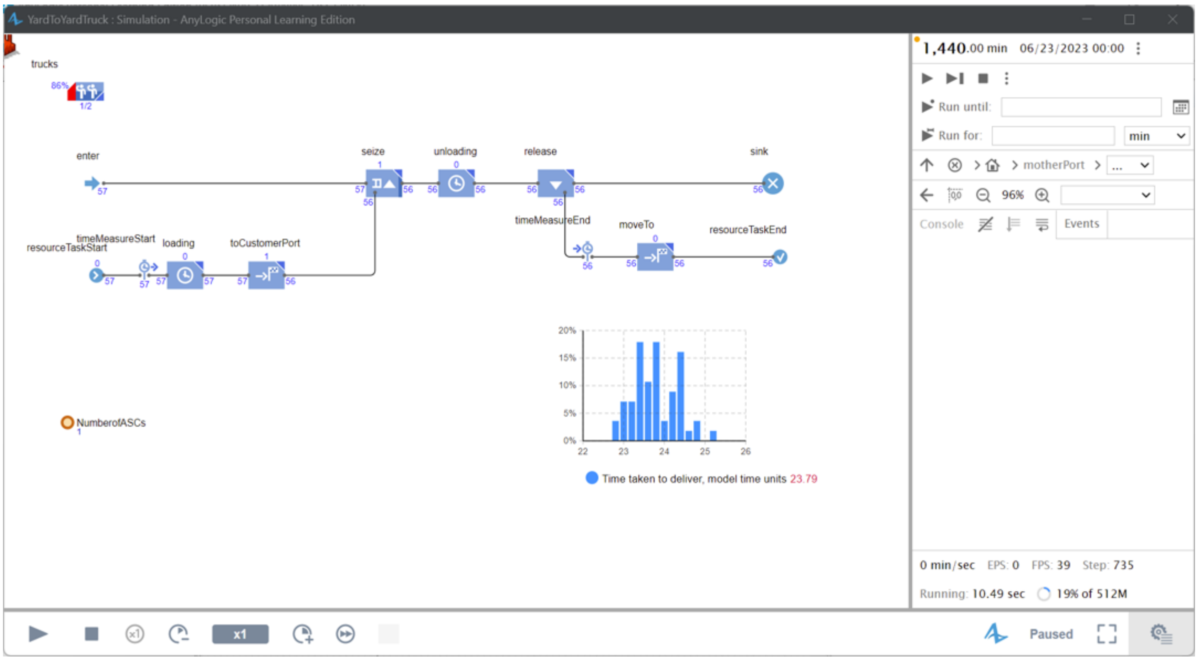


Figure C.15: Route Case SS Truck 4

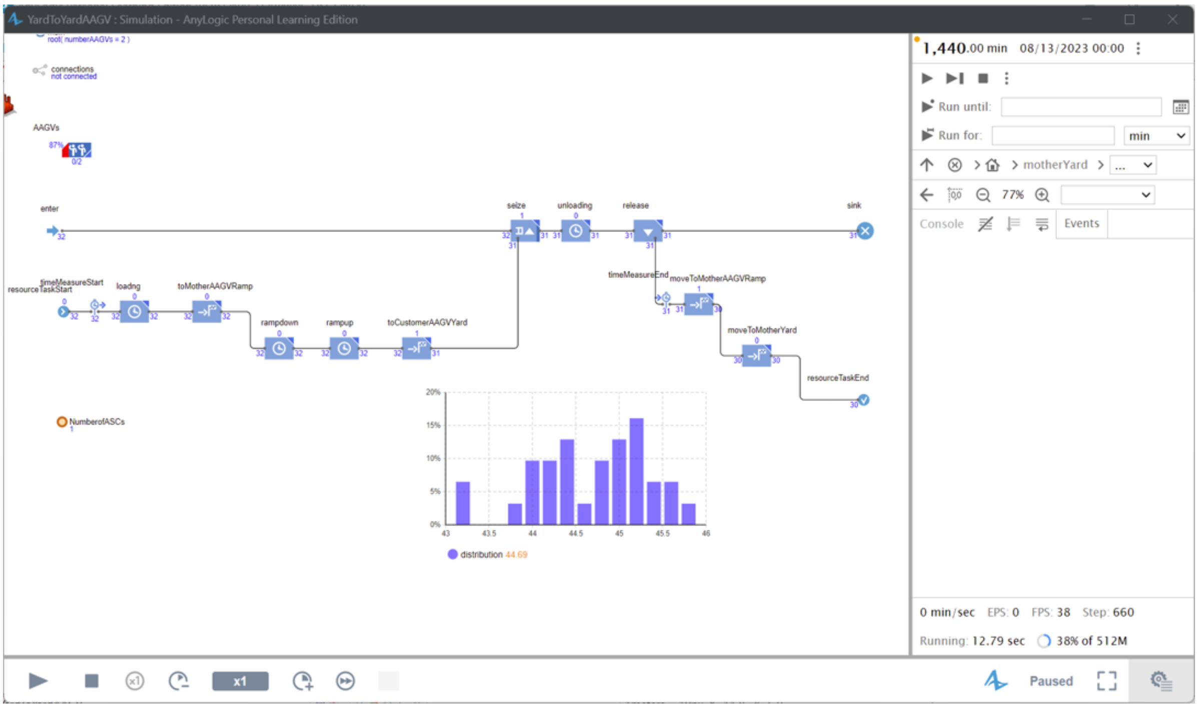


Figure C.16: Route Case SS AAGV 4

Results

Table C.3: Route: Case SS Data

Inputs	Yard To Yard							
	Euromax To RWG		Euromax To APMT2		Euromax To Delta 2		Euromax To Delta	
	Truck	AAGV	Truck	AAGV	Truck	AAGV	Truck	AAGV
Overall Container Input	940	940	940	940	940	940	940	940
Container Input	71	29	59	26	58	38	57	32
Average Time per vehicle (Minutes)	18,9	48,67	22,93	54,74	23,4	37,1	23,79	44,69
Throughput (TEU/hr)	75,83	74,67	72,5	75	76	74	74,67	74,92
Fleet Size	26	64	30	72	32	48	32	58
Container Output	70	28	58	25	57	37	56	31
RunTime(Minutes)	1440	1440	1440	1440	1440	1440	1440	1440
Number of Parallel Process Required	13	32	15	36	16	24	16	29
Overall Container Output	910	896	870	900	912	888	896	899

Table C.4: Route: Case SS Results

Outputs	Euromax to RWG		Euromax to APMT2		Euromax to Delta 2		Euromax to Delta	
	Truck	AAGV	Truck	AAGV	Truck	AAGV	Truck	AAGV
Time(minutes)	18,9	48,67	22,93	54,74	23,4	37,1	23,79	44,69
Throughput (TEU/hr)	75,83	74,67	72,5	75	76	74	74,67	74,92
FleetSize	26	64	30	72	32	48	32	58
Fulfillment rate (%)	96,81	95,32	92,55	95,74	97,02	94,47	95,32	95,64

C.2 Case VV: Quay To Quay

C.2.1 Results

These are the Results of Case VV.

Table C.6: Case VV Results

Mode	Average Time per container (minutes)	Throughput (TEU/hr)	Re-Handling Points	Total Fleet Size	Fulfillment rate (%)
Truck	35,16	278,92	4	186	88,99
AAGV	48,15	299,75	2	231	95,64
Barge	473,47	201,75	4	121	64,37

C.2.2 Route Analysis

These are the results of Case VV route breakdown.

Table C.8: Route: Case VV Results

Outputs	Euromax to RWG		Euromax to APMT2		Euromax to Delta 2		Euromax to Delta	
	Truck	AAGV	Truck	AAGV	Truck	AAGV	Truck	AAGV
Time(minutes)	31,65	49,78	33,94	54,48	39,26	39,85	36,61	48,47
Throughput (TEU/hr)	69,67	76,25	69	75	59,17	75,83	68,67	74,67
FleetSize	44	64	46	72	50	52	50	64
Fulfillment rate (%)	88,94	95,32	88,09	95,74	75,53	96,81	87,66	95,32

C.3 Case SV: Yard To Quay

C.3.1 Results

These are the results of Case SV.

Mode	Average Time per container (minutes)	Throughput (TEU/hr)	Re-Handling Points	Total FleetSize	Fulfillment rate (%)
Truck	27,63	280,67	3	146	89,55
AAGV	46,44	298,67	2	224	95,29
Barge	473,46	201,75	4	121	64,37

Table C.10: Case SV Results

Table C.5: Case VV Data

	Truck						Barge(100%)						AAGV
	AGV	Truck	AGV				AGV	Barge	AGV				
Overall Container Input	3761	3660	889	889	889	889	3761	3636	675	675	675	675	3761
Container Input	184	258	208	280	144	206	203	1200	97	101	76	43	113
No. of Cranes for loading	6	20	4	4	4	4	6	3	3	3	3	3	6
No. of Cranes for unloading	20	14	4	3	6	4	3	3	6	6	6	6	6
Average Time per vehicle (Minutes)	7,52	22,05	5,22	3,49	8,35	5,3	6,75	454,94	8	7,64	10,97	20,51	48,15
Throughput(TEU/hr)	305	297,89	70,79	71,21	73	69,77	303	226,06	70,65	73,6	73,6	79,12	299,75
Fleet Size	40	112	8	6	12	8	36	15	12	12	16	30	231
Container Output	183	254	208	279	143	205	202	900	96	100	75	43	109
RunTime(Minutes)	1440	1432,48	1410,43	1410,43	1410,43	1410,43	1440	1433,25	978,31	978,31	978,31	978,31	1440
Barge Input								12					
Barge Output								9					
Number of Parallel Processes Required	20	14	4	3	6	4	18	3	6	6	8	15	33
Overall Container Output	3660	3556	832	837	858	820	3636	2700	576	600	600	645	3597

Table C.7: Route: Case VV Data

Inputs	Quay To Quay															
	Euromax to RWG				Euromax to APMT2				Euromax to Delta 2				Euromax to Delta			
	Truck			AAGV	Truck			AAGV	Truck			AAGV	Truck			AAGV
	AGV	Truck	AGV		AGV	Truck	AGV		AGV	Truck	AGV		AGV	Truck	AGV	
Overall Container Input	940	915	910	940	940	915	870	940	940	915	855	940	940	915	896	940
Container Input	184	70	210	29	184	59	277	26	184	58	143	36	184	57	206	29
Average Time per vehicle (Minutes)	7,52	18,9	5,23	49,78	7,52	22,93	3,49	54,48	7,52	23,4	8,34	39,85	7,52	23,79	5,3	48,47
Throughput(TEU/hr)	76,25	76,23	70,97	74,67	76,25	72,88	70,49	75	76,25	71,62	60,46	75,83	76,25	75,06	70,19	74,67
Fleet Size	10	26	8	64	10	30	6	72	10	30	10	52	10	32	8	64
Container Output	183	70	209	28	183	58	276	25	183	57	142	35	183	56	206	28
RunTime(Minutes)	1440	1432,48	1413,58	1440	1440	1432,48	1409,55	1440	1440	1432,48	1409,08	1440	1440	1432,48	1408,69	1440
Number of Parallel Process Required	5	13	4	32	5	15	3	36	5	15	5	26	5	16	4	32
Overall Container Output	915	910	836	896	915	870	828	900	915	855	710	910	915	896	824	896

Table C.9: Case SV Data

	Truck					Barge						AAGV
	Truck	AGV				AGV	Barge	AGV				
Overall Container Input	3761	892	892	892	892	3761	3582	675	675	675	675	3761
Container Input	259	210	281	145	207	199	1200	97	101	76	43	116
No. of Cranes for loading	14	4	4	4	4	18	3	3	3	3	3	32
No. of Cranes for unloading	14	4	3	6	4	3	3	6	6	6	6	32
Average Time per vehicle(Minutes)	22,04	5,23	3,49	8,35	5,3	6,88	454,8	8	7,64	10,97	20,51	46,44
Throughput(TEU/hr)	297,5	70,75	71,09	73,12	70,07	298,5	226,08	70,65	73,6	73,6	79,12	298,67
Fleet Size	112	8	6	12	8	36	15	12	12	16	30	224
Container Output	255	209	280	144	207	199	900	96	100	75	43	112
RunTime(Minutes)	1440	1417,96	1417,96	1417,96	1417,96	1440	1433,12	978,32	978,32	978,32	978,32	1440
Barge Input							36					
Barge Output							9					
Number of Parallel Process Required	14	4	3	6	4	18	3	6	6	8	15	32
Overall Container Output	3570	836	840	864	828	3582	2700	576	600	600	645	3584

Table C.11: Route: Case SV Data

Inputs	**Yard To Quay**											
	Euromax To RWG			**Euromax To APMT2**			**Euromax To Delta 2**			**Euromax To Delta**		
	Truck		**AAGV**	**Truck**		**AAGV**	**Truck**		**AAGV**	**Truck**		**AAGV**
	Truck	**AGV**		**Truck**	**AGV**		**Truck**	**AGV**		**Truck**	**AGV**	
Overall Container Input	940	910	940	940	870	940	940	912	940	940	896	940
Container Input	71	210	29	59	279	27	58	146	37	57	207	31
Average Time per vehicle(Minutes)	18,9	5,23	49,1	22,93	3,49	53,33	23,4	8,34	38,54	23,79	5,3	45,83
Throughput(TEU/hr)	75,83	70,93	74,67	72,5	70,62	73,67	76	73,7	75	74,67	70,16	75
Fleet Size	26	8	64	30	6	68	32	12	50	32	8	60
Container Output	70	210	28	58	278	26	57	145	36	56	207	30
RunTime(Minutes)	1440	1421,1	1440	1440	1417,07	1440	1440	1416,6	1440	1440	1416,21	1440
Number of Parallel Process Required	13	4	32	15	3	34	16	6	25	16	4	30
Overall Container Output	910	840	896	870	834	884	912	870	900	896	828	900

C.3.2 Route Analysis

Table C.12: Route: Case SV Results

Outputs	Euromax to RWG		Euromax to APMT2		Euromax to Delta 2		Euromax to Delta	
	Truck	AAGV	Truck	AAGV	Truck	AAGV	Truck	AAGV
Time(minutes)	24,13	49,1	26,42	53,33	31,74	38,54	29,09	45,83
Throughput (TEU/hr)	70	74,67	69,5	73,67	72,5	75	69	75
FleetSize	34	64	36	68	44	50	40	60
Fulfillment rate (%)	89,36	95,32	88,72	94,04	92,55	95,74	88,09	95,74

C.4 Case VS: Quay To Yard

C.4.1 Results

Table C.13: Case VS Data

	Truck		Barge						AAGV
	AGV	Truck	AGV	Barge	AGV				
Overall Container Input	3761	3660	3761	3636	675	675	675	675	3761
Container Input	184	258	203	1200	91	92	90	47	116
No. of Cranes for loading	6	20	6	3	3	3	3	3	1
No. of Cranes for unloading	20	14	14	3	7	7	7	14	1
Average Time per vehicle (Minutes)	7,52	22,05	6,75	454,94	8,7	8,46	8,85	18,83	46,83
Throughput(TEU/hr)	305	297,89	76,42	226,06	77,28	78,99	76,42	78,99	298,67
Fleet Size	40	112	14	15	14	14	14	28	224
Container Output	183	254	202	900	90	92	89	46	112
RunTime(Minutes)	1440	1432,48	1440	1433,25	978,31	978,31	978,31	978,31	1440
Barge Input				12					
Barge Output				9					
Number of Parallel Process Required	20	14	18	3	7	7	7	14	32
Overall Container Output	3660	3556	3636	2700	630	644	623	644	3584

Table C.14: Case VS Results

Mode	Average Time per container (minutes)	Throughput (TEU/hr)	Re-Handling Points	Total FleetSize	Fulfillment rate (%)
Truck	29,57	296,33	3	152	94,55
AAGV	46,83	298,67	2	224	95,29
Barge	472,9	211,75	4	99	67,56

Table C.15: Route: Case VS Data

Inputs	Quay To Yard											
	Euromax To RWG			Euromax To APMT2			Euromax To Delta 2			Euromax To Delta		
	Truck		AAGV	Truck		AAGV	Truck		AAGV	Truck		AAGV
	AGV	Truck		AGV	Truck		AGV	Truck		AGV	Truck	
Overall Container Input	940	915	940	940	915	940	940	915	940	940	915	940
Container Input	184	70	28	184	59	25	184	58	38	184	57	31
Average Time per vehicle(Minutes)	7,52	18,9	50,47	7,52	22,93	56,48	7,52	23,4	37,54	7,52	23,79	45,32
Throughput(TEU/hr)	76,25	76,23	74,25	76,25	72,88	74	76,25	71,62	74	76,25	75,06	75
Fleet Size	10	26	66	10	30	74	10	30	48	10	32	60
Container Output	183	70	27	183	58	24	183	57	37	183	56	30
RunTime(Minutes)	1440	1432,48	1440	1440	1432,48	1440	1440	1432,48	1440	1440	1432,48	1440
Number of Parallel Process Required	5	13	33	5	15	37	5	15	24	5	16	30
Overall Container Output	915	910	891	915	870	888	915	855	888	915	896	900

C.4.2 Route Analysis

Table C.16: Route: Case VS Results

Outputs	Euromax to RWG		Euromax to APMT2		Euromax to Delta 2		Euromax to Delta	
	Truck	AAGV	Truck	AAGV	Truck	AAGV	Truck	AAGV
Time(minutes)	26,42	50,47	30,45	56,48	30,92	37,54	31,31	45,32
Throughput (TEU/hr)	75,83	74,25	72,5	74	71,25	74	74,67	75
FleetSize	36	66	40	74	40	48	42	60
Fulfillment rate (%)	96,81	94,79	92,55	94,47	90,96	94,47	95,32	95,74

C.5 Route Analysis

Table C.17: Case wise route analysis: Hutchinson Ports ECT Euromax to Rotterdam World Gateway

KPI	Case SS		Case VV		Case SV		Case VS	
	Case SS-T	Case SS-A	Case VV-T	Case VV-A	Case SV-T	Case SV-A	Case VS-T	Case VS-A
Re-Handling Points	2	2	4	2	3	2	3	2
Fleet Size	26	64	44	64	34	64	36	66
Time (minutes)	18,9	48,67	31,65	49,75	24,13	49,1	26,42	50,47
Throughput (TEU/hr)	75,83	74,67	69,67	76,25	70	74,67	75,83	74,25
Fulfillment Rate %	96,81	95,32	88,94	95,32	89,36	95,32	96,81	94,79

Table C.18: Case wise route analysis: Hutchinson Ports ECT Euromax to APM Terminals Maasvlakte 2

KPI	Case SS		Case VV		Case SV		Case VS	
	Case SS-T	Case SS-A	Case VV-T	Case VV-A	Case SV-T	Case SV-A	Case VS-T	Case VS-A
Re-Handling Points	2	2	4	2	3	2	3	2
Fleet Size	30	72	46	72	36	68	40	74
Time (minutes)	22,93	54,74	33,94	54,48	26,42	53,33	30,45	56,48
Throughput (TEU/hr)	72,5	75	69	75	69,5	73,67	72,5	74
Fulfillment Rate %	92,55	95,74	88,09	95,74	88,72	94,04	92,55	94,47

Table C.19: Case wise route analysis: Hutchinson Ports ECT Euromax to Hutchinson Ports Delta 2

KPI	Case SS		Case VV		Case SV		Case VS	
	Case SS-T	Case SS-A	Case VV-T	Case VV-A	Case SV-T	Case SV-A	Case VS-T	Case VS-A
Re-Handling Points	2	2	4	2	3	2	3	2
Fleet Size	32	48	50	52	44	50	40	48
Time (minutes)	23,4	37,1	39,26	39,85	31,74	38,54	30,92	37,54
Throughput (TEU/hr)	76	74	59,17	75,83	72,5	75	71,25	74
Fulfillment Rate %	97,02	94,47	75,53	96,81	92,55	95,74	90,96	94,47

Table C.20: Case wise route analysis: Hutchinson Ports ECT Euromax to Hutchinson Ports ECT Delta

KPI	Case SS		Case VV		Case SV		Case VS	
	Case SS-T	Case SS-A	Case VV-T	Case VV-A	Case SV-T	Case SV-A	Case VS-T	Case VS-A
Re-Handling Points	2	2	4	2	3	2	3	2
Fleet Size	32	58	50	64	40	60	42	60
Time (minutes)	23,79	44,69	36,61	48,47	29,09	45,83	31,31	45,32
Throughput (TEU/hr)	74,67	74,92	68,67	74,67	69	75	74,67	75
Fulfillment Rate %	95,32	95,64	87,66	95,32	88,09	95,74	95,32	95,74

C.6 Sensitivity Analysis

C.6.1 Case VV: Quay To Quay

Table C.21: Sensitivity: Case VV Data

	AAGV						
Overall Container Input	2945	3385	3573	3761	3949	4137	4576
Container Input	100	99	100	100	100	113	114
Average Time per vehicle(Minutes)	48,02	48,16	48,03	48,2	48,19	48,13	48,08
Throughput(TEU/hr)	232	269,17	280	296	312	327	366,67
Fleet Size	174	204	210	222	234	252	280
Container Output	96	95	96	96	96	109	110
RunTime(Minutes)	1440	1440	1440	1440	1440	1440	1440
Number of Parallel Process Required	29	34	35	37	39	36	40
Overall Container Output	2784	3230	3360	3552	3744	3924	4400

Table C.22: Sensitivity: Case VV Results

	Container Input	Throughput (TEU/hr)	FleetSize	Fulfillment rate (%)	Time (minutes)
Projected Average Demand -10%	3385	269,17	204	95,42	48,16
Projected Average Demand -5%	3573	280	210	94,04	48,03
Projected Average Demand	3761	296	222	94,44	48,2
Projected Average Demand +5%	3949	312	234	94,81	48,19
Projected Average Demand +10%	4137	327	252	94,85	48,13
Projected Reduced Demand Scenario	2945	232	174	94,53	48,02
Projected High Demand Scenario	4576	366,67	280	96,15	48,08

C.6.2 Case SV: Yard To Quay

Table C.23: Sensitivity: Case SV Data

	AAGV						
Overall Container Input	2945	3385	3573	3761	3949	4137	4576
Container Input	116	116	116	116	116	116	116
Average Time per vehicle(Minutes)	46,52	46,52	46,48	46,44	46,5	46,43	46,42
Throughput(TEU/hr)	233,33	270,67	280	298,67	317,33	326,67	364
Fleet Size	175	203	210	224	238	245	273
Container Output	112	112	112	112	112	112	112
RunTime(Minutes)	1440	1440	1440	1440	1440	1440	1440
Number of Parallel Process Required	25	29	30	32	34	35	39
Overall Container Output	2800	3248	3360	3584	3808	3920	4368

Table C.24: Sensitivity: Case SV Results

	Container Input	Throughput (TEU/hr)	FleetSize	Fulfillment rate (%)	Time (minutes)
Projected Average Demand -10%	3385	270,67	203	95,95	46,52
Projected Average Demand -5%	3573	280	210	94,04	46,48
Projected Average Demand	3761	298,67	224	95,29	46,44
Projected Average Demand +5%	3949	317,33	238	96,43	46,5
Projected Average Demand +10%	4137	326,67	245	94,75	46,43
Projected Reduced Demand Scenario	2945	233,33	175	95,08	46,52
Projected High Demand Scenario	4576	364	273	95,45	46,42