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Performance Evaluation and Capacity Planning of Port-Hinterland Transport Chains with System Dynamics Modeling: Analysis of the Railway Network

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Abstract

The performance of ports is fundamental for an efficient, competitive and sustainable global supply chain, for which the effective management of the multiple flows present becomes crucial. Particularly, land-side flows are often a critical and operationally intensive link, since rail and road networks must ensure a rapid dispatch of trains and trucks to prevent congestion, bottlenecks and delays.

This thesis aims to study, model and simulate a port node, focusing on the rail flows and their interaction with truck flows as the networks intersect within the limited space of port areas.

Given the non-linear dynamics of these processes, a static analysis would fail to capture emergent behaviors, therefore, a System Dynamics (SD) modeling approach was adopted, suited to capture the feedback mechanisms, interdependencies and time delays within logistic systems.

The analysis was conducted through a case study of an Italian port based on real operation data, developing n initial analysis on normal conditions, and assessing multiple demand growth and disruption scenarios in the studied networks.

The key findings demonstrate that the system's bottlenecks originate in shared sections of the railway that connect terminals, and at conflict points between both rail and road flows, where regulations give priority to trains which leads to queues, cascading delays and risk a systemic gridlock. In such way, the model effectively identifies critical sections and vulnerabilities, offering valuable insights for future improvements regarding the node's resilience, capacity and efficiency in its operations.

The present document was developed in multiple sections as shown below.

Chapter 1 - context of reference

Presents a theoretical background on port logistics, multimodal transport and hinterland connectivity. The chapter concludes with a literature review that establishes the innovative contribution of this thesis.

Chapter 2 - Methodology: System Dynamics Simulation

Describes the research methodology used, introducing simulation as a tool for analyzing complex port systems and comparing multiple approaches, justifying the selection of a System Dynamics (SD) given its ability to capture system's feedback loops and aggregate flows.

Chapter 3 – Case Study

Details the simulation model, based on a real Italian port case study. It explains the development of the rail and road network model, and the crossings between them and outlines the demand growth and disruption scenarios that were tested.

Chapter 4 – Results

Presents the simulation results, beginning with model validation. It analyzes the rail network's performance under various scenarios and then quantifies the impact of rail-road interactions at crossings, focusing on system throughput and congestion.

Chapter 5 – Conclusions

Summarizes the key findings, identifying segment A, hub B and crossing X3 as the primary sources of bottlenecks. It concludes that rail priority at crossings reduces the road network's throughput revealing critical points of operational friction.

Chapter 6 – Scope and limitations

Outlines the study's boundaries clarifying that the model focuses on internal dynamics and uses necessary simplifications.

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1. *Context of Reference*

Developed in collaboration with Sara Cardinale

1.1. Overview of freight transport and logistics.

Logistics refers to the strategic coordination of activities that ensure goods, services, and information move smoothly and efficiently between two points. Its purpose is not only to satisfy customer expectations but also to optimize performance across the entire flow, balancing speed, reliability, and cost-effectiveness.

While logistics' approach is more related to the movement of goods in the right way, time and place, supply chain management manages the full journey of a product end-to-end. In other words, while logistics' concern is on how goods move from A to B, supply chain management focuses on how the whole journey is managed from first supplier to final customer.

Freight transportation is a milestone in global trade, ensuring that goods move efficiently from producers to consumers across continents. Today, the rise of multimodal and intermodal transportation solutions is reshaping industry, improving flexibility and connectivity while addressing growing challenges such as environmental pollution and the need for sustainable practices.

1.1.1. Freight transport systems

Freight transportation refers to the movement of goods and materials from one place to another and plays a crucial role in the global economy by providing a critically important service within supply chains, linking distant points of supply and demand. Over the years, freight flows have steadily increased due to various factors, such as population growth, reduced trade barriers, and decreasing transportation costs. In addition, increased consumption and growing demand for personalized products and services, as well as the development of online purchasing platforms, have further contributed to this expansion. This growth has also been supported by significant infrastructure developments, such as the expansion of roads, railways, waterways, ports, and storage and transshipment facilities. Nowadays, the effectiveness of freight transportation characterizes the competitiveness of countries, as it directly affects the cost and efficiency of international trade. [1]

Core components of transportation

According to Rodrigue, in its book "The Geography of Transport Systems" [2], there are four main components that are necessary for transportation to take place, and they are the same for freight and passenger transportation.

- *Modes*: they represent the vehicles used for activities; some vehicles are designed exclusively for transporting people or goods, while others can perform both functions.
- *Infrastructure*: they constitute the physical support of transportation assets and include both routes (such as railways, canals or highways) and terminals (such as ports or airports). Infrastructure also includes superstructures, or movable assets; in the port context, infrastructure refers to piers and shipping channels, while superstructures include cranes, handling equipment and yard equipment.
- *Transportation networks*: they are systems consisting of interconnected locations that define the functional and spatial organization of mobility. Networks indicate which points are interconnected and how service occurs between them.
- *Flows*: they represent the movements of people, goods, and information through their respective networks. Each flow has an origin, possible intermediate stages and a final destination.

Modes of transport

There are four main modes of freight transport: road transport, rail transport, sea transport and air transport. The efficiency of freight transport modes varies greatly between them, and each mode has unique advantages and disadvantages.

Road transport provides high distribution capillarity, offers low costs over short distances, and provides fast and reliable service. However, it is constrained by transporting limited volumes of goods, is highly prone to congestion, has higher accident rates, and is the mode of transportation that contributes most to environmental pollution. [3]

Rail transport can move a significant amount of freight, allows scheduled operations, operates efficiently over medium to long distances, is considered safe and tends to be sustainable. However, it is limited to tracks, where passenger trains often take priority, requires cost and waiting time at terminals, and is suitable primarily for large volumes of lower-value raw materials. [3]

Sea transport can accommodate large quantities of cargo, adapting to a wide range of cargo types, is highly energy efficient, and is cost-effective for long-distance, high-volume shipments. However, it requires considerable time and cost for terminal operations, depends on large volumes of cargo to remain economically viable, and operates at relatively low transport speeds. [3]

Air transport allows minimal travel time over long distances and reduces the likelihood of goods being lost or damaged. On the other hand, it generates high environmental pollution, incurs higher costs than other modes, and is not suitable for all types of goods due to capacity and cost constraints. It tends to be used for the transport of high-value goods. [3]

Some other minor modes are, for example, inland waterways and pipelines.

1.1.2. Multimodal and intermodal transport

The evolution of global trade is driving significant changes in transportation strategies, and examples include intermodal and multimodal transportation. In particular, key trends such as the continued globalization of the economy, the increasing demand for faster product delivery, the adoption of agile business practices, and the need for efficient supply chain management are reshaping the way companies move goods. These factors highlight the growing importance of flexible and integrated transportation solutions to meet modern business needs. [4]

Differences and benefits of multimodal and intermodal strategies

Multimodal freight transport refers to the movement of goods through a sequence of at least two different modes of transport. In this context, the transport unit can be of any type: a box, a container, a swap body, a road/rail vehicle or even a vessel.

Intermodal freight transport is a specific type of multimodal transport in which cargo is transported from origin to destination in a single standardized intermodal unit, such as a TEU container, without the goods being moved during mode changes. [5]

According to Gordon and Young [6], the main outcomes from the transportation market services embracing intermodalism are:

1. A key economic advantage is improved asset utilization, wherein equipment, whether ships, trucks, or railcars, is not unduly idled during the loading and unloading process.
2. Goods to be transported are secured within a vehicle at the origin and do not undergo intermediate transloading, a task that is typically a prime target for damage, theft, or tampering.

3. It speeds the movement of goods between producer and consumer, thereby reducing the volume of inventory in transit and its holding cost, which may be substantial.

Intermodal transport is often preferred because of its economic and environmental and social benefits. First of all, the use of the most appropriate means of transportation for different types of trips and loads gives the possibility to exploit the cost advantages of each mode; then, this type of system leads to less pollution and congestion. The main drawbacks of the intermodal cycle are linked to cost increase at terminals, long trans-shipment times, and greater vulnerability at nodes. Multimodal transport can be expensive as well, mainly because of the costs of managing and coordinating the passage of goods between one system and another. On the other hand, it allows for superior geographic coverage, while intermodal can be more limited, especially if certain infrastructure, such as rail, is not available. Often, in intermodal cycles this problem is solved by operating the initial and final part of the transport by road. [3]

Hub and spoke networks

The hub and spoke system is a transportation model consisting of central nodes, called hubs, connected to surrounding nodes, called spokes. High-capacity transport services are frequently carried out between hubs, while low-capacity transport services are less frequently carried out between spokes. [3]

This type of model has developed as a result of the introduction of solutions related to intermodality and multimodality and has partly replaced the traditional point-to-point approach. Previously, in fact, transportation took place directly from producer to consumer, without taking advantage of intermediate stopping points or mode changes. [2]

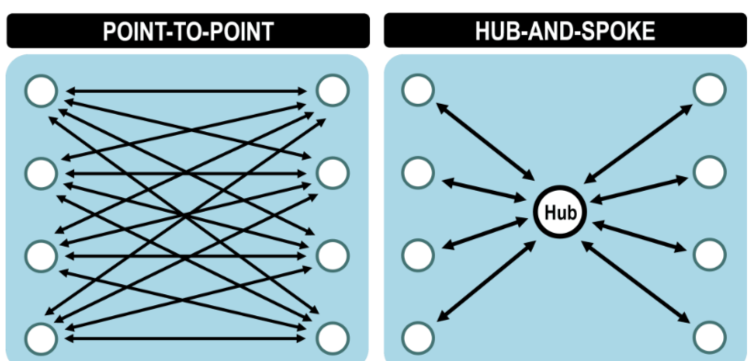

Figure 1: Point-to-point and hub-and-spoke networks [2]

Compared with point-to-point systems, hub-and-spoke models offer many advantages, which are able to improve operational efficiency and overall quality of transportation service (View Figure 1). Some of these advantages, according to Rodrigue [2] are:

1. Cost reduction, in the sense of lowering transportation costs for the individual unit, is achieved by concentrating traffic flows at hubs, which allows them to benefit from economies of scale.
2. Increased frequency of services, referring to the possibility of ensuring more regularity of connections to the hubs, allowing more daily departures between origin-destination pairs that would otherwise be underserved.
3. Expansion of network coverage, achieved by connecting peripheral nodes to central hubs, allowing access to more destinations without the need to activate direct connections for each terminal pair.
4. Operational simplification, the centralized nature of the system, allows a reduction in management complexity compared to traditional management of multiple direct links.
5. Environmental benefits, resulting from the concentration of shipments and route optimization, contribute to the reduction of energy consumption and emissions.

Importance of transport mode integration for efficiency

Considering what has been discussed until now, it is possible to draw the conclusion that the integration of different modes of transport plays a key role in the overall improvement of the efficiency of transportation and logistics systems. Combining different modes of transport in a differentiated manner allows the best features of each to be exploited: the flexibility and capillarity of road transport, the sustainability of rail transport, and the high capacity of maritime transport. As can be deduced, even considering the case of introducing hub-and-spoke systems instead of traditional point-to-point systems, proper coordination of transportation allows optimizing its performance and thus, reducing overall costs, travel time and the number of handling operations.

There are several studies, one of which considers the case of an Italian company, which show how the modal shift from unimodal road transport in favor of combined transport brought several benefits. In particular, it is shown that one of the main benefits has been a significant reduction in generalized transportation costs on shipments, but also on the costs of negative externalities. Other remarkable benefits were a reduction in transportation time and an improvement in punctuality.

Some modes of transport, such as rail transport, are less affected by delays due to traffic, for example, in the case of road transport. [7]

3.2.3 Challenges in freight transport

As the transportation sector expands to meet growing demand, it faces significant challenges that inhibit its performance and sustainability. There are four critical issues for which solutions are always being sought, and they are: infrastructure limitations, technology integration, and environmental sustainability.

Infrastructure limitations

Infrastructure is a critical bottleneck to achieving efficient freight transport. The main physical constraints that currently exist are aging road networks, limited rail capacity, and congestion at transfer points. In general, infrastructure constraints lead to increased transit times, operational costs, and environmental impacts, as freight operators are forced to rely on less efficient modes of transportation, such as road transport, due to the lack of connections to other types of transportation considered more sustainable, such as rail. The problem could be solved through a comprehensive policy approach that prioritizes targeted investments in infrastructure improvements and the development of smart, integrated transportation hubs. Such improvements would enable a smoother modal shift and ensure that freight flows are less disrupted by capacity constraints, ultimately contributing to a more resilient and cost-effective transportation network.

Technology integration

Digital technologies are transforming logistics from a purely operational function to an integrated, proactive, data-driven system. Through IoT, automation, blockchain, AI and data analytics, it is now possible to gain end-to-end visibility throughout the supply chain, dynamically optimize routes and inventory, reduce downtime and enable new service models. These innovations, if properly implemented, play a key role not only in reducing costs and lead times, but also in the overall sustainability of transportation and warehousing operations.

Digitization is rapidly transforming the freight industry, enabling more efficient, data-driven decision making and operational optimization. The adoption of new technologies such as data analytics, Internet of Things (IoT) devices and other ICT solutions can greatly improve the operation of the industry. These technologies enable real-time monitoring of freight movements and more accurate forecasting of demand, which in turn helps logistics operators optimize routes and reduce unnecessary idle runs. However, despite these innovative solutions, there are still issues that limit them, including integration into pre-existing systems, data interoperability issues, and data privacy issues. Addressing these challenges requires coordination among industry stakeholders and policymakers, with a range of investments in both technology and training to facilitate a smoother digital transition. [8]

Environmental sustainability

Despite the many benefits of its development, freight flows have increasingly attracted public policy attention from an environmental and sustainability perspective in recent decades. This attention aims to reduce the negative impacts of freight growth, including local emissions affecting public health, greenhouse gas emissions, and traffic accidents. These issues that also concern passenger transport. [1]

According to the European Environment Agency (EEA), transport was responsible for approximately 25% of the European Union's total greenhouse gas emissions in 2020, ranking second after the energy sector. Within this share, road transport alone generated more than 70 percent of transport-related emissions, ranking first as the main pollutant in the sector. [9]

The European Union has set itself the goal of becoming the first continent in the world to achieve climate neutrality by 2050, and to achieve this, it assumes that greenhouse gas emissions related to the transport sector will reach a 90% reduction by that deadline. To achieve this goal, different solutions have been devised so far, [10] the most effective ones consists of providing incentives for the use of low-emission lorries. [11]

1.2. Shipping sector

When talking about the transport sector, the concept of "shipping" is related to the transport of goods in ships. The core function of a port system is for the secure transfer of goods between sea and land modes of transport. [12]

1.2.1. General overview of maritime transport

Sea transport is the oldest means of transport of goods in mankind, and the current predominant way to transport goods internationally, representing 80% of the global volume of trade, or 70% in terms of value. [3] In a global context, the shipping sector has grown in the last decades and has been an indicator of the global economic trend. Both maritime transport and port management have had considerable evolution, and due to the increased competition between shipping lines and between ports, the costs of operations have gradually decreased. [10]

Ever since World War II, maritime trade has been expanding at a rapid pace, and world economies have become reliant on the efficiency of the shipping sector. Therefore, both the industry and the port operators are making great efforts to reduce the costs of operation, through strategies such as economies of scale, container handling, and, more recently, technological innovations that enhance efficiency. [10]

Regarding container handling, the containerization rate has been growing at a high pace, thanks to the possibility of efficiency and standardization in operations that these transport units allow. And with it, the maximum capacity of the vessels has increased to adapt to demand, though its growth remains constrained by port infrastructure limitations. [10]

On another hand, economies of scale contribute to a more effective transport system and are related to a core principle of transportation: the balance between massification and atomization. While massification involves higher capacity and larger terminals, it has limited flexibility. Yet, atomization, related to lower quantities, leads to more expensive costs for moving but allows for greater flexibility. [3]

1.2.2. Current economic situation of the maritime transport sector

After understanding the overall role of port in global trade, it's possible to review deeper the recent situation of the shipping sector. Despite its rapid growth and continuous strategies to reduce operational costs, and enhance connectivity between ports around the world, recent challenges in maritime trade have intensified. Various elements shape shipping trends, including geopolitical conditions, economic fluctuations, and global factors such as e-commerce growth, the decentralization of production processes, the evolution of global supply chains, port and transport operations, and technological advances. [3]

Geopolitical tensions in key chokepoints and vulnerable economies to rising shipping costs are significantly impacting global trade flows. According to the Review of Maritime Transport by the UN [], checkpoints such as Suez and Panama channels had a reduction of about half of their transit during 2023, with further declines in 2024. In particular, the Panama channel disruptions, led to an increase in 31% of the sailing distances. Additionally, connectivity has also dropped, and small islands and developing countries have suffered the impact, with a drop in connectivity of 9%. [13]

All these conditions caused rerouting, port congestion and rising operational costs, which led to increased freight rates during 2024, impacting mainly nations that highly rely on maritime transport, threatening stability and driving inflation. Although in 2023, global maritime trade had a growth of 2.4% achieving 12.3 billion tons transported, following a contraction in 2022, these disruptions call for actions, including the implementation of monitoring systems for detecting early disruptions in chokepoints, along with other actions such as international cooperation. [13]

In addition to these issues, another major one has arisen in the last decades: climate change. Shipping is responsible for 3% of the global greenhouse gas emissions. One of the possible strategies would be to renew fleets to more sustainable and efficient ones, but due to high costs this solution is developing very slowly. In contrast to the growth of cargo capacity, only 14% of new tonnage was fuel-alternative, which accentuates the failure to assess decarbonization. Moreover, due to policies implemented in relation to climate change, costs of operations have been impacted, since upon failure to assess decarbonization penalties are applied, which increases costs, and reduces competitiveness. [13]

1.2.1. Demand and supply in ports

As already mentioned, maritime transport plays a fundamental role and is tightly related to world economy. This leads to great importance of demand and supply at port level, influenced by multiple factors. In sports, and in general in transportation, demand is considered a derived demand, which means that it exists because of the need for another good or service, whether it is moving freight or passengers. [14]

Maritime transport arises meets different needs. In the case of freight, it is influenced by factors such as a country's Gross Domestic Product (GDP), how sensitive demand is to changes in price, transport costs and alternatives of transport available. On another hand, for passenger transport, factors such as people's income, time for leisure, the purpose of passenger's journey, and the possibility to choose between different destinations are more determinant in alternative to GDP or price elasticity. [14]

Ports also serve as demand generators. This is accentuated if they offer a good range of port and related services of good quality, if they are specialized and facilitate transportation, and if they are well interconnected with landside networks. This may be evidence for example in containerized cargo, as they not only manage local economy goods, but also intermediate goods that require other services such as storage, transshipment or assembly nearby. [14]

1.2.2. Port operations: structure, stakeholders and process

Ports represent a complex system with dynamic operations related to handling, transporting and storing the units of goods, becoming critical nodes in global supply chains.

General port functioning

Generally, ports are composed of maritime access to either a natural or artificial area. This access goes to the basins that are surrounded by breakwater to reduce the hit of waves in the area, and then inland they include surfaces and piers. The fundamental physical elements are the following seen in Figure 2:

Figure 2: Fundamental physical elements of a port [14]

- *Harbor*: a sheltered natural or artificial area where port operations take place, having careful control regarding depth and navigation.
- *Anchorage areas:* designated areas for ships to anchor while waiting for an available berth. Delimited with buoys, and in some cases located within the harbor.
- *Breakwater*: protective barriers built in harbors to shield them against strong waves, tides, winds and currents.
- *Navigation channels*: routes that guide ship to the harbor, including outer access channels, and inner approach channels. Their depth is controlled, and navigation is assisted by pilots and tugboats.

- *Turning basin:* A circular area where vessels are able to turn around with the help of tugboats, with at least twice the length of the largest that is allowed.
- *Berthing basin:* also known as docks, is the area next to a berth where ships are moored. It is important that they ensure enough capacity, length, and depth.
- *Berths*: docking structures that support both berthing and mooring.
- *Wharves*: structures made up of one or more berths parallelly aligned with the shore.
- *Piers*: structures that extend into the harbor as an extension of the terminal facility, often equipped with storage facilities such as storage sheds and warehouses.
- *Jetties*: thin docking structures that extend to the sea in order to support loading and unloading of cargo into ships.
- *Dry docks:* enclosed basins that may be filled or emptied to allow ship construction, maintenance and repairing.

Their characteristics, logistics and organization differ according to aspects such as flow of goods, service categories, functionality, among others. [14]

Classification of services

Regarding service categories, shipping may be divided into two. First, tramp services which handle bulk shipping of both liquid and solid bulk on demand, including petroleum, chemical products, food, coal, minerals, among others. On the other hand, liner services are related to both general cargo and passengers, with pre-established regular lines. General cargo may be conventional for elements like wood or cars, or containerized for goods such as finished products, components, machinery and food. Meanwhile, passengers may be transported through ferries or cruises.

These services may be done through different types of ships, which may handle several amounts of goods, including deep-sea vessels, feeder ships, and barges. The last are for transport in the hinterlands through rivers or canals. As for which ship is used, an important distinction has to be done: hub and spoke networks. As mentioned before, and applying it to the case of maritime transport, this concept is related to connectivity between ports, in such a way that the number of connections needed is reduced. In this case, smaller or less important ports (spokes) are all connected to main ones (hubs), which have the most frequent and higher capacity services. For these, ships such as deep-sea vessels with capacities of up to 24,300 TEUs serve hub ports, while feeder ships of 800-2800 TEUs serve smaller regional ports. This also implies that hubs need infrastructure for bigger ships, which affects depth, logistics, size, among other factors of its design and management. Also, in relation to the flow of goods, they may be classified as: gateway ports where flow is given between ship and trucks or trains either as import or export, or as transshipment ports, when flow goes from bigger ships to smaller ones (hubs) that are feeder vessels. [3]

Finally, regarding the general functioning and classification of ports, it is also useful to understand the institutional models, for which three categories may be defined. The private model has both property of the land and provisions of services in private way, while public model has both public. In this order of ideas, private models allow for better flexibility and quicker response to demand but less government oversight which could be the example of United Kingdom. While for public models there are more regulations and public funding, but a more rigid operation, which is usually seen in regions such as Africa and Latin America. In Italy, before 1994, the model adopted was public, but as it created a lack of efficiency and competitiveness, the land-lord model was introduced. This last model consists of public property of land either at regional or national level, and private provision of services. In this way, the new law in Italy separated two roles: port authorities as public entities who manage infrastructure and regulate port activities without a direct involvement in operations, and terminal operators as private companies that become responsible for economic and commercial services under concession. [3]

Main stakeholders in port operations

To better understand the stakeholders involved in such a complex process, it is useful to divide them into three main groups: seaside, port or terminal, and landside or hinterland. Within each of these phases, and in the interaction between them, both public and private bodies play essential roles. (View Figure 3) [3]

First, starting with the seaside, two main stakeholders are involved. First, *port guards*, a public authority responsible for administrative activities related to maritime safety, whose main task is to ensure safety in port activities and safeguarding of human life in the sea. The second major stakeholder in seaside is the shipping line, which Is a private company in charge of transporting good by sea on behalf of a specific client, either with ships they own or chartered ones. *Shipping lines* may be composed of different figures: the shipowner, responsible for ship's operation and technical safety compliance, the owner who actually possesses the vessel's holdings, the renter who leases the ship if shipowner is not the direct owner, and the carrier who has the contractual obligation of delivering goods by sea under a bill of lading. Finally, supporting the shipping line is the *ship agent*, a private actor with the task of administrative, operational and commercial formalities related to ship arrival and departure, in charge of representing the interests of the shipowner before institutions and port authorities. [3]

Regarding the connection between vessels and port infrastructure, *technical-nautical services* play a fundamental role. Tho public in nature, they are carried out by private companies operating under concession, who are in charge of three main activities: piloting, where a specialized port pilot is authorized to perform navigation within port waters to guide it safely to berth, towing which involves using cables or tugboats to assist vessels without propulsion, and mooring, related to securing and releasing ships at the dock and its movement within the port. [3]

Then, regarding the terminal domain, three main actors take part. The *port authority* is responsible for managing the governance of port areas, planning, coordinating and promoting operations oversee, and granting authorizations and concessions when needed to *terminal operators*. These last, usually private, are responsible for the core logistics such as handling, loading and unloading of cargo along ship to storage areas and vice versa. These functions are supported by the stevedores, who do the physical labor related to cargo handling. [3]

For a proper transition between the port and inland destinations, additional stakeholders operate. *Inspectorates and customs* are in charge of verifying compliance I information, classification and documentation of goods. [3]

Finally, regarding the hinterland side, transport operations include multiple critical actors, such as the *railway infrastructure manager* who is a public company that must construct and maintain the rail infrastructure, the *shunting company* which operates diesel locomotives for the movement of goods between the terminals and the intermodal yards, the actual *rail operator* that conducts the rail freight transport service by itself, and *road carriers:* which are responsible for accepting orders, loading and unloading, movement of cargo, among others. [3]

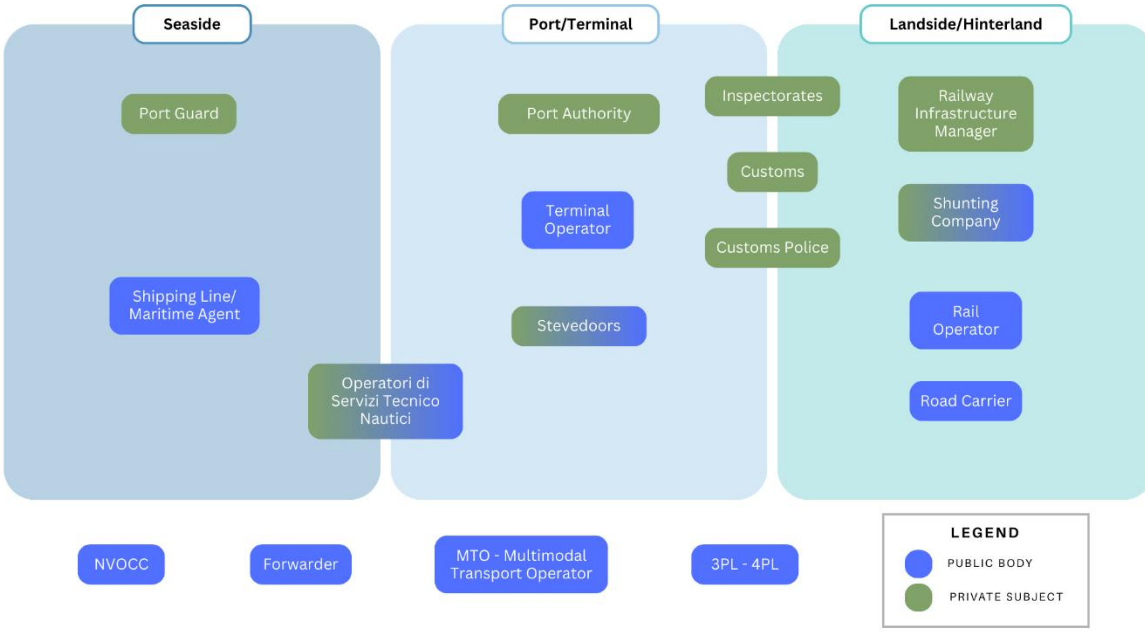

Figure 3: Port stakeholders – Made by the author adapted from: [3]

Additional to these actors, other important stakeholders operate not on a specific activity but mostly throughout the entire logistics process, like the case of the *Non-Vessel Operating Common Carrier (NVOCC),* which acts as a type of maritime carrier but without owning any vessels but instead shopping portions of cargo space from actual shipowners and issuing their own bill of lading. Regarding the *freight forwarder* they manage the overall logistic chain across multiple transport modes, coordinate interactions among the agents and carriers, optimize transport without actually owning vessels or cargo, etc. In more complex and large-scale logistics operations, a *multimodal transport operator (MTO)* may be involved in overseeing the integrated transport services and managing the entire flow of transport for the entire cycle. Finally, both *third party logistics (3PL)* and *fourth party logistics (4PL)* offer coordination of multiple service providers and optimize the entire supply chain on behalf of the client. [3]

Types of cargo handling technologies and systems

Handling of the goods may be done in two ways: LO-LO (Lift-on/Lift-off) a technique where cranes are used to move the loading units, like for example with containers. Or, RO-RO (Roll-on/Roll-off), a technique that does not use cranes, as vehicles get on the ship by themselves with the goods loaded by using ramps. This las way of transport may be either accompanied in which the driver stays during the ship trip (or train trip), or unaccompanied, where the driver loads the vehicle to the ship or train and then leaves it there, until the next destination where a new driver receives it. [3]

As mentioned before, containerization has emerged and settled as a useful and efficient solution. Beginning in 1952, it allowed for a reinvention of managing merch. Containerization allows for higher efficiency, as it lowers costs by 35% and loading and discharging time by more than 80%. [15]

As introduced before, intermodal transport does not handle directly goods, but handles intermodal transport units, which may be containers, swap bodies, and semitrailers. Containers are mainly useful for maritime transport and were introduced as a standardized box for transportation, revolutionizing freight transport and giving importance to maritime transport which thanks to this became cheaper and more agile. [16]

A container is a rectangular prism with corner fittings for handling it, a bottom and side rail, and multiple other elements that allow movement and handling of it. They can be stacked, which allows for an optimal organization in storage, and are usually handled using cranes. They are given by three measurements. The most used are TEU, related to 20 ft length containers. Their width and height are usually between 8 and 9 ft. [16]

There are two main container handling systems: Indirect Transfer System (ITS) and Direct Transfer System (DTS). In ITS containers are moved in stages by using yard cranes and trucks before reaching the final spot where they are stored, being a space-efficient system. On the other hand, in DTS, containers are picked up and placed directly with specialized vehicles without needing extra cranes, which requires more space but is faster and common in European ports. [12]

Bulk handling, on the other hand, consists of carrying out loose cargo. The load is defined by the size of the ship and the storage capacity in port and is handled in a different way depending on whether its liquid or dry bulk. Therefore, each bulk terminal specializes in a specific commodity, for example natural gas, grain, coal, among others, as they require different techniques and infrastructure. [14]

Key port operation activities

Along the whole logistical process from the arrival of the ship up to the internal procedures, the activities could be classified into three main groups of processes: waterside, yard and landside; the same classification framework used to categorize the stakeholders involved in each phase. [3] [17]

- **Waterside operations**

They include all activities occurring from the arrival of the vessel near to the port up to the preparation for cargo operations. The main operations are: arrival and berthing, piloting, towing, mooring, and initial clearance procedures.
Upon arrival, vessels arrive to berths, with the coordination between ship and port authorities. In most ports, it is compulsory for a different pilot to guide the boat through internal waters for safe maneuvering, as piloting is more complex than in open water. For bigger ships or for any ship with limited maneuvering, tugboats may provide propulsion support for vessels, this is known as towing. Following the arrival to the berth, the vessel must be secured using mooring lines. Finally, vessels undergo control checks in order to have initial clearance prior to cargo handling. [3] [17]

- **Yard operations**

Inside the yard or terminal area an interface between vessel and inland transport systems is given. In this zone key processes such as cargo handling, storage, internal transfer, and customs and clearance procedures consolidate the terminal operations.
Continuing from the process finished in the waterside, the goods must be loaded and unloaded, which depends on the cargo type. Handling technologies include cranes, straddle carriers, Ro-Ro ramps, grabs, suction systems or pipelines. After discharge, goods need to be stored temporarily in designated terminal areas, which also depend on the cargo requirements, but usually are container stacks, warehouses, silos, among others. During this phase internal transfers are performed between the vessels and the storage facilities throughout the gate areas, through vehicles such as terminal tractors, forklifts or conveyor systems. In this moment, customs and clearance procedures may be done, in which documentation is controlled, goods are classified, and inspections are performed before the cargo may continue inland. As mentioned before, the terminal operations are handled by terminal operators and supported by stevedores. [3] [17]

- **Landside operations**

Once cargo is cleared for inland movement, it’s annexed to the hinterland logistics chain, which includes activities such as gate operations, modal transfer, inland distribution and support services.

In this final process, first the cargo must exit the port area through controlled access points. Here, additional checks to documentation, weight and safety are performed. For this, a modal transfer must be done depending on the mode of transport selected, either trucks, trains or barges, or for the case of bulk: pipelines, conveyors or trucks. At this point inland distribution begins to deliver to the final destination. [3] [17]

1.2.3. Trends and innovations in maritime logistics

Port management has been in constant evolution over the past decades, leading to new technologies and a shift in trade patterns. For instance, thanks to Information Technology, satellite systems and software's are being used to facilitate communication between ports, ships and along the supply chain, which enables better cargo handling, operations and monitoring for better performance. Among strategies, the use of locations beacons is an important tool, including Automatic Identification System (AIS) to locate vessels emergency location beacons, transponders, radios, among others.

The maritime sector has responded to changes at a macroeconomic level given by globalization, relocation of production activities and consumption changes. Between the responses, one would be naval gigantism and technology advances in disciplines such as ship design and engineering and in ship operations, in order to adapt to port requirements and to be able to accommodate the client's requirements through efficient and safe operations. Another significant change would be unitization given by containerization, which as mentioned before, is able to increase significantly efficiency as it reduces loading and discharging times and costs. In relation to this, nowadays ports must have container handling facilities and appropriate equipment that allow for economies of scale by greater productivity, increased ship size and lower traffic. [3] [15] Another recent phenomenon to respond to macroeconomic changes is transshipment, in which the system is given by hub-and-spoke, where main and bigger ports are fed by smaller ports. [3]

It is of great importance to understand that nowadays globalization and the development of the maritime sector allow for supply chains to concentrate not in a single country or region but to have a global reach, with multiple headquarters and supplies coming from different countries. [3]

1.3. The shipping sector and hinterland connectivity

1.3.1. Port-hinterland concept

Ports have a role of gateways to inland networks, in which nodes are formed in between transport between intercontinental and continental flows. Thanks to containerization, larger container vessels and economies of scale, the role of ports as major gateways has expanded significantly. This, along with intermodal transport implementation, has allowed for a greater reach of the hinterlands. [14]

The study of operations and logistics in the hinterland is crucial, given the fact that the majority of transport costs happen inland and not at sea, even though sea journeys are longer. Inland logistics, including port connectivity with road and rail networks, often represent the most complex and expensive part of the supply chain. [14]

Port connectivity refers to the ability to connect ports and cities through logistics and transport networks such as road and rail, playing a crucial role in the efficiency of transport in a country. [3]

A port hinterland is a strategic component for the supply chain and refers to the piece of land over which a port extends its influence and operations regarding its activities and interaction with the users. Therefore, they encompass both business activities and customer areas. Nevertheless, it is not easy to objectively define the limit of a port hinterland, since they vary according to the type of commodities, season, economic cycles, and transport technologies. For instance, for the case of dry and liquid bulk it is more common to have customers within close proximity to the port, as inland transportation has high costs and is complex. Usually, it involves one direction only of flows, either incoming or outgoing, along with a low number of market players and destinations. On the contrary, containerized cargo involves bidirectional flow directions as multiple origins and destinations are scattered over the hinterland, therefore involving more competitors and economic players. This results in bigger hinterland areas for container terminals. [14]

In fact, containerization has fundamentally changed the hinterlands' dynamics. Before containers were invented, goods were transported between where they were produced to the closest port, meaning ships would have to stop in many ports along the way to have good coverage. In this way, ports served their own territory and nearby area, known as captive hinterland, and did not actually compete between each other. Then, with the rise of containerization, goods became easier to move in ships, trucks and trains, so goods may travel longer distances in a faster and more economic way, resulting in ports now reaching farther inland and attracting goods from bigger areas. This meant that hinterlands between ports started to intersect, so now businesses get to choose between which ports to use, leading to more competitivity between ports, in which their success depends greatly on their hinterland access and connectivity. Larger ships stopping at fewer ports also means that inland distribution must be cost-effective for customers further away, reinforcing the importance of inland transport systems. [14]

1.3.2. Internal port logistics and layouts

Port connectivity and internal transport

Port regionalization is a phenomenon in which maritime transport and inland freight transport systems are integrated, instead of them evolving separately, thanks especially to intermodal transportation opportunities. This phase happens after an integration of transshipment hubs and is characterized by the formation of regional load center networks with multimodal logistics platforms in its hinterland. Port regionalization is achieved through developing rails and corridors between a port and a network of inland load centers. These corridors facilitate freight transportation in an uninterrupted and continuous way. It addresses two important issues: externalization of local constraints in relation to growth and efficiency such as lack of available land or increased port traffic, supply chain integration. [14]

The transport connection between ports and inland areas is shaped by four key components which, in relation to maritime-land connectivity, are particularly important in long-distance trade. First, the foreland which represents the sea routes and connection that a port has with other ports around the world. Then, the port system, referring to the infrastructure that connects the port to the inland. Third, the transport modes, including ships, trains, trucks, and barges that move the goods inland. Finally, the hinterland, which as mentioned before, refers to the inland area that the port serves. [14]

Following this logic, to further understand a port's hinterland reach, four interrelated layers may be analyzed as seen in Figure 4: locational, infrastructural, transport and logistical. The first is the location layer, which considers the geographical location of a port relative to main maritime routes, productions or consumption centers and demand hubs. The second is the infrastructure layer, which allows port dynamics by providing basic infrastructure for both links and nodes in the system such as roads and railways in links, or terminals in nodes. In this layer, accessibility materialized and relies on availability of capital. Then, the third one is the transport layer, which are the actual services that operate on links and corridors within the system. Finally, the logistical layer involves the organization of transport chains and their integration with broader logistics systems. Each layer provides added value to the one before it, contributing additional value and enhancing the port's accessibility and competitiveness. [14]

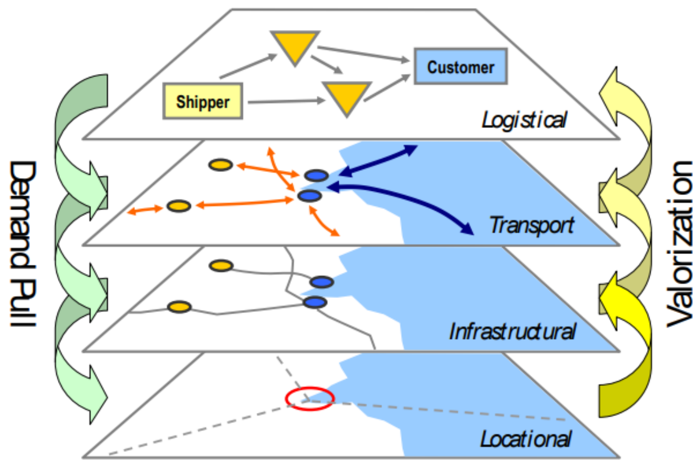

Figure 4: Layers of a port's hinterland reach [18]

From a logistical standpoint, transport organization can be viewed through two perspectives. Outside-In or import logistics, is a port driven form of development that seeks to serve the port terminal in a more effective way. While the Inside-Out or export logistics refers to a method focused not on the port sector but on their accessibility to global trade. In terms of flows, inland flows have two main directions: inbound or outbound. Inbound traffic consists of goods arriving at the hinterland, often for local consumption mainly of finished products. On the other hand, flow leaving the hinterland, usually for export of raw materials or manufactured goods is known as *outbound traffic.* [14]

1.3.3. Integration with other modes of transport

At the interface between maritime and inland transportation systems, ports must manage complex logistical operations. An access from the port to the industrial complexes ensures a complete chain of transport and requires enough infrastructure either with fluvial barges, rail unit trains or roads which usually handle heavy traffic. To understand this connection, connectivity with both rail and road internally at port level is explained below.

Port-rail connectivity and transport corridors

Port-rail interfaces are the strategic and physical locations where maritime and rail transportation systems connect, facilitating the transfer of goods and information between these two systems; in the intermodal context, the port-rail interface is of particular strategic importance.

In this precise intermodal system, one of the most important operators is the shunting operator and railway infrastructure managers, who enable the port to benefit of this type of service. In a port context, the railway infrastructure managers are identified as the company that operates the railway line, while the shunting operators are those who take care, usually using diesel locomotives, of transporting the cargo from the yard where the goods are stored to the electric line, where the exchange between locomotives takes place. [3]

Nevertheless, several stakeholders are involved regarding hinterland access, including national and regional authorities, carriers, stevedoring companies, logistic service providers, port authorities and shipper and cargo owners. [14]

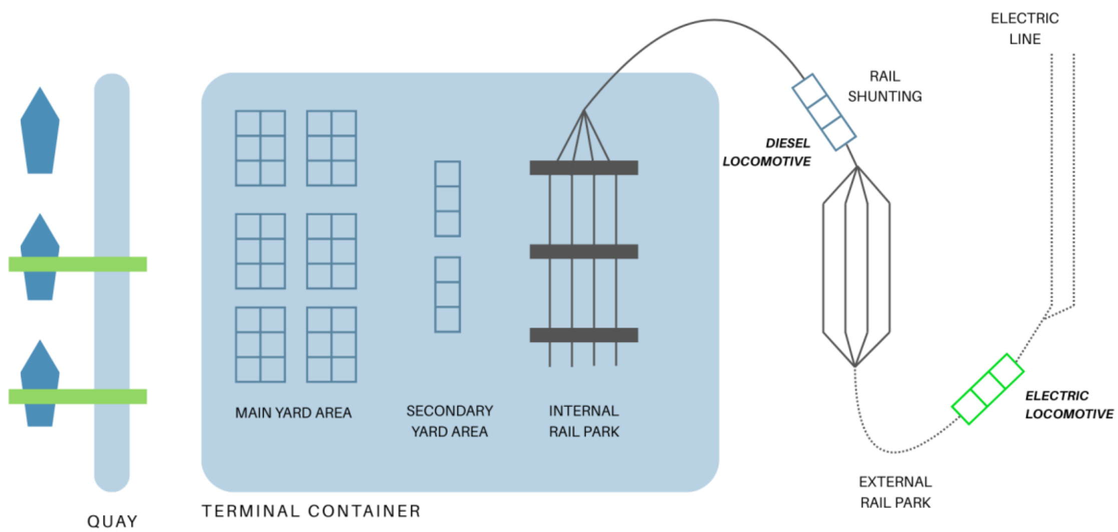

Figure 5: Railway facilities in a port – Made by author adapted from [3]

Upon arrival at the port, the unloading and transfer of cargo onto the national rail network follows a series of carefully managed steps to ensure both efficiency and safety as can be visible in Figure 5. First, cargo is lifted out of the ship's hold and placed in the landing area alongside the vessel. Next, forklifts and terminal tractors move the cargo to the port's marshalling yard, where port authorities carry out all necessary documents.

In the marshalling yard, shipments are then sorted by type and destination. At this stage, shunting operators take over, employing diesel locomotives provided by specialized companies or third-party rail operators. These operators manually couple the wagons, and cargo loading onto the wagons is performed using either cranes or automated spreaders. The wagons are then hauled along a non-electrified line until they reach the electrified mainline.

The traction changeover occurs in a dedicated exchange zone: the diesel locomotive is uncoupled and replaced by an electric locomotive for onward movement over the national network. Finally, once the train has been fully assembled and inspected, it departs for the hinterland under the authority of the rail infrastructure manager.

Port regionalization and hinterland transport are also closely tied up to the concept of transport corridors. These corridors refer to an orientation of transport routes and flows in such a way that they connect origins, destinations and points of transshipment. When talking about the movement of goods, it refers to freight corridors, which need the support of infrastructure such as roads, railways or ports. These, both through land and sea, are essential for port connectivity with inland areas and distribution networks. [14]

Specifically, rail corridors are important to analyze, not only on the perspective in which they complement the articulation and connectivity of ports, but also as competitors, since in particular, long distance rail corridors appear as competitors with maritime routes. [14]

Port-rail connectivity in the European context

Recently, in the European context, ports with rail infrastructure have begun to gain special attention, mainly because of the environmental benefits of rail freight transport. Shifting freight transport from road to rail is increasingly seen as important for reducing emissions caused by logistics and transportation. Several countries in Europe have already introduced road restrictions for trucks for years, thus incentivizing the shift to modal transport by rail. [19]

The European Union has developed several initiatives to encourage sea-rail connections in the ports of member countries. Examples of these initiatives are:

- *TEN-T (Trans-European Transport Network)*, a project that aims to create a set of integrated transport infrastructures, promoting multimodality.
- *Shift2Rail*, a public-private partnership that aims to renew the European railway network, also contributing to increasing the competitiveness of the Union.

- *European Green Deal*, a set of political initiatives with the aim of reducing emissions and zeroing the climate impact of the European Union by 2050.

Currently, the largest rail port in Europe is the port of Hamburg. In 2023, 45.6 million tons of goods, out of 78 million total, were transported by rail; it is the highest ratio among ports in the Union. The rail network stretches 300 kilometers and can accommodate more than 5500 wagons per day, making it one of the most important in Germany. [20] Several European ports have taken the port of Hamburg as a model to follow, trying to achieve the same statistics from the point of view of ship-to-rail integration.

Other ports in Europe that exploit this type of multimodal link are the port of Antwerp (Netherlands) and the HAROPA port system (Le Havre-Rouen-Paris, France). Although equipped with a good rail link, only less than 10 percent of freight takes advantage of this connection in these ports; they have established a target of reaching 20 and 15 percent, respectively, in the coming years. [21]

Among Italian ports, the one that stands out most for domestic multimodal transport is the port of Trieste, from which about half of the containers and 40 percent of the semi-trailers are forwarded by rail to Central-Eastern Europe. On the other hand, as far as the ports on the Tyrrhenian side are concerned (and thus, mainly, Genoa, La Spezia and Livorno), rail transport, although present, does not turn out to be as high performing as in the previous case. Ports in Liguria, in particular, are particularly disadvantaged in this context, as the number of trains adopted is shorter than European standards. [22]

Port-road connectivity

Within the spectrum of intermodal and multimodal solutions examined until now, road transport recurs in almost all cases, due to its capillary nature, and thus the ability to reach every destination. Ports, in particular, rely essentially on road routes, and hinterland traffic is dominated by trucks in the majority of ports: in most logistics' chains, in fact, road transportation covers the initial and final stages of the freight journey. Port-road connectivity, therefore, refers to the integration between the maritime and road systems, aimed at optimizing the flow of goods, especially along the last mile and the first mile of transportation.

From yard to landside, the connection with road transport is facilitated through designated access roads to the port. These roads typically have gated entry points where documentation is checked and compliance with port regulations is verified. Access is restricted to authorized personnel, and entry is granted only to those who have the correct permits, which control not only who can enter the port, but also regulate the date and duration of their stay and ensure adherence to all laws and regulations within the port.

One of the main issues is that in these access points bottlenecks are generated. They may happen due to three different factors: political or legal, operational inefficiency, or physical capacity constraints. Regarding policies it could include regulations or political decisions related to environmental standards or regulations for access, rules or nighttime bans, among others. Operational in efficiency may happen due to transport operators or by the logistics service. Finally, regarding capacity, it is given by both the infrastructure in place and in the nodes. It is important to understand that having enough capacity regarding infrastructure does not guarantee steady operations. Many conditions impact steadiness, including: the mix of freight and passenger flows, weather, incidents, peaks in supply and demand, among others. [18]

Port-related Road congestion emerges as one of the main issues related to this connectivity, affecting not only port activities but also impacting life in the cities and traffic nearby the port. One of the principal strategies to mitigate traffic is to target the inactive trucks at port gates, specifically with truck appointment systems, incentives for off-peak traffic, and virtual container yard systems. [18]

Truck appointment systems are based on a system of scheduling appointments for trucks who choose to have one, for which preferential treatment is given. This system, which may be optional or enforced, allows for better planning and distribution of trucks along the day, such that the accumulated queue is reduced, and prior activities necessary upon the arrival may be performed in advance. On the other hand, incentives for off-peak traffic, achieved through extended gate hours, also allow for better traffic distribution throughout the day in a different way. Another alternative is to improve the connecting infrastructure. Finally, virtual container yards systems are also being used to reduce unnecessary container movements, in which, instead of returning empty containers to the port and then picking up the net one, a truck can be directly reassigned to pick up and export load nearby and in a certain way to recycle containers withing the chain to avoid redundant trips. [18] It is important to understand that the success of these strategies is not always achieved, as it depends on market, political and other factors.

Another key element in relation to road transport is parking management within port areas, which have designated parking facilities in the yards, especially for the vehicles involved in freight and cargo handling, as parking is necessary to guarantee efficient queuing and maneuvering. They are usually equipped with security and monitoring, temporary parking spots, and have operations all day. For instance, in the case of Ro-Ro activities, they require a lot of space for parking.

Dry ports and inland terminals

The evolution of freight distribution networks has gradually shifted the focus from maritime port terminals to inland solutions supporting coastal operations. In particular, “dry ports,” or inland ports, originated as rail or barge terminals, connected with regular services to the seaport, taking on a role as a true onshore extension of port functions. These integrated nodes offer a range of logistics activities; from warehouses and storage facilities to distribution centers and value-added services, enabling them to overcome the capacity and congestion limitations of coastal ports.
Underlying the growth of inland ports are several factors: high land and labor costs in port areas incentivize the relocation of some operations to areas with lower rents and wages; congestion and the increasing energy consumption of road transport require the massification of flows via rail or river corridors; the need to penetrate ever-larger inland markets pushes ports to extend their catchment area through high-capacity connections to the hinterland; finally, dedicated economic and customs policies can facilitate the transfer of port functions inland, creating favorable conditions for the development of free zones and inland logistics centers. [14]
Three main types of dry ports, as noted in Figure 6, often combined, can be identified:

- Satellite terminals, located in close proximity (less than 100 km) to the port, handle ancillary functions such as empty container storage and freight sorting, easing the operational impact on the coastal terminal.
- Freight distribution clusters (load centers), large intermodal hubs integrated into logistics parks or free zones, act as collection and distribution centers for regional markets, with warehousing activities and related services.
- Transshipment facilities, located along international corridors or near borders, enable freight handling operations between different modes of transport (rail-truck, barge-truck) and often perform integrated customs procedures.

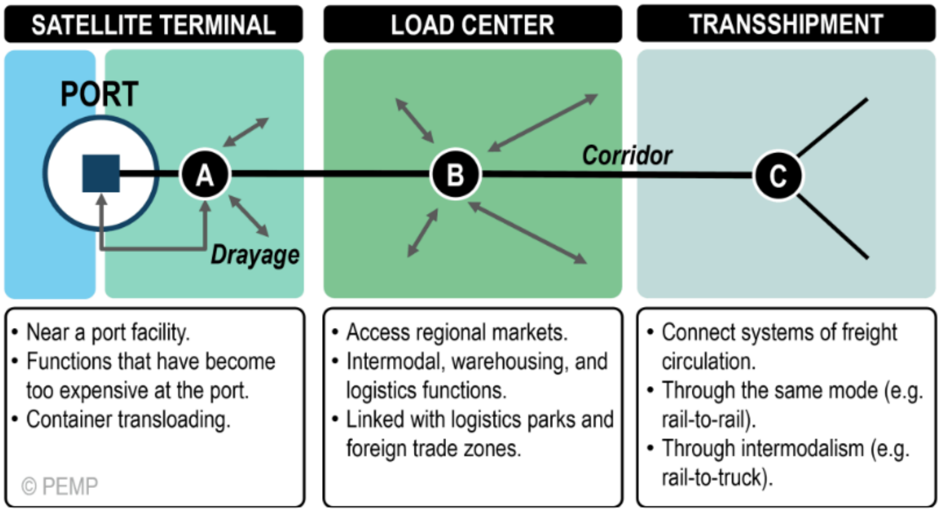

Figure 6: Different types of dry ports [14]

In terms of regional impacts, inland ports extend the reach of seaports, fostering the development of logistics hubs inland and contributing to more efficient freight distribution. In Europe and North America, where the phenomenon is more mature, articulated networks of rail terminals and inland ports connected via barge and rail corridors are observed; in East Asia, the focus has grown especially on load centers along major rivers or along the Eurasian Landbridge. Looking to the future, the role of dry ports is likely to increase further: they will be crucial in handling growing container volumes, optimizing the repositioning of empty space, and exploiting new intermodal technologies, although residual risks of overinvestment require careful governance and strategies tailored to each economic and regulatory context. [14]

Dry ports and inland terminals in the European context

In Europe, dry ports and inland terminals have evolved from simple intermodal terminals to full-scale logistics hubs extended inland, supported by high-capacity multimodal corridors and innovative operating models. The heart of this system lies in the Rhine-Scheldt delta, where ports such as Rotterdam and Antwerp stretch via the Rhine to integrated logistics clusters (Dordrecht, Moerdijk, Duisburg). Here, boat and rail terminals not only ease coastal traffic, but house container depots, distribution centers and value-added services, configuring themselves as “extended gates” that transport many of the port operations directly to the hinterland. [14]

In Italy, the main dry ports are Turin-Orbassano and Bologna, and they take use of the TEN-T corridors to connect to the ports of Genoa and Trieste. [3]

Looking ahead, shared governance between port authorities, private operators and EU institutions will play a crucial role in defining sustainable dry port models. Key prospects for the future include the adoption of digital solutions for intermodal tracking, integrated customs incentive schemes, and public-private partnerships to finance green infrastructure that can shift more and more traffic from road to rail and barge. The goal would be to consolidate inland terminals as pillars of European logistics, while maintaining high adaptability to regional specificities and the needs of local markets.

Interaction between different Hinterland Transport Modes

Each transportation system has its own traffic and limits and therefore it is necessary for ports to organize in such a way that the different modes are carefully separated and get their own area in the terminal, which is somehow shown in Figure 7. This separation implies also a temporary differentiation, as each transport should be able to work on its own schedule. This last consideration leads to the need for space of storage while goods wait to be moved known as buffer zones between ship operations and inland transport. [14]

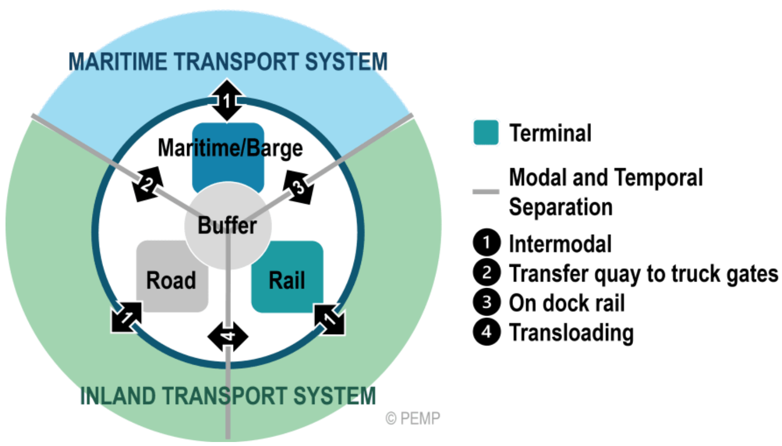

Figure 7: Interaction between maritime and inland transport systems [14]

When different transport modes intersect in the port Hinterland, vertical or horizontal separation elements are used to ensure smooth flow, safety and efficiency. The choice between level crossing, overpass, underpass or underground track depends mainly on cost, traffic volumes, service continuity and spatial constraints. [2] [14]

The main elements that are used to ensure efficient connections are listed below.

- *Level crossings*: represent the cheapest but also the least protected intersection between rail and road; they allow direct crossing with barriers and signals but quickly become unsustainable beyond a certain threshold of vehicle or rail traffic, due to delays, accident risks and congestion.

- *Overpasses and underpasses*: achieve complete flow separation; eliminate conflicts between rail and road vehicles, allowing independent schedules and increasing safety. However, they are characterized by much higher initial investment and require space for approach ramps, which are often chosen in urban settings with encumbrances and elevation constraints.
- *Underground tracks and tunnels*: these are usually adopted in densely built-up or environmentally valuable areas; this solution, the most expensive per kilometer, frees up surface area for urban uses, reduces noise pollution and barriers to the urban fabric, but involves lengthy designs and complex ventilation and safety systems.

The choice of the type of solution is determined by a counterbalance of four main factors. Firstly, traffic and capacity define the threshold beyond which level crossings become inadequate in terms of both efficiency and safety, imposing elevated or underground solutions; secondly, costs and construction time for elevated or underground works, which are significantly higher than for a simple level crossing, make the latter preferable only in low-flow contexts with ample space available; moreover, spatial and environmental constraints, typical of densely built-up urban areas or protected sites, push toward underground solutions to limit the impact on the territory and preserve the continuity of the landscape; finally, the evolution of safety regulations on rail-road intersections, which are increasingly stringent especially along high traffic corridors or near intermodal terminals, favors the complete separation of traffic levels. [2] [14]

1.3.4. Challenges of linking ports to inland destinations

Linking seaports to inland destinations is obstructed by three interconnected challenges, which are congestion at terminals and on access routes, limited capacity of rail and river infrastructure, and environmental and regulatory constraints. Congestion reduces the reliability of logistics chains, with average delays of more than an hour per vehicle at port gates, while the scarcity of dedicated tracks and adequate barge corridors prevents the transfer of large volumes of freight by rail and water. Finally, procedures for environmental assessments and national regulations lengthen the time it takes to build new hinterland connections. Again, an effective strategy would combine digital solutions, targeted investment in intermodal infrastructure, and regulatory simplification. [2] [14]

Congestion at port terminals and access roads

Congestion is most pronounced at terminal access gates and on adjacent arterial roads, where trucks can wait an average of more than 60 minutes before entering. This phenomenon is aggravated by the absence of coordinated reservation systems and the low capacity of near-dock yards, which force vehicles to make longer stops on access roads. The result is increased operating costs, reduced asset utilization, and higher emissions due to prolonged operation of parked engines. [2] [14] Some elements that could address these issues are:

- Appointment systems are integrated with Port Community Systems, which distribute access slots throughout the day and reduce traffic peaks.
- Inland ports/dry ports placed along rail and river corridors, to move the loading/unloading point inland and decongest the main port area.
- IoT platforms for real-time monitoring of vehicular flow and predictive traffic management systems, enabling better coordination between port operators and local authorities.

Limited rail and inland waterway capacity

Rail infrastructure dedicated to freight traffic is often underpowered relative to the needs of containerized and bulk movement: many rail-on-dock terminals have limited tracks, inadequate tunnel profiles, and an absence of high-capacity corridors. Similarly, barge service encounters frequent bottlenecks due to river ports with obsolete docks, variable depths, and overloaded locks. Poor interoperability among network operators and the absence of central coordination further complicates the optimization of intermodal flows. Two interventions that would improve this condition are the creation of dedicated freight rail corridors, with upgraded tracks and double track, capable of supporting longer and heavier freight trains; and the modernization and presence of regular dredging along major navigable waterways to maintain consistent depth levels and carrying capacity. [2]

Environmental and regulatory constraints

The construction of new port-hinterland connections is often slowed by environmental impact assessment (EIA) processes, EU directives on air/water emissions, and national regulations that limit the freedom of service barge between regions. In addition, the multiplicity of regional and national offices and approvals generates a “regulatory drag” that can last for years, discouraging investment in “green” infrastructure such as fully electrified terminals or photovoltaic docks. This process could be streamlined by the presence of incentives linked to the hinterland link's ability to reduce emissions (such as modulated subsidies based on km-bar, as envisioned in the Green Deal), to promote low-emission technologies and the use of sustainable modes. [2]

Dead leg or empty return

Another issue related to inland connectivity is related to the management of containers after they are emptied and need to be returned to the port. It is common for them to return empty to its destination, causing a significative issue in the logistics chain when there is no cargo to transport on the way back, increasing traffic, costs and pollution, longer times for containers to be reused, unnecessary pressure to port and road infrastructure. Strategies to reduce empty trips have been implemented. For instance, triangulation, which means that instead of the container to be taken back empty to the port, it could be used nearby for another export load, but it’s challenging in terms of coordination. Another strategy is sharing containers between different shipping lines or using containers for local deliveries. [17]

1.4. Analysis of existing literature

An analysis was made to review existing literature related to the objective and sector of the current study, in order to evaluate the state of the art, and understand in which areas there is need for further studying and how this thesis fills those blanks.

Recent academic literature focuses on the optimization of port logistic systems, driven by the need to manage increasingly complex global supply chains. Ports are no longer seen as isolated entities, but as a complex network made up of interdependencies between the different stakeholders involved, in which the efficiency of one of them has effects on the entire system. Given the nature of these systems, they are well-suited for being analyzed through simulation modeling.

Dragović, Tzannatos, and Park [12] performed a comprehensive literature review, in which they confirmed that simulation is currently being studied as a methodology for analyzing operations within ports and container terminals. In their work, the studies found were systematically categorized based on the subsystem that was being analyzed such as berth allocation, quay crane scheduling and yard management. As a common factor, most studies focused on the identification of operational bottlenecks and evaluation of the performance of terminals under different scenarios. Therefore, a strong precedent on use of simulation as analytical tool on this domain is established, aligning with the objectives of the present thesis.

Nevertheless, there is a wide range of possibilities within simulation modeling. In recent decades, System Dynamics (SD) simulation has gained popularity in the port sector, as a well-suited methodology for analyzing non-linear behaviors where operational complexity requires tools capable of representing interactions, delays, and feedback loops between different components. For instance, Liu, Zhang and Zeyi [23] analyzed through SD the collaborative operations between the different stakeholders including port authority, custos and terminal operators. Their model, built with Vensim software, was able to quantify the way in which changes in micro-level operational rules and infrastructure constraints alter the overall throughput of the port, therefore concluding that the efficiency of the port ecosystem is very sensitive to the operation policies and strategies. This includes interconnected activities such as the scheduling of vessel arrivals, allocation of berths, yard operations, customs inspection efficiency, among others.

A significant contribution in this area is a study by Caballini, Sacone and Siri [24], who interpret ports as a “system of systems”. In other words, a port can be conceived as a set of autonomous subsystems that share resources and must coordinate to ensure the smooth functioning of the whole, including for example, customs, sea-side operations, land interface, handling and storage areas. The management of such contexts is made more complex by the presence of actors with different interests, non-uniform procedures, and uneven levels of digitization. Within their framework they highlight the importance of optimizing the rail cycle into a more sustainable transport. Their study presents a SD model using Power Sim Studio’s software that reproduces the railway cycle of three Italian container terminals including phases such as loading/unloading, storage and customs check, finding that the terminals were not fully exploiting their rail capacity. The study evaluated potential improvements such as implementing new technology, moving operations to a dry port and increasing resources, finding that simply investing in infrastructure or equipment had little effect on the reduction of delays, since the main obstacles resulted in work organization, document management and poor synchronization between actors involved. This contribution serves as an example of the application of SD to real cases, showing, with empirical data, that better organization and inter-organizational cooperation can have a more significant effect on overall performance than infrastructure interventions alone.

In a more granular approach, Sacone and Siri [25] focused on the internal management of a rail freight terminal, with a model used to analyze operational variables such as the available shunting locomotives, the length of receiving and departure tracks, impact of train arrival schedules on internal congestion, among others. This work approaches the importance of more specific operational details such as the service time in hubs and dwell time in terminals as critical factors on the system's efficiency.

In order to further understand the contribution of this thesis, the existing literature on port simulation can be broadly categorized into two levels of analysis: micro and macro level.

On one hand, macro-level studies focus on a strategic perspective, and on ports as an aggregated node within a larger economic or logistical network. These models are concerned with overall flows and interactions between major components. In this order of ideas, Liu, Zhang and Zeyi [23] present a macro-level port as it analyses interactions between the stakeholders rather than the physical movement of the assets.

In contrast, micro-level studies focus on detailed processes and physical constraints within a specific subsystem of the port. Therefore, these models are concerned with a more granular and particular performance. The study by Sacone and Siri [25] is a clear example of this, by focusing on a single rail freight terminal and the flows on it.

Finally, the work by Caballini, Sacone and Siri [24] could be classified in both perspectives, as it begins with a macro framework when approaching the port as a system of systems, but building the actual simulation model in a specific operational process as is the railway cycle within the container terminal.

1.5. Innovative contribution of the Thesis

While the existing literature provides valuable foundations, it is notable that most studies tend to analyze road and rail operations as separate systems on either macro or micro-level processes. Few works have developed integrated SD models explicitly designed to capture the mutual influence between rail and road traffic flows at critical intersection points within a port.

The novelty of this thesis is articulated in the following points:

- The development of an integrated SD model that directly couples the dynamics of the rail and road networks, thus enabling the analysis of interaction effects such as cascading delays and capacity constraints.

- The introduction of a methodology to use the results of the rail network simulation as input for the road network model, creating a dynamic interaction rather than one based on static assumptions.

This thesis focuses on an internal operative context of both the rail and road network. Granular variables are analyzed, and capacity of terminals, tracks and hubs become a critical variable of analysis. It was developed considering the complex interdependencies between modes of transport; an increasingly necessity as ports evolve toward more sustainable and coordinated logistics systems.

2. Methodology: System Dynamics Simulation

Developed in collaboration with Sara Cardinale

Ports and their intermodal connections with the hinterland are complex and interdependent systems, characterized by continuous interaction between resources and flows. The variety of factors that influence these systems makes studying their behavior using purely analytical methods particularly complex. In this context, simulation stands out as an effective tool that is well suited to this type of problem.

The goal of simulation is to replicate real-world processes in a digital and controlled environment. This offers the possibility to observe the behavior of the system, test hypotheses, and evaluate the impact of potential changes without the costs, risks, or operational disruptions that a physical implementation would entail.

In the port operations sector, simulation is an important decision-making support tool; it allows planners to explore different possible scenarios, identify bottlenecks, and evaluate strategies under varying operational and demand conditions.

2.1. Different simulation approaches

In the study of logistics and transportation, several simulation methodologies are available. Three main modeling approaches are used: System Dynamics (SD), Discrete Event Simulation (DES), and Agent-Based Simulation (ABS).

While they share the common goal of reproducing real dynamics, each of these approaches is based on different modeling principles, which make them more suitable for certain cases and not useful for others depending on the nature of the problem being analyzed.

The fundamental difference between these methodologies lies in their level of abstraction and in their core unit. Table A below summarizes the main aspects of each of them.

- SD focuses on the stock as a core unit, which represents an accumulation of resources (such as trains or trucks). [26]
- DES focuses on events, which are a specific occurrence at a point in time that changes the state of the system. An event in the port sector could be a train arriving at a signal or a crane starting to unload or load a container. [27]
- ABS focuses on agents, which are autonomous, decision-making entities (such as a truck driver or a shipping line). Each agent has its own set of behavior and rules. [28]

Aspect	Discrete Event Simulation (DES)	Agent-Based Modeling (ABM)	System Dynamics (SD)
Description	Focuses on the performance of a system based on a chronological sequence of events. Core unit: the event	Models a system as a set of autonomous interacting agents focusing on how they interact and behave. Core unit: the agent	Models feedback loops, flows, and time delays to analyze the behavior of a system over time. Core unit: the stock
Level of Abstraction	High operational detail: it models at a micro level (e.g., position of the train at each moment).	Medium to high (behavioral detail).	Aggregated: models at macro-level, not focused on single elements but focused on flows.
Best For	Decision making for systems with well-defined processes and with predictable events.	For systems with complex interactions, where individual behavior impacts the overall system.	Modeling the long-term trends for systems with complex relationships and feedback loops (chains of cause-effect relationships).

Table A: Differences between simulation techniques [Made by the author]

In the port logistics context, each of them serves for different applications under certain strengths and weaknesses:

- System Dynamics (SD) focuses on capturing the aggregate behavior of a system over time by analyzing feedback loops, stocks, and flows. It is particularly effective for representing high-level interactions and long-term trends. It is typically used for: strategic planning, demand forecasting, policy impacts, bottlenecks, capacity analysis, modal shift scenarios, CO2 impact of port policies, among others. An advantage is that it is easy to visualize feedback loops, and it needs less data as it is at aggregate level, but as it also gives results at this level, it ends up having lack of operational detail. It works with trend-level data, and general causal relationships. [26]
- Discrete Event Simulation (DES) models the system as a sequence of discrete events occurring at specific points in time. This approach is particularly suitable for detailed operational modeling, where the exact timing of events and resource allocation are critical. It is used for analyzing terminal operations, queuing, berth/crane scheduling, gate congestion, yard operations, among others. It is a very realistic process modeling and allows to quantify queues and delays, but it requires high quantity of detailed data and becomes complex for larger systems. It needs data related to process times, resources, use, among others. [27]

- Agent-Based Simulation (ABS) models the system as a set of autonomous agents, each with individual behaviors and decision-making rules. ABS is useful when the heterogeneity of actors and behaviors emerging from local interactions are central elements of the analysis. Therefore, it is used for behavior modeling, routing, interaction of stakeholders, truck driver choices, logistics chain decision. This kind of modeling captures heterogeneity and has flexibility for “What-If” scenarios, but it is very data-intensive and presents difficulties during validation and calibration. It needs data related to agent rules and interactions. [28]

The choice of methodology is critical as it defines the scope of the analysis and the types of questions that may be answered with it. It has to be aligned with the specific objectives and the nature of the system that is being investigated. For this thesis, which analyses the complex interaction between a port’s rail network, road network and their critical intersection points, the most appropriate framework was to choose System Dynamics (SD)

Although DES and ABS approaches have proven valid in port operations research (e.g., in the simulation of ship scheduling or yard operations), their strength lies in the granular representation of processes. The main objective of this thesis, on the other hand, is to understand the behavior at the system level and the long-term effects of interactions between road and rail networks within the port environment.

System Dynamics is particularly well suited to this purpose for several reasons:

1. Focus on aggregate flows. The goal is to capture the evolution of traffic and resource utilization at the systemic level, rather than modeling individual vehicles or events.
2. Representation of feedback mechanisms. The model must take into account causal loops, such as congestion affecting delays and delays affecting productivity; SD is inherently designed to handle such dynamics.
3. Exploration of strategic scenarios. The study requires testing strategic interventions and assessing their impact over extended time horizons, a typical strength of SD models.
4. Simplified data requirements. Compared to DES or ABS, SD can provide strategic insights even with less detailed operational data sets, making it a viable choice in contexts where granular data is difficult to obtain.

In such way, System Dynamics was selected due to its core principles that align with the research objectives and data availability.

2.2. *Software selection: Vensim PLE*

The selection of an appropriate software tool is fundamental for the implementation of a simulation model. For this thesis, Vensim PLE (Personal Learning Edition) was chosen to develop it. The decision was driven by three main reasons: it's direct alignment with the System Dynamics methodology, its strong feature set availability, and its widespread use for academic purposes.

This software package is specifically designed for System Dynamics models, and therefore it was developed around the principles of its paradigm. Its strengths lay on its visual modeling interface which allow for visual diagrams such as causal loop and stock and flow maps. The graphical interface is very intuitive and allows to communicate better both the structure of the model and the results.

Regarding its simulation engine it is optimized for solving systems of non-linear differential equations, which are the core of SD models, ensuring that the model is implemented with software with numerical stability and precision.

Finally, the software includes comprehensive analysis built-in tools that allow a better understanding of the results, such as dynamic graphing and tabular data output. These features allowed for a better analysis of the multiple scenarios simulated, to visualize a direct comparison of the different operational policies and infrastructural changes.

In such way, the complexity and size of the model implemented, fit sufficiently within the operational limits of the PLE version, and allow for a precise and efficient simulation with the SD methodology from its conceptualization and implementation to the final analysis of the results.

3. Case Study

A performance evaluation and capacity planning were conducted on a real-life port situated in Italy through a quantitative analysis grounded in a System Dynamics simulation model in the software Vensim PLE. As an SD model, a continuous flow paradigm was considered, in which the study focuses on aggregate behaviors rather than on discrete tracking of individual train units.

The analysis of the port consisted of developing three models that represented the rail network, the road network and the crossings and interaction between them, with the objective of analyzing the system's throughput and identifying the operational bottlenecks under a series of operational constraints and disruptive scenarios.

The model developed serves as an analytical tool for examining the resilience and efficiency of the infrastructure, and to assess the impact of alternative configurations, operational policies, or other changes.

3.1. Port Description

Information used comes from a real port case, for which data was proportioned by Next Freight. For confidentiality reasons the specific data of the port will not be mentioned, and no concrete names or data is revealed in this document.

The port selected is a major multi-terminal and multi-modal port located in Italy and acts as a crucial commercial artery for significant part of the continent. As one of the major ports of the nation, it processes a broad range of cargo including intermodal containers, liquid bulk and general goods, for which it hosts multiple specialized terminals to respond to specific needs of cargo types. Some key characteristics are its deep-water access and its intermodal connectivity, converting it into a key node between maritime, road and rail transport. Its operations are performed with advanced handling infrastructure such as cranes, dedicated Ro-Ro ramps, and specialized vehicles used to manage its substantial annual traffic.

Additionally, due to the historical development of Italian cities within a limited physical space, its infrastructure lacks enough space for a large-scale development of its ports and transport infrastructure, incrementing in such way operational friction between the modes of transport inside

and outside the ports as they often share much of the space and are forced to coexist in multiple intersection points. This particular port is interesting to study in this aspect, as its layout is made up of multiple specialized terminals situated along a slim coastal strip near urban infrastructure.
Combining both high traffic volumes, diverse types of cargo, along with the physically constrained space, this port becomes an ideal subject for studying its logistical challenges, providing a real-world example of issues related to intermodal efficiency, conflict between road and rail, bottlenecks, among others, that must be assessed and controlled to have a better management of complex logistics.

The port is of significant scale, therefore composed of multiple terminals, from which a section of study was selected including a cluster with 9 of them. This focused area, while representing only part of the larger port complex, provides a detailed case study of port operations, and allows for an in-depth examination of logistical and operational dynamics within this specific area. The selected terminals serve as a highly representative sample of the challenges and advantages faced by the whole port and other similar facilities around the world.

3.2. Generalities

3.2.1. Terminals: cargo types and modal connectivity

Each of the 9 terminals has varying specialization regarding the type of freight they handle, and the mode of transport that connects it. Below, Table B summarizes the characteristics of each terminal, demonstrating a varied distribution regarding these two aspects.

ID Terminal	Cargo Type	Network connectivity
T1	Containers	Road and Rail
T2	Ro-Ro	Road
T3	Bulk	Road
T4	Bulk	Road and Rail
T5	Containers	Rail
T6	Bulk	Road
T7	Bulk	Rail
T8	Containers	Road and Rail
T9	Containers	Road

Table B: Port terminals with cargo type and network connectivity

3.2.1. Access points

The terminals are accessible through multiple entry/exit points: one dedicated to railway traffic (V1) and two dedicated to road traffic (V2 and V3).
Access point V1, by train, therefore, serves terminals 1, 4, 5, 7 and 8. While for trucks, they may use access V2 to access terminals 1, 2, 3 and 4; or V3 to access terminals 2, 3, 4, 6, 8 and 9.
These access points connect the external national network with the internal port network.

3.2.2. Components of the model developed

To model the port's interconnected networks, three separate components of a single model were developed using Vensim PLE, which are:

1. Rail network Model component, *developed by Daniela Restrepo Ruiz.*
2. Road network Model component, *developed by Sara Cardinale.*
3. Crossings between networks Model component, *developed in collaboration by Daniela Restrepo Ruiz and Sara Cardinale.*

This thesis focuses specifically on the rail network and the crossings, but to achieve the last one a collaboration was done with Sara Cardinale, who developed the road network model. Then, cooperative work was done to ensure proper integration between the two systems.

3.2.3. General model conditions

Initially, to understand the functioning and logically comprehend the model, a generalized diagram was developed, in which both the rail and road network were divided into sub segments and accordingly named. Terminals are represented with numbers from 1 to 9, railway segments with characters A to E, and road segments with characters J to W.
The scheme in Figure 8 represents this generalized model, in which on the left, in green, the railway network is presented, and in red, on the right, the road network, each with its own access/exit points, segments, and connectivity to terminals. It is important to clarify that this model is not to scale and doesn't correspond to the spatial or geographical distribution of the actual port, but consists of a logical distribution of its elements.

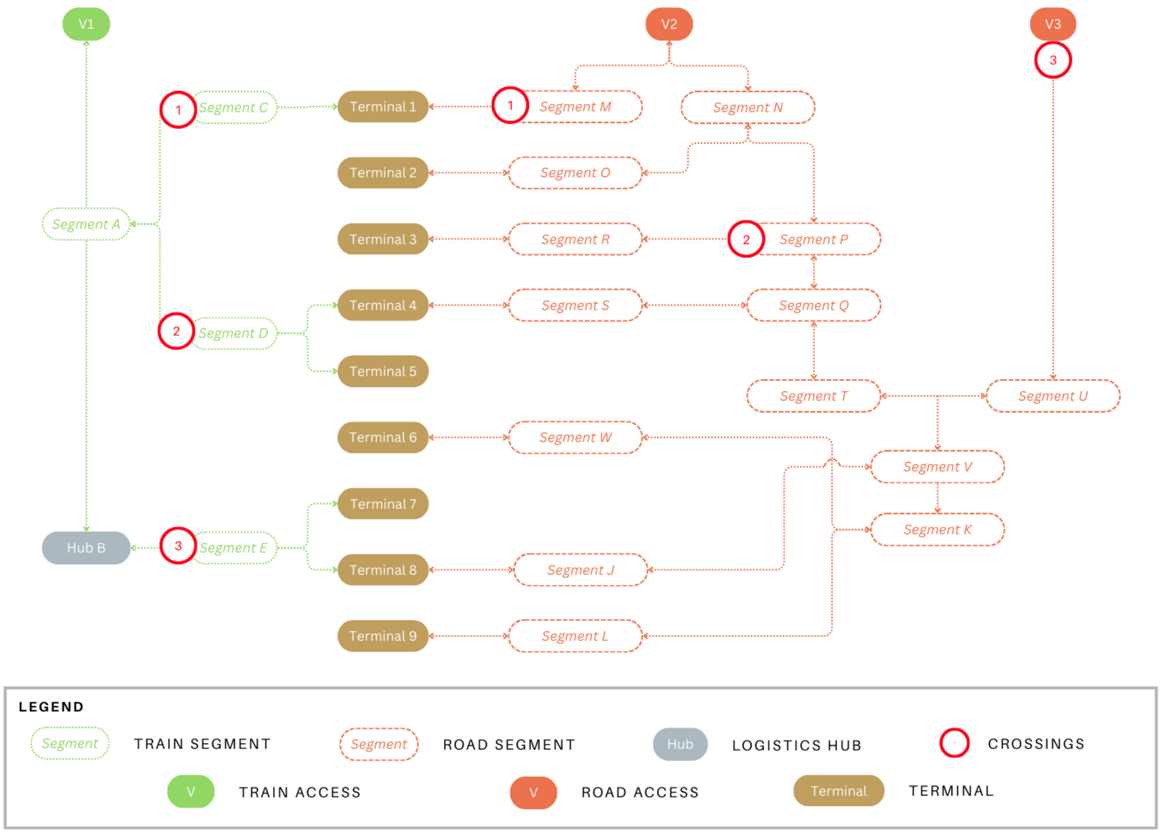

Figure 8: Generalized scheme for the simulation model

Railway network

The rail network has a single entry/exit point, which was identified as V1, the central logistics hub identified as B, and five terminals (T1, T4, T5, T7 and T8) reachable by a series of single-track, bidirectional segments (C, D, and E) and a double-track segment (A).

The core operational rules could be summarized as follows:

- *Track capacity:* rail segments C, D and E have a capacity of one train during any given time, and rail segment A has capacity of two trains. Therefore, the model implemented a logic that prevents collisions by ensuring the segments ahead of each trip are clear before allowing the train to enter. In order to guarantee this, for each segment capacity parameters, and occupancy auxiliary variables were implemented, that guarantee that occupancy never exceeds capacity, and that trains entering the segment are not greater than the space available, represented by the difference between capacity and occupancy.

- *Location capacity:* central hub B and each of the five terminals possess a fixed capacity, which limits the maximum number of trains they can hold simultaneously. This capacity is verified in the same way as for the segments, as if a destination is at full capacity, trains must queue at the preceding location.
- *Mandatory services:* trains are subject to mandatory dwell service times at central hub B, both upon entrance and before departure, varying their duration for inbound and outbound journeys.
  - *Inbound stop:* it is a relatively quick operational process, related to the change of locomotives. As trains arrive from the main line locomotives, designed for long-distance travel, they must change into internal, industrial networks, therefore being decoupled and then replacing it with a shunting locomotive. Moreover, the external port network is usually electrified, while the internal ones are usually reconfigured as non-electrified, handling operations with diesel or diesel electric shunting locomotives.
  - *Outbound stop:* the outbound stop, therefore, implies changing the locomotive back to the electric main line for the long-distance journey ahead. But it is significantly longer as the trains also undertake an extensive regulatory and safety check including braking system tests, cargo inspections and administrative clearance. These are all legal requirements before a train can be allowed to depart into the national networks, as any problems in it would fall to the port.
- *Exclusive outbound capacity:* for hub B and segment A there is exclusive capacity for trains on their outbound journey. This is in order to guarantee there is always a way out of the system, else it is likely to get blocked in such way that trains may not leave the system, and therefore no trains may enter the system if it's at full capacity and having no solution. The capacities destined will be quantified ahead when explaining the base scenario input.

In such way, each train unit follows a sequential lifecycle from its entry to its exit from the system. The scheme in Figure 9 shows the cycle trains that follow once in the network.

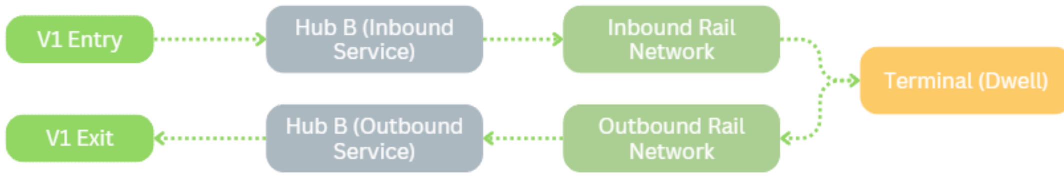

Figure 9: Train lifecycle

The process flow diagram in Figure 10 provides a simplified, conceptual overview of the train's journey and the overall network layout. This scheme serves as a foundational guide to the system's logic. However, it is important to understand that this diagram does not represent the final simulation structure. As will be explained, the operational model is developed under a more detailed approach where each possible train route is modeled as a distinct path. This disaggregated structure is fundamental for an analysis of train dynamics.

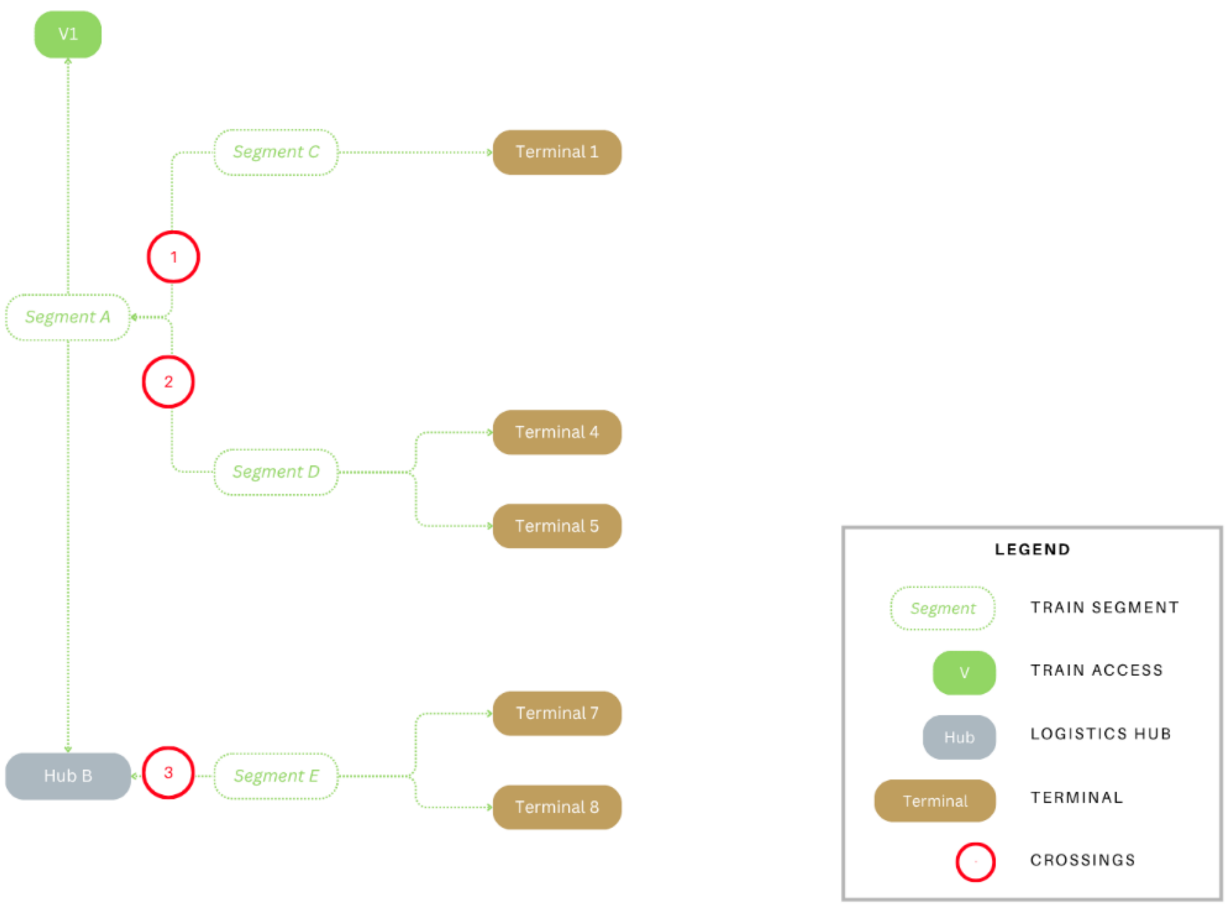

Figure 10: Schematized train journey

Road network

The road network is accessible through entry/exit points V2 and V3, which connect the seven terminals it serves through a series of road segments with two one-way lanes. A generic scheme of the segments that compose it are illustrated in the graph below in Figure 11.

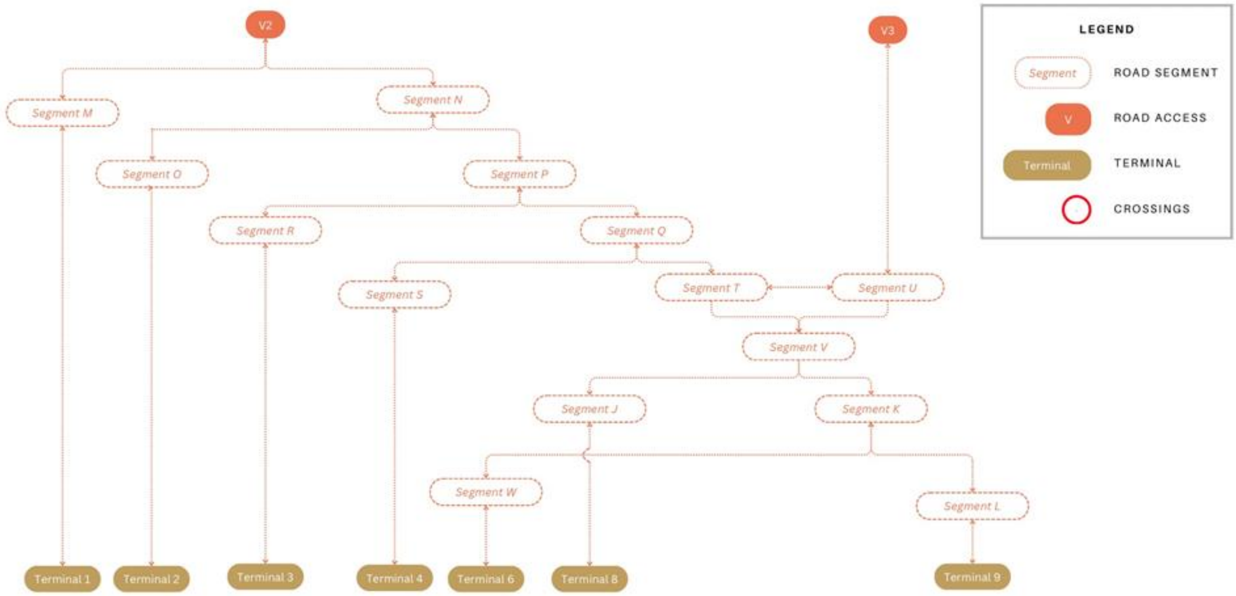

Figure 11: Schematized truck journey

Differently from the train network, the operational rules are as follows:

- *Segment capacity:* the segment capacity was defined by the length of the road and an average length of the trucks of 18 meters, accounting in that value a safety distance between them. The quotient between these two lengths defines the number of trucks a segment may host. Additionally, it must be considered that each segment has two lanes, one in each direction of travel, therefore varying for each segment.
- *Terminal access capacity:* each terminal has a dedicated gate area to process trucks entering and leaving, each with a particular capacity established.
- *Terminal internal capacity:* in the internal operational area of the terminals there's also a fixed capacity.
- *Dwell time:* in this case, the trucks enter the system directly to the terminals without a previous stop at a hub like for the trains. Trucks must be processed internally at each terminal for a given duration.

Trucks movement may also be understood with their lifecycle, from entering the port to leaving it, as seen in Figure 12:Truck journey life cycle

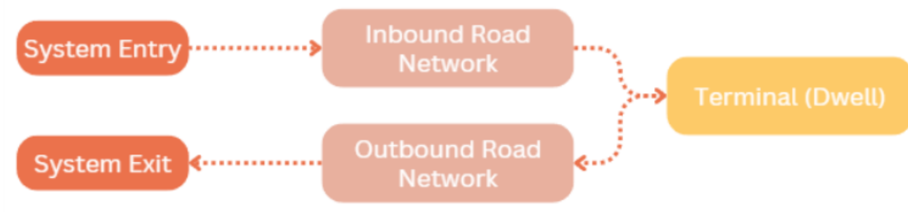

Figure 12:Truck journey life cycle

Crossings: intersection between road and rail network

As previously introduced, a key issue within the ports logistics is the intersection between the modes of transport. In this case, the at-grade crossings between the rail and road networks. These conflict points may generate bottlenecks, mainly in the road network, as port regulations dictate that rail traffic has priority over road traffic, which in other words means that trucks must wait for trains to pass in case of coexistence in an intersection, leading to formation of queues and cascading delays along the whole road network.

Three critical at-grade crossings inside the port were identified:

- Crossing 1 - X1: intersection in access to terminal 1 positioned between the access points and the terminals, specifically in segment C of the rail network and segment M of the road network.
- Crossing 2 - X2: links segment D from the rail network to segment P of the road network, being therefore located between the terminals and the core logistics node to serve several terminals.
- Crossing 3 - X3: intersection between segment E from the rail network and segment U of the road network near the V3 entrance, affecting vehicles entering or exiting from this point and trains going to terminals 7 and 8.

The management of these crossings is therefore a crucial factor in determining the efficiency and capacity of the port's landside operations.

Cargo type consideration

Given the focus of the thesis, the analysis requires movement through rail and road segments and the logistic hub (B), through which the operational behavior of a train or truck is independent of the cargo it carries, including speed and occupancy time, as they are subject to the same signaling. For methodological reasons, for each of the models, trains and trucks were considered analogue regardless of their cargo type (Ro-Ro, bulk cargo, containers, etc.) into a homogeneous flow. Nevertheless, some differences are given between cargo types at the terminals themselves, as loading and unloading activities may take different times and effort. Therefore, to account for this variability, without introducing an irrelevant complex load to the model, the time was accounted as a uniform distribution within a range instead of a fixed dwell time for all models. In this way, the slight difference between operational times was considered, representing both faster unloading processes such as containerized transport, against slower processes such as liquid bulk.

3.3. Model development

3.3.1. System process flow

The complex path of the trains follows a logical sequence through stocks (states) and transitions (flows). The following description attempts to explain this process by phases.

- *Phase 1: System Entry*
  - Trains arrive from outside in the national network to the arrival entry V1. From there they may depart at any of the terminals.
  - **In the model:** to represent the entering flow, a path for each of the terminals was included separately in the model, so each terminal has its own entering flow.
- *Phase 2: Journey to Hub B*
  - In order to go to Hub B from V1, track A must be used. Upon completing the transit trains arrive at Hub B.
  - **In the model:** Before moving from V1 to B, the availability of the segments needed must be checked, and the number of trains that go must not exceed the capacity of each of the segments involved and jointly controlled as mentioned previously through an occupancy auxiliary variable and a capacity parameter. In this model, the movement from V1 to B is represented through 5 different flows (one for each

of the terminals) but keeping into account that each of the 5 flows contributes to the occupancy and must therefore be subject to verification prior to departure.

- *Phase 3: initial service and dispatch.*
  - After a stop for several minutes in B, for logistics purposes previously explained, the train is ready in B to leave for the corresponding terminal. In the different terminals different companies and types of cargo are managed, decision which is stated from input information proportioned. The way in which this data is inputted will be further discussed later.

    In the model: Before the journey for each of the tracks it is important again to check the capacity of the segments that will be utilized to get to each terminal, as they must all be available, as well as when the train starts advancing, as it must always check availability ahead.
- *Phase 4: journey and dwell at terminals.*
  - Trains must travel along different tracks according to the terminal they are going to, and upon arrival they must wait for a certain time at the terminal stocks.

    The journeys from hub B to the multiple terminals are described as follows regarding the notation used throughout the model:
    - To go to terminal 1: B → A → C → T1
    - To go to terminal 4 and 5: B → A → D → T4 or T5
    - To go to terminal 7 and 8: B → E → T7 or T8
  - **In the model:** two different parameters regarding times must be defined.
    - On one hand, there is the time it takes a train to pass by a segment, which depends on the speed of travel and the length of each segment which was taken from satellite measurements. The values obtained were then approximated to the nearest whole minute.
    - Then, the time which a train spends on each terminal is defined (dwell time), which, as mentioned before, takes into consideration the type of cargo as a range through a random uniform distribution.
- *Phase 5: Return Journey and final service*
  - To return, the same journey as the inbound is taken, the only difference would be the time spent at hub B, which is now increased to a longer dwell time. One

important thing to note is that during exit both B and A have exclusive capacity reserved in order for the system not to get blocked so that trains may exit, as explained before.

  - **In the model:** the same process is modeled as before, using same times, speed, and constraints. Up until trains meet in B to leave the terminal, each flow for each terminal has its own stock variables and flow arrows, and then when they arrive at B, as it is no longer important to differentiate by terminal but to know total exit, all trains converge in a same stock.
- *Phase 6: System Exit*
  - After the final service in B, trains leave by going onto track A and then leaving for exit V1. Here trains have again priority binary for exit through A.
  - **In the model:** Trains exit via V1 which accumulates flow in a sink to account for trains that exit.

As mentioned, the model uses a continuous flow process. Variables that represent train quantities are modeled as continuous levels or stocks, while their movements are represented by rates of flow, which allows for an adequate approach to focus on aggregate behaviors rather than the specifics and particular characteristics or the exact path each element in the flow follows. Consequently, stock variables can assume non-integer values.

As explained in phase 1, the model uses directional stocks. Meaning a track, such as segment A, is disaggregated into multiple stocks, each corresponding to a direction of travel (Trains on A to B, Trains on A returning to B, among others, which all sum up to take up the capacity). This is done when specific data of arrivals of each train for each terminal is available, which was the case. Nevertheless, it’s possible to get a model, only with the total arrivals to the port along with the probabilities of the trains going to each of the terminals. The result is a model that smoothens the occupancies, as it constantly sends portions of flow to each terminal, instead of the initial one which is a much more realistic and accurate approach. Both options were simulated for trains in order to get insight into how specific the information must be collected, getting like these two options for model:

- ***Model 1* - disaggregate approach**: it separates the flows of each terminal as separate flows integrated by their capacity constraints. It is expected to give more accurate results as it comes from more precise and complete data. Therefore, it requires better access to data and more computational effort. (View Figure 13)

- *Data needed*: hourly (or the time unit selected) entrances of trains to each of the port terminals.
- *Output expected*: more precise as it actually simulates the entrance of the trains in the exact hour it happens, and it flows to the actual terminal to which it is intended to.

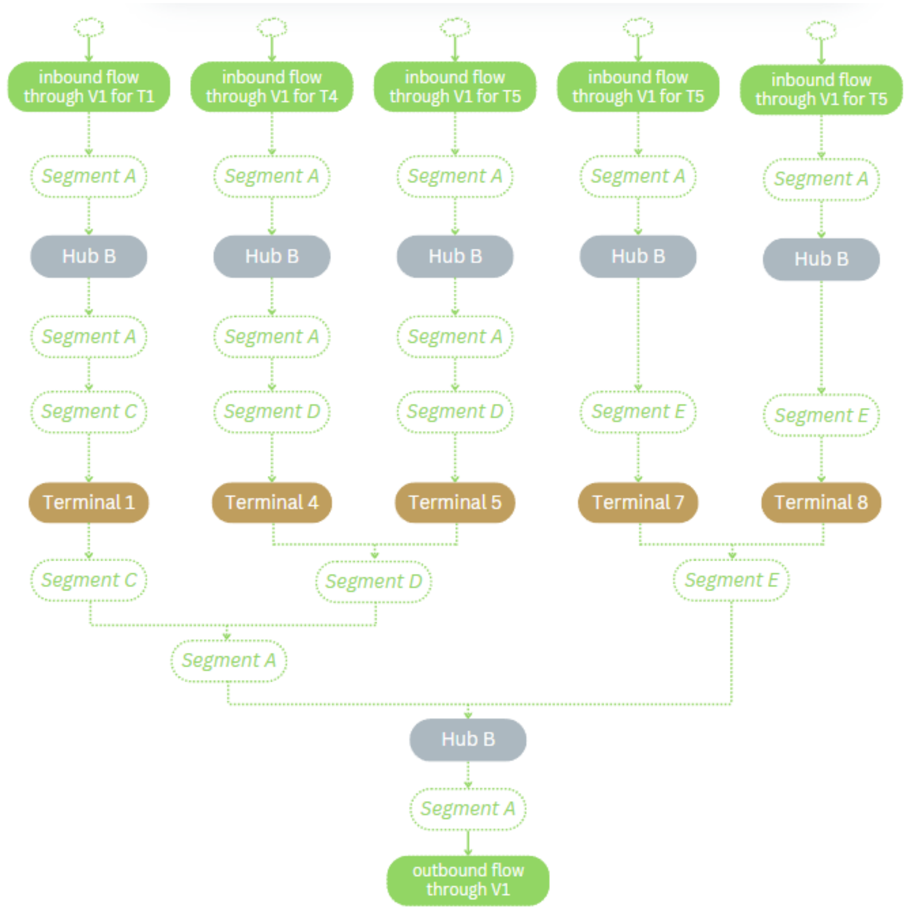

Figure 13: Schematized train network for Model 1

- ***Model 2 -* aggregate approach:** this case, uses a general flow for all terminals which is then separated based on probabilities of the train going to each of them. It is expected to smooth the results, as it distributes more the entrance of each train throughout all the terminals, since with every train entrance a "portion" of its flow is taken to each of the terminals proportionally to the probability of using each. (View Figure 14)

- *Data needed*: hourly (or the time unit selected) entrances of trains in general to the port, and fixed probability or proportion of trains entering to each of the terminals.
- *Output expected*: smoother results as it simplifies the input and computational effort. Every time flow enters, it is expected for it to be distributed across all the terminals proportionally on the same instant, distributing better the traffic, and leading to slightly less occupancy.

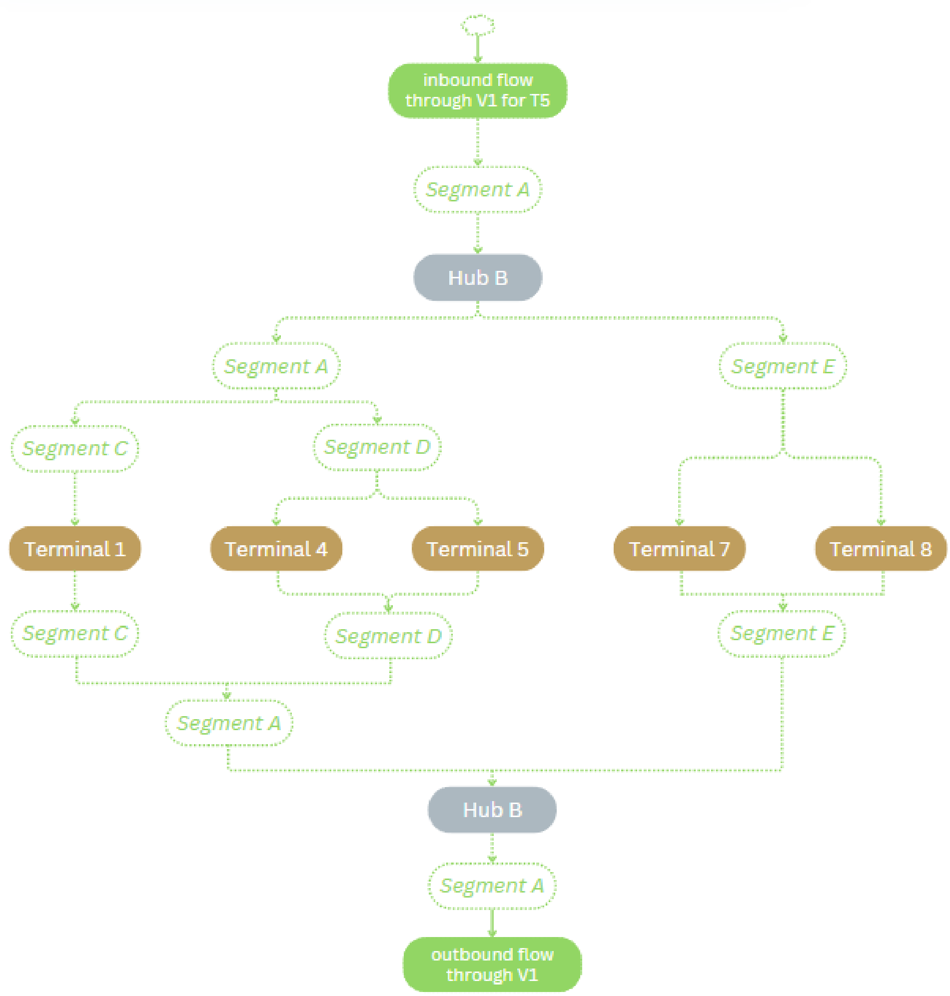

Figure 14: Schematized train network for Model 2

3.3.2. Simulation parameters

The model is built with the following global parameters:

- *Time units:* hours
- *Simulation horizon*: 168 hours (1 week)

- *Integration timestep* (TIME STEP): 0.05 Hours, to ensure numerical precision and stability.

The input values for the base scenario, which is further explained below, are the following:

- *Time of travel on each segment:* with the speed of travel of 5 km/h and the distance of each segment which was taken from satellite measurements, times on each segment were estimated. The values obtained were then approximated to the nearest whole minute and are displayed on Table C.

Segment	Length (km)	Time (h)	Time (min)
A	1.18	0.24	15
C	0.24	0.05	3
D	1.01	0.20	13
E	1.39	0.28	17

Table C: Length and time per segment

- *Total trains entering:* the value for the flow of entrance are used as input for the base scenario, where a total of 34 trains enter the system. The actual distribution as for which they enter, and the data related to dwell times and capacity are provided by Next Freight under confidentiality.
- *Dwell time at terminals:* The time which a train spends on each terminal is defined, which, as mentioned before, takes into consideration the type of cargo as a range through a random uniform distribution. Values for dwell time are not shown for confidentiality reasons.
- *Dwell time at hub B:*The time on which a train spends on each terminal, as mentioned before, varies if its inbound or outbound. Values are not shown for confidentiality reasons.

3.3.3. Model variables and equations

Table D provides a detailed dictionary of all variables used in the model, auxiliary and parameters, in order to define the system's fixed rules and to understand the decision-making logic. For sure, for a better understanding of the model it should be seen in the software, but through these definitions it is possible to comprehend the way it functions.

- Model 1: disaggregate approach

Variable Name	Formula/Value	Units	Description
Simulation Control Parameters			
Custom Time	INTEG (Time Flow, 0)	Hours	An integrator that acts as the master clock for the simulation, used as the input for scheduled events.
Time Flow	1	Dmnl	A constant flow of 1, used to drive the Custom Time clock forward.
Model Inputs (Arrival Schedules)			
Arrivals T1	WITH LOOKUP(...)	Trains/Hour	Pre-defined arrival schedule for trains destined for Terminal 1.
Arrivals T4	WITH LOOKUP(...)	Trains/Hour	Pre-defined arrival schedule for trains destined for Terminal 4.
Arrivals T5	WITH LOOKUP(...)	Trains/Hour	Pre-defined arrival schedule for trains destined for Terminal 5.
Arrivals T7	WITH LOOKUP(...)	Trains/Hour	Pre-defined arrival schedule for trains destined for Terminal 7.
Arrivals T8	WITH LOOKUP(...)	Trains/Hour	Pre-defined arrival schedule for trains destined for Terminal 8.
Train Arrivals at T1	Arrivals T1	Trains/Hour	Alias for Arrivals T1, feeding into the initial waiting stock.
Train Arrivals at T4	Arrivals T4	Trains/Hour	Alias for Arrivals T4.
Train Arrivals T5	Arrivals T5	Trains/Hour	Alias for Arrivals T5.
Train Arrivals T7	Arrivals T7	Trains/Hour	Alias for Arrivals T7.
Train Arrivals T8	Arrivals T8	Trains/Hour	Alias for Arrivals T8.

Variable Name	Formula/Value	Units	Description
System Parameters (Constant and Stochastic Values)			
Capacities			
Capacity B General	6	Trains	Maximum number of inbound/waiting-for-dispatch trains Hub B can hold.
Capacity at T1	Confidential	Trains	Maximum number of trains Terminal 1 can hold simultaneously.
Capacity at T4	Confidential	Trains	Maximum number of trains Terminal 4 can hold simultaneously.
Capacity at T5	Confidential	Trains	Maximum number of trains Terminal 5 can hold simultaneously.
Capacity at T7	Confidential	Trains	Maximum number of trains Terminal 7 can hold simultaneously.
Capacity at T8	Confidential	Trains	Maximum number of trains Terminal 8 can hold simultaneously.
Capacity of A General	2	Trains	Track capacity for segment A when used for inbound/dispatch journeys.
Capacity of C	1	Trains	Track capacity for the bidirectional segment C.
Capacity of D	1	Trains	Track capacity for the bidirectional segment D.
Capacity of E	1	Trains	Track capacity for the bidirectional segment E.
Fixed Times			
Inbound Stop time at B	20/60 confidential	Hours	Service time (20 minutes) for all

Variable Name	Formula/Value	Units	Description
			inbound trains at Hub B.
Outbound Stop Time at B	Confidential	Hour	Service and inspection time (2 hours) for all outbound trains at Hub B.
Time on segment A	15/60	Hour	Travel time (15 minutes) required to traverse segment A.
Time on Segment C	3/60	Hour	Travel time (3 minutes) required to traverse segment C.
Time on Segment D	13/60	Hours	Travel time (13 minutes) required to traverse segment D.
Time on Segment E	17/60	Hours	Travel time (17 minutes) required to traverse segment E.
Stochastic Dwell Times			
Time in T1	RANDOM UNIFORM(min, max, 0)	Hours	Random dwell time at T1 (between 2.5 and 4.5 hours).
Time in T4	RANDOM UNIFORM(min, max, 0)	Hour	Random dwell time at T4 (between 10 and 16 hours).
Time in T5	RANDOM UNIFORM(min, max, 0)	Hour	Random dwell time at T5 (between 3 and 6 hours).
Time in T7	RANDOM UNIFORM(min, max, 0)	Hours	Random dwell time at T7 (between 7 and 12 hours).
Time in T8	RANDOM UNIFORM(min, max, 0)	Hours	Random dwell time at T8 (between 3 and 6 hours).
Auxiliary and Occupancy Variables			
Occupancy at T1...T8	Trains in T1... etc.	Trains	The current number of trains located at each respective terminal.

Variable Name	Formula/Value	Units	Description
Occupancy of C	Trains on C returning + Trains on C to T1	Trains	Total trains currently on segment C (in either direction).
Occupancy of D	Trains on D returning + ...	Trains	Total trains currently on segment D (in either direction).
Occupancy of E	Trains on E returning + ...	Trains	Total trains currently on segment E (in either direction).
Occupancy B General	Sum of all inbound/ready-for-dispatch stocks at B	Trains	Total trains at Hub B that are part of the inbound journey.
Occupancy B Exit	Trains at B ready to exit + Trains at B Outbound	Trains	Total trains at Hub B that are part of the outbound journey.
Occupancy of A General	Sum of trains on A moving towards terminals	Trains	Total trains on segment A moving from V1->B and B->C/D.
Occupancy of A Exit	Trains on A returning to B + Trains on A to V1 Exit	Trains	Total trains on segment A moving from C/D->B and B->V1.
Capacity B Exit	+ MAX(0, Capacity B General - Occupancy B General)	Trains	Dynamic capacity for outbound trains at B. Allows outbound use if inbound space is free.
Capacity of A Exit	1 + MAX(0, Capacity of A General - Occupancy of A General)	Trains	Dynamic capacity for segment A's exit direction. Ensures bidirectional use is mutually exclusive.
Total entrances	Arrivals T1 + Arrivals T5 + Arrivals T4 + Arrivals T7 + Arrivals T8	Trains/Hour	The total rate of all trains arriving at the port entrance.
Total trains inside...	Sum of all 31 train stock variables	Trains	A snapshot of the total number of trains currently

Variable Name	Formula/Value	Units	Description
			anywhere within the port network.
State Variables (Stocks)			
At Entry V1			
Trains waiting at V1 T1	INTEG (Train Arrivals at T1 - Depart V1 for B T1, 0)	Trains	Trains queued at V1 for T1, waiting to enter segment A.
Trains waiting at V1 T4	INTEG (Train Arrivals at T4 - Depart V1 to B T4, 0)	Trains	Trains queued at V1 for T4, waiting to enter segment A.
Trains waiting at V1 T5	INTEG (Train Arrivals T5 - Depart V1 for B T5, 0)	Trains	Trains queued at V1 for T5, waiting to enter segment A.
Trains waiting at V1 T7	INTEG (Train Arrivals T7 - Depart V1 for B T7, 0)	Trains	Trains queued at V1 for T7, waiting to enter segment A.
Trains waiting at V1 T8	INTEG (Train Arrivals T8 - Depart V1 for B T8, 0)	Trains	Trains queued at V1 for T8, waiting to enter segment A.
On Segments (Inbound)			
Trains on A to B T1...T8	INTEG (Depart V1... - Arrivals at B..., 0)	Trains	Trains traveling from V1 to Hub B, segregated by destination.
Trains on A returning for T1	INTEG (Depart B for T1 - Arrive C from A, 0)	Trains	Trains traveling from B backwards on A to reach segment C.
Trains on A returning for T4	INTEG (Depart B for T4 - Arrive D from A T4, 0)	Trains	Trains traveling from B backwards on A to reach segment D for T4.
Trains on A returning for T5	INTEG (Depart B for T5 - Arrive D from A T5, 0)	Trains	Trains traveling from B backwards on A to reach segment D for T5.
Trains on C to T1	INTEG (Arrive C from A - Arrive at T1, 0)	Trains	Trains traveling from segment A to T1 via segment C.
Trains on D to T4	INTEG (Arrive D from A T4 - Arrive at T4, 0)	Trains	Trains traveling from segment A to T4 via segment D.
Trains on D to T5	INTEG (Arrive D from A T5 - Arrive at T5, 0)	Trains	Trains traveling from segment A

Variable Name	Formula/Value	Units	Description
			to T5 via segment D.
Trains on E to T7	INTEG (Depart B for T7 - Arrive at T7, 0)	Trains	Trains traveling from Hub B to T7 via segment E.
Trains on E to T8	INTEG (Depart B for T8 - Arrive at T8, 0)	Trains	Trains traveling from Hub B to T8 via segment E.
At Hub B			
Trains at B inbound T1...T8	INTEG (Arrivals at B... - Start journey..., 0)	Trains	Trains at B undergoing the 20-min inbound service.
Trains at B ready for T1...T8	INTEG (Start journey... - Depart B..., 0)	Trains	Trains at B that finished service and are waiting for a clear path.
Trains at B Outbound	INTEG (Arrive at B... - Finish Outbound Service, 0)	Trains	Trains returned to B and are undergoing the 2-hour outbound service.
Trains at B ready to exit	INTEG (Finish Outbound Service - Depart B for Exit, 0)	Trains	Trains that finished outbound service and are waiting to exit.
At Terminals			
Trains in T1...T8	INTEG (Arrive at T... - Depart T..., 0)	Trains	Trains currently dwelling at their destination terminal.
On Segments (Outbound)			
Trains on C returning	INTEG (Depart T1 - Arrive at A from C, 0)	Trains	Trains returning from T1 towards segment A.
Trains on D returning	INTEG (Depart T4+T5 - Arrive at A from D, 0)	Trains	Trains returning from T4 & T5 towards segment A.
Trains on E returning	INTEG (Depart T7+T8 - Arrive at B from T78, 0)	Trains	Trains returning from T7 & T8 towards Hub B.
Trains on A returning to B	INTEG (Arrive at A... - Arrive B from A, 0)	Trains	Trains from C/D now on segment A, traveling to Hub B.
Trains on A to V1 Exit	INTEG (Depart B for Exit - Exit System via V1, 0)	Trains	Trains on segment A heading for the final exit at V1.
System Sink			

Variable Name	Formula/Value	Units	Description
Trains Exited	INTEG (Exit System via V1, 0)	Trains	A cumulative count of all trains that have left the system.
Flow Variables (Rates)			
Inbound Flows			
Depart V1 for B T1...T8	IF THEN ELSE(Occupancy of A General < Capacity of A General, IF THEN ELSE(Occupancy B General < Capacity B General, MIN(Trains waiting at V1 Tx, MIN(Capacity of A General - Occupancy of A General, Capacity B General - Occupancy B General)) / (0.1 * Units Aux), 0), 0)	Trains/Hour	Rate of trains leaving V1 for B, checking for space on segment A and at Hub B.
Arrivals at B T1...T8	Trains on A to B T1 / Time on segment A... etc.	Trains/Hour	Rate of trains arriving at Hub B after traversing segment A.
Start journey to terminal T1...T8	Trains at B inbound T1 / Inbound Stop time at B... etc.	Trains/Hour	Rate at which trains complete inbound service at B.
Depart B for T1...T8	IF THEN ELSE(..., MIN(...) / (0.1*Units Aux2), 0)	Trains/Hour	Rate of trains leaving B for terminals, checking all path segments for capacity.
Arrive C from A	IF THEN ELSE (Occupancy at T1<Capacity at T1, IF THEN ELSE (Occupancy of C<Capacity of C, MIN(Trains on A returning for T1, MIN(Capacity at T1-Occupancy at T1, Capacity of C-Occupancy of C))/Time on segment A,0),0)	Trains/Hour	Rate of trains moving from segment A onto segment C. Checking again all path segments for capacity.
Arrive D from A T4/T5	IF THEN ELSE (Occupancy at Tx<Capacity at Tx, IF THEN ELSE (Occupancy of D<Capacity of D, MIN(Trains on A returning for Tx,	Trains/Hour	Rate of trains moving from segment A onto segment D towards terminal x. Checking

Variable Name	Formula/Value	Units	Description
	MIN(Capacity at Tx-Occupancy at Tx, Capacity of D-Occupancy of D))/Time on segment A,0),0)		again all path segments for capacity.
Arrive at T1...T8	IF THEN ELSE(Occupancy at Tx<Capacity at Tx, MIN(Trains on Y to Tx, Capacity at Tx-Occupancy at Tx)/Time on Segment Y,0)	Trains/Hour	Rate of trains arriving at their final terminal (x) through segment (Y). Checks again that terminal has capacity.
	Outbound Flows		
Depart T1...T8	IF THEN ELSE(..., MIN(...)/ Time in T..., 0)	Trains/Hour	Rate of trains leaving their terminal based on their dwell time. Checking for availability in hub B and segments used to arrive
Arrive at A from C/D	IF THEN ELSE(..., MIN(...)/ Time on Segment..., 0)	Trains/Hour	Rate of trains from C/D arriving back at segment A. Checking availability in B and segments left to be used to arrive.
Arrive at B from T78	IF THEN ELSE(Occupancy B Exit < Capacity B Exit, MIN (Trains on E returning, Capacity B Exit-Occupancy B Exit) / Time on Segment E, 0)	Trains/Hour	Rate of trains from T7/T8 arriving back at Hub B.
Arrive B from A	IF THEN ELSE(Occupancy B Exit < Capacity B Exit, MIN (Trains on A returning to B, Capacity B Exit-Occupancy B Exit) / Time on segment A, 0)	Trains/Hour	Rate of trains from segment A arriving back at Hub B.
Finish Outbound Service	Trains at B Outbound / Outbound Stop Time at B	Trains/Hour	Rate at which trains complete the 2-hour outbound service at B.
Depart B for Exit	IF THEN ELSE(Occupancy of A Exit < Capacity of A Exit , MIN (Trains at B ready to exit, Capacity of A Exit-Occupancy of A Exit)/ (0.1*Units Aux), 0)	Trains/Hour	Rate of trains leaving Hub B towards the final exit, checking availability of A

Variable Name	Formula/Value	Units	Description
Exit System via V1	Trains on A to V1 Exit / Time on segment A	Trains/Hour	The final rate of trains leaving the system.

Table D: List of Vensim PLE functions for train Model 1

- Model 2: aggregate approach

The model of the aggregate approach follows the same logic as the model previously presented, therefore only the key differences will be explained. The biggest one, is that instead of having an Arrival for each terminal it has generic arrivals that wrap up the total of all terminals into one flow.

Variable Name	Formula/Value	Units	Description
Arrivals	WITH LOOKUP (Custom Time, ([(0,0)-(168,1.1)],(0,0),(1,0), ...,(168,0)))	Trains/Hour	The scheduled total arrival rate of trains for all terminals at the port entrance (V1), defined by a lookup table over 168 hours.

Table E: List of Vensim PLE functions for train Model 2

Then, up until arriving at the departure from B to each terminal it is one generic flow instead of 5 stocks and flows, using the same logic procedure as the one before, but wrapping up all arrivals in one flow. Then, when trains at B are ready to depart for terminals, the flow separates into three. Here, the probability of using each terminal is needed, which are given by data proportioned by Next Freight and kept confidential. These probabilities were used when departing for each terminal as a multiplication factor inside each of the formulas, having the majority of trains into terminal 5 and terminal 1, and a low amount to terminal 4.

For the flow departing from B towards each terminal, the expressions used are as follows (Table F):

Variable Name	Formula/Value	Units	Description
Depart B for T1	IF THEN ELSE(Occupancy of A General < Capacity of A General, IF THEN ELSE(Occupancy of C < Capacity of C, IF THEN ELSE(Trains in T1 < Capacity at T1,	Trains /Hour	The scheduled total departure rate of trains from B to terminal 1, that checks available capacity throughout the segments ahead

	(Trains at B ready for Terminal / (0.1*Units Aux2)) * Prob T1, 0), 0), 0)		up until the destination
Depart B for T45	IF THEN ELSE(Occupancy of A General < Capacity of A General, IF THEN ELSE(Occupancy of D < Capacity of D, IF THEN ELSE(Occupancy T45 Block < Capacity T45, (MIN(Trains at B ready for Terminal, MIN(Capacity of A General-Occupancy of A General,MIN(Capacity of D-Occupancy of D,Capacity T45-Occupancy T45 Block))) / (0.1*Units Aux2)) * (Prob T4 + Prob T5), 0),0),0)	Trains /Hour	The scheduled total departure rate of trains from B to terminals 4 and 5, that checks available capacity throughout the segments ahead up until the destination
Depart B for T78	IF THEN ELSE(Occupancy of E < Capacity of E, IF THEN ELSE(Occupancy T78 Block < Capacity T78, ((MIN(Trains at B ready for Terminal, MIN(Capacity of E-Occupancy of E,Capacity T78-Occupancy T78 Block)) / (0.1*Units Aux2))) * (Prob T7 + Prob T8), 0), 0)	Trains /Hour	The scheduled total departure rate of trains from B to terminals 7 and 8, that checks available capacity throughout the segments ahead up until the destination

Table F: List 2 of Vensim PLE functions for train Model 2

3.3.4. Validation and calibration

In order to guarantee the correct functioning of the model it's fundamental to perform some tests. Two kinds of tests were performed which were useful to fix logic issues within the model, mainly related to the constraints.

- **Saturated system tests**
  Initially the system was saturated to abnormal flows, in order to check if even for a very saturated system capacity constraints were being followed.
- **Single train passing tests**
  Afterwards, the opposite was performed, by assigning in four cases unitary values of flows entering:
  a) Test 1: Only 1 Train Enters at Hour 12 Through T1
  b) Test 2: Only 1 Train Enters at Hour 12 Through T4

c) Test 3: Only 1 Train Enters at Hour 12 Through T5

d) Test 4: Only 1 Train Enters at Hour 12 Through T7

e) Test 5: Only 1 Train Enters at Hour 12 Through T8

f) Test 6: Only 1 Train Enters at Hour 12 Through Each Terminal at Once

3.3.5. Scenarios Modeled

After building the model and performing several tests to validate and calibrate it, its primary function becomes to use it as a strategic tool to evaluate it under various real-world conditions, approaching possible situations in order to identify their effects. These scenarios (shown in Table G) are divided into two main categories: those that examine the impact of the growth of demand, and those that assess the system's resilience to disruptions.

Scenario	Demand	Disruption	Description
0	Base demand	None	Flow of all segments according to base conditions
1	+30% demand	None	Flow of entrance is incremented by 30% respect base conditions
2	+100% demand	None	Flow of entrance is incremented by 100% respect base conditions
2a	+100% demand	-1 binary in segment A	Flow of entrance is incremented by 100% respect base conditions. Decrease of capacity of A is evaluated in peak demand conditions.
3	Base demand +30% demand +100% demand	At terminal 5	Closure of T5 during Wednesday from 10:00 to 18:00. Evaluated under multiple demand scenarios.
4	Base demand +30% demand +100% demand	At segment A	Closure of segment A all days during 20:00 to 4:00 Evaluated under multiple demand scenarios.
5	Base demand +30% demand +100% demand	At segment E	Closure of segment E all days during 20:00 to 4:00 Evaluated under multiple demand scenarios.
6	Base demand +30% demand +100% demand	Adverse weather	Decrease in speed of trains. Evaluated under multiple demand scenarios.

Table G: Scenarios modeled in railway network

- **Demand Increment Scenarios:** the base scenario is given in average normal weekly conditions of a year, but a port's traffic volume is not static due to seasonal fluctuations or long-term growth. Alternate scenarios were used to quantify the network's capacity under increased traffic. This is particularly pertinent to understand the operational limits of the port's network, to plan for peak seasons and for decision-making regarding future investment in infrastructure or improvements.

Scenario 0 – normal demand: The base scenario has a total demand of 34 trains, entering throughout the week to the different terminals served by railway accessibility. It serves as the benchmark against which all other scenarios modeled will be measured.

Scenario 1 – 30% incremented demand: The first increment in demand was given by 30% increase in traffic of trains entering during the week, for a total of 45 trains. It was modeled by adding these trains to the flow. This scenario represents peak season demand to test whether the system can absorb a plausible but realistic increase with manageable delays or if the system cannot absorb such capacity.

Scenario 2 – 100% incremented demand: The second increment in demand was given by doubling the base scenario trains entering during the week, for a total of 68 trains. It was also modeled by adding these trains to the flow. This scenario is modeled to approach long term traffic growth. It is a more extreme test that identifies the system's total saturation point and allows to evidence the behavior of bottlenecks when pushed beyond capacity. An additional scenario is evaluated in this condition in which segment's A capacity is reduced by 1, in order to assess a critical closure in peak demand conditions.

- **Disruption Scenarios:** disruption scenarios are related to effects that interrupt the passing of traffic or other possible unexpected events that affect the flow. They could be for instance related to sudden closure of binaries or tracks due to maintenance or damage, and closure of terminals also for maintenance or damage. This could also be associated with sudden changes in capacity of terminals or tracks, among others.

Scenario 0 – base scenario: The base scenario has all facilities and binaries working and available at all times during the week.

Scenario 3 – temporary closure of terminal 5: The first disruption will be to temporarily disable terminal 5 during Wednesday from 10:00 to 18:00 (meaning from hour 58 to hour 66). This could happen, for example if critical equipment in the terminal fails such as a crane breakdown, or with isolated safety incidents or emergency maintenance activities. It was modeled by changing the capacity into a lookup function, which is 1 when it is available, and 0 during the hours of closure.

Scenario 4 – temporary closure of segment A: The second disruption will be to block binary track A for 6 hours from 20:00 to 4:00 every day (from hours: 20-28; 45-52; 68-76; 92-100; 116-124; 140-148; 164-168), to approach maintenance activities overnight. It was modeled by creating an auxiliary variable that serves as stoplight and pauses flow through track A during these hours, both on capacity of A general, and the capacity of A for exit only.

Scenario 5: The third disruption, similarly to before, will be to block binary track E for 6 hours from 20:00 to 4:00 every day (from hours: 20-28; 45-52; 68-76; 92-100; 116-124; 140-148; 164-168). It was modeled by changing the capacity into a lookup function, which is 1 when it is available, and 0 during the hours of closure. that serves as stoplight and pauses flow through track E during these hours.

Scenario 6 – temporary closure of segment E: The fourth disruption consists of the reduction of speed due to bad weather conditions that force trains to go slower for reasons such as visibility. It is scheduled to occur between Wednesday and Thursday, meaning from hours 49 to 96, not as a localized failure but as a general failure, as it affects the movement of all trucks across the system. The reduction of speed leads to double the speed of the segments C, D, E, as the duration of the journey through segment A is mostly composed of dwell time at the entrance therefore no speed increment was considered. In such way, the new times are shown in Table H:

Segment	Normal weather conditions time (min)	Adverse weather conditions time (min)
A	15	15
C	3	6
D	13	26
E	17	34

Table H: List of times under adverse weather conditions for scenario 6

3.4. Crossings between networks

Developed in collaboration with Sara Cardinale

After analyzing the road and rail networks separately, a third integrated model was developed, capable of providing an overview of all land transport operations in the port. The aim is to move beyond the isolated analysis of the two systems and to investigate the emerging behaviors that result from their interaction.

In particular, this model focuses on analyzing the dynamic conflicts that occur at level crossings (X1, X2, and X3), assessing the impact of giving priority to rail traffic over road traffic, and identifying how localized disruptions can propagate throughout the entire system. By coupling rail and road simulations, it is possible to obtain a more realistic representation of phenomena typical of complex multimodal contexts, such as cascading delays and the formation of prolonged queues.

3.4.1. Model integration methodology

The integration between the two models was achieved by using the outputs of the Rail simulation as dynamic inputs for the Road model. The core of the process lies in modeling the presence of trains at the three critical crossings and thereby conditioning the road flow according to the rail schedule.

- The occupancy data for the railway segments corresponding to the crossings (segments C, D, and E) were extracted and converted into three lookup table variables: *Train Presence at Crossing X1, Train Presence at Crossing X2,* and *Train Presence at Crossing X3*. These variables express at what times during the simulated week a train occupies a given crossing.
- To regulate the passage of heavy vehicles, binary 'permission' variables (*Trucks Permission to Cross X1, X2, X3*) were introduced, calculated using an *IF–THEN–ELSE function*. When the probability of a train being present exceeds a pre-set threshold (0.01), the permission variable takes the value 0, preventing transit; otherwise, it remains equal to 1, allowing passage.

The integration of these variables into the flow equations allows the movement of trucks at occupied intersections to be instantly reset to zero, realistically simulating the effect of a temporary closure.

3.4.2. Expected system dynamics

Given the structure of the model, the following dynamics are anticipated:

- Queues are expected to develop immediately upstream of intersections subject to closure, with the most significant occurrences predicted on segment M for X1, segment P for X2, and segment U for X3.
- Locally generated queues may propagate along the network, such as a slowdown at X3 extending to gate V3, increasing the stock of *Trucks Waiting at V3* and affecting all incoming traffic from that gate, regardless of destination.
- Interruptions are likely to reduce the effective capacity of the affected segments, leading to a decrease in overall throughput for the terminals served (T1, T3, and those accessed via V3), with the magnitude of this reduction representing one of the main outputs of the simulation.

3.4.3. Simulation parameters

The simulation is configured with the following global parameters:

- *Time units*: hours
- *Simulation horizon*: 168 hours (one week)
- *Integration timestep (TIME STEP)*: 0.01 hours, to ensure numerical precision and stability with the complex feedback loops.

The total weekly arrivals for trucks are implemented in the model through *some lookup functions*. The distribution is the same as the one adopted for Scenario 1 of the road network model.

3.4.4. Model variables and equations

To adapt the road network model to include the crossing conflicts, new variables were introduced to handle the logic of train presence, and several existing flow equations were modified. All other parameters, stocks, and flows remain as defined in the base road network model.

- **New Parameters and Constants**

These variables introduce the external data from the rail model and translate it into the control logic for the road network. (Table I)

Variable Name	Formula/Value	Units	Description
Train Presence at Crossing X1	WITH LOOKUP(Custom Time, ...)	Dmnl	Time-based lookup table representing the occupancy of the rail segment at crossing X1, taken as input from the rail model.
Train Presence at Crossing X2	WITH LOOKUP(Custom Time, ...)	Dmnl	Time-based lookup table for the occupancy of the rail segment at crossing X2.
Train Presence at Crossing X3	WITH LOOKUP(Custom Time, ...)	Dmnl	Time-based lookup table for the occupancy of the rail segment at crossing X3.
Trucks Permission to Cross X1	IF THEN ELSE(Train Presence at Crossing X1 > 0.01, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X1 and 1 otherwise.
Trucks Permission to Cross X2	IF THEN ELSE(Train Presence at Crossing X2 > 0.05, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X2 and 1 otherwise.
Trucks Permission to Cross X3	IF THEN ELSE(Train Presence at Crossing X3 > 0.05, 0, 1)	Dmnl	A binary switch that is 0 if a train is present at X3 and 1 otherwise.

Table I: List of Vensim PLE parameters and constant for the crossings Model

- **Modified Flows**

The following flow equations were modified from the original road network model. The multiplication by the Trucks Permission to Cross variable is the key change that enables the simulation of crossing interruptions. (Table J)

Variable Name	Modified Formula/Value	Units	Description
Arrive at V2 for Exit from M	(Trucks on M Outbound/Time Segment M) * Trucks Permission to Cross X1	Trucks/Hour	Rate of trucks arriving at V2 for exit, now conditional on X1 being clear.
Arrive at V3 Exit from U	(Trucks on U Outbound/Time Segment U) * Trucks Permission to Cross X3	Trucks/Hour	Rate of trucks arriving at V3 for exit, now conditional on X3 being clear.
Depart P for R	MIN(...) * Trucks Permission to Cross X2	Trucks/Hour	Departure rate from P towards R, now conditional on X2 being clear.
Depart R for P Outbound	MIN(...) * Trucks Permission to Cross X2	Trucks/Hour	Outbound departure rate from R towards P, now conditional on X2 being clear.

Variable Name	Modified Formula/Value	Units	Description
Depart V2 for T1	MIN(...) * Trucks Permission to Cross X1	Trucks/Hour	Departure rate from V2 towards T1, now conditional on X1 being clear.
Depart V3 for T2	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T2, now conditional on X3 being clear.
Depart V3 for T3	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T3, now conditional on X3 being clear.
Depart V3 for T4	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T4, now conditional on X3 being clear.
Depart V3 for T6	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T6, now conditional on X3 being clear.
Depart V3 for T8	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T8, now conditional on X3 being clear.
Depart V3 for T9	MIN(...) * Trucks Permission to Cross X3	Trucks/Hour	Departure rate from V3 towards T9, now conditional on X3 being clear.

Table J: List of Vensim PLE flow variables functions for the crossings Model

By implementing these modifications, the integrated model can accurately simulate the stop-and-go dynamics imposed on the road network, allowing for a detailed analysis of throughput reduction and queue propagation caused by rail priority.

3.4.5. Scenarios modeled

To evaluate the impact of rail traffic on the road network under different operational conditions, two distinct scenarios were simulated. In both scenarios, the road network's configuration and the truck arrival distribution (as displayed in Figure 15) remain constant.

Scenario	Case	Description
Version 1	Road only	Base demand for only road
Scenario 1	Road + Rail	Base demand for road interrupted by train's flow.
Scenario 2	Road + Rail (adverse weather)	Base demand for road interrupted by train's flow under adverse weather conditions

Table K: Scenarios modeled on the crossings between networks

The sole difference between the scenarios is the train schedule, which is imported as an external input from the corresponding simulations of the rail network model. This approach allows for the direct isolation and analysis of the effects of rail disruptions on road traffic.

Scenario 1: Base Conditions

This scenario serves as the baseline for performance analysis, representing the port's landside operations under normal, everyday conditions. The train schedule is derived from the base scenario of the rail network model, which assumes standard train speeds, loading/unloading times, and no unplanned disruptions. The resulting train presence distributions at the three crossings for the simulated week are exported and depicted in the graph below (Figure 15). This schedule reflects the standard operation of the port's rail system.

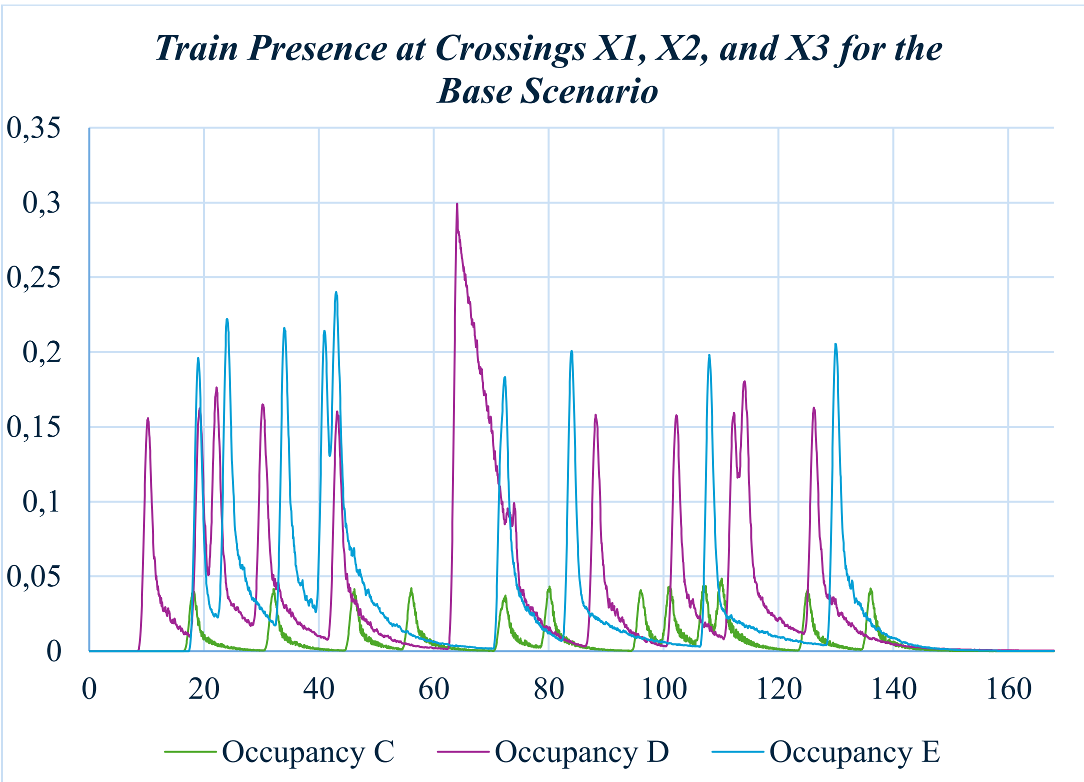

Figure 15: Train Presence at Crossings X1, X2, and X3 for Scenario 1

Scenario 2: Adverse Weather Conditions

This scenario is designed to test the resilience of the port's road network when the rail system is under stress. It simulates the impact of adverse weather conditions, which are assumed to primarily affect the efficiency of rail operations. In the rail network model, this was simulated by increasing the time trains spend at terminals and slightly reducing their travel speed, leading to delays and increased track occupancy for the entire duration of the simulation.

The resulting train schedule is significantly different from the baseline. As displayed in Figure 16, the crossings are occupied for longer and more frequent intervals, representing a more disruptive pattern of rail movements. By comparing the results of this scenario to the baseline, it is possible to quantify the cascading effects of rail delays on truck queues, waiting times, and overall terminal throughput.

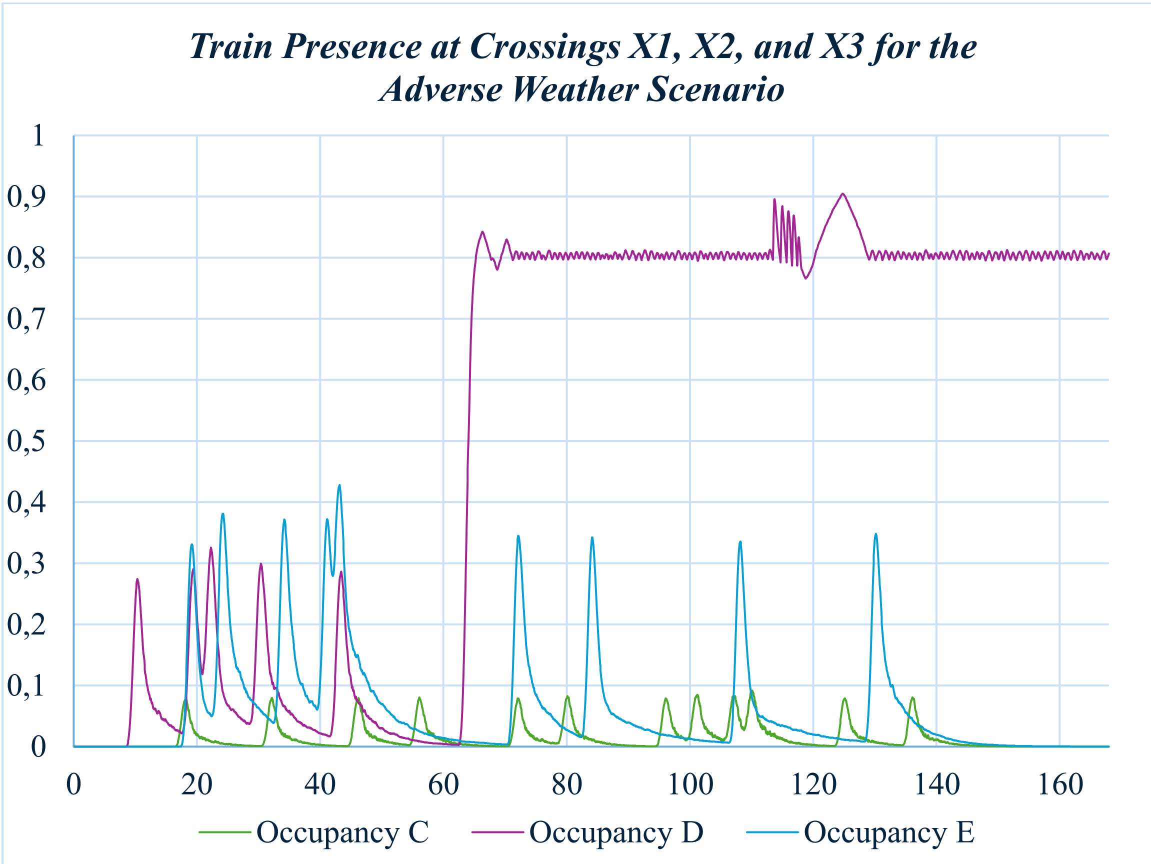

Figure 16: Train Presence at Crossings X1, X2, and X3 for Scenario 2

4. Results

4.1. Model validation

The validation process was conducted through six tests previously mentioned, simulating single isolated events in each track and in all tracks at once, all at hour 12 of simulation. After conducting them the results obtained not only confirmed the model's logical integrity but also revealed a hierarchy of constraints within the port's rail operations.

- **Test 1 - 1 train on T1**

For the first test, which simulates the entrance of the single pulse towards terminal 1 that can be seen as a sharp blue line in the graph below (Figure 17), the train fully exits the system at hour 40, meaning it takes 28 hours to fully process a train with destination to terminal 1, though this value may vary according to the dwell time in the terminal.

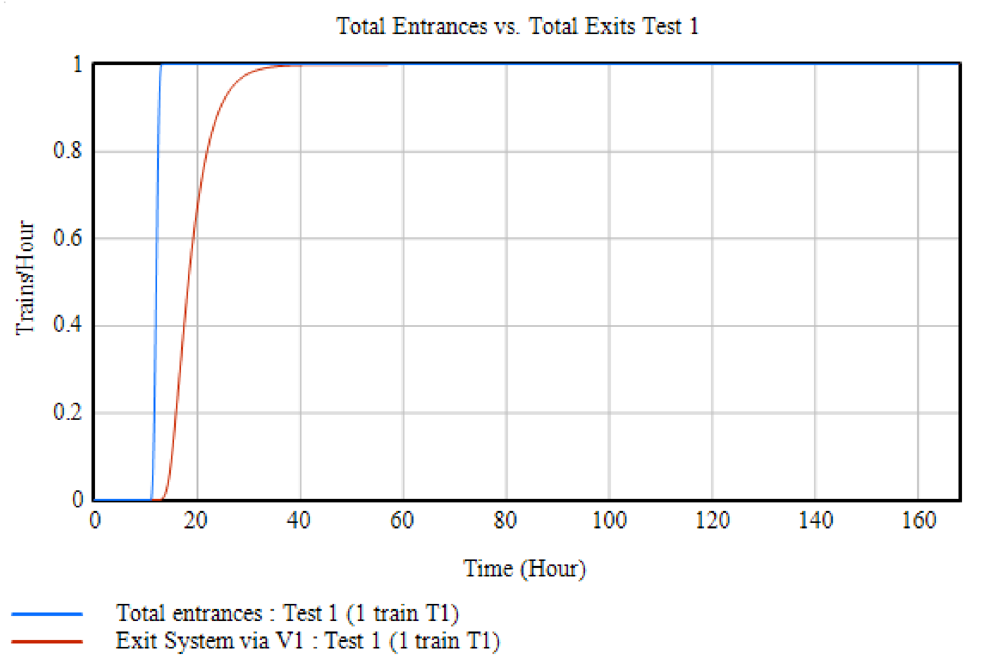

Figure 17: Total entrances and exits for test 1

Figure 18 was elaborated, to show the pulses generated throughout the entire journey from entering the port, going towards B, then towards the terminal, and then the same outbound journey. The initial phase from V1 towards B is characterized by a rapid succession of short-duration pulses, showing that this initial section has a minor duration with respect to the rest of the journey.

It may also be seen that the most significant activity (time wise) is the dwell time in the terminal, which becomes a dominant phase. This operational activity contributes significantly to the total transit time.

Finally, the return journey and exit seem visibly wider than the inbound pulse, reflecting in the purple line the longer time needed at hub B for exiting. The pink curve represents the exit of the train and shows how at hour 40 it is fully out of the system.

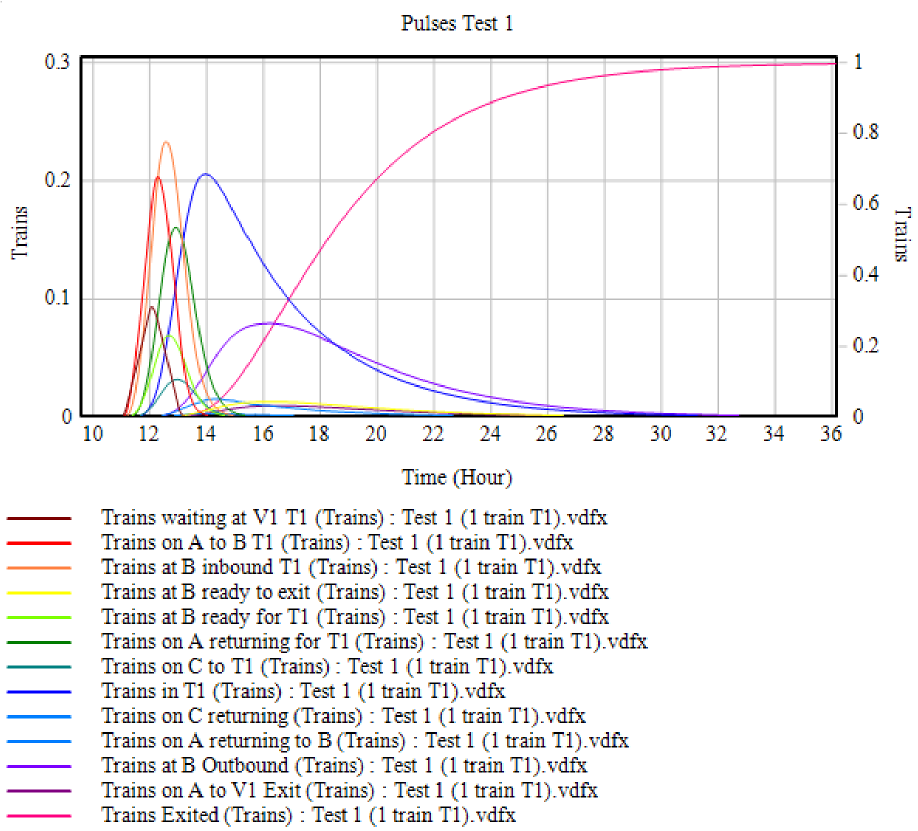

Figure 18: Pulses for journey of terminal 1 for test 1

- **Test 2 - 1 train on T4**

Following the baseline established in the first test, the second one replicated the same process but for terminal 4. A significant difference was apparent, as the transit time for this terminal was substantially longer, as the train completely left at around hour 100, for a total of 88 hours of transit time, which makes sense since the dwell time in T4 is longer than the dwell time in T1 due to the type of cargo they manage. The rest of the activities present a similar behavior to the previous test as observed in the graph of pulses. (Figure 19 and Figure 20)

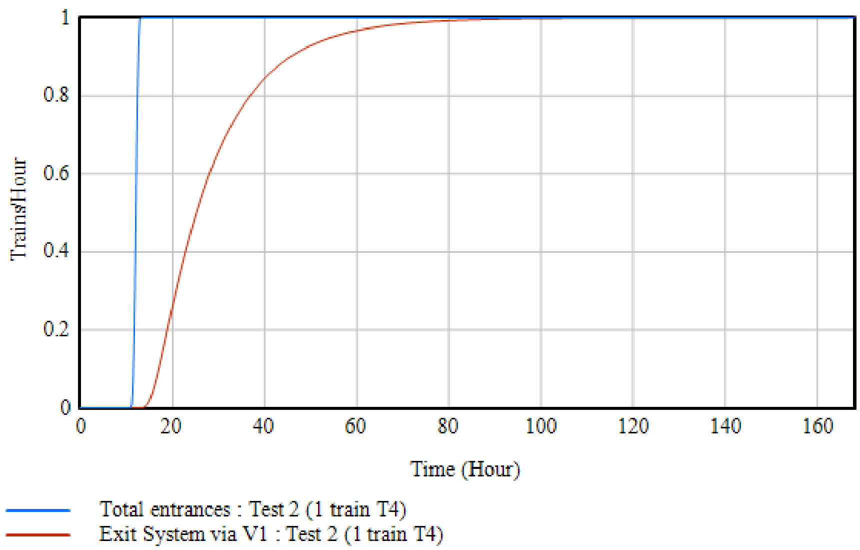

Figure 19: total entrances and exits for test 2

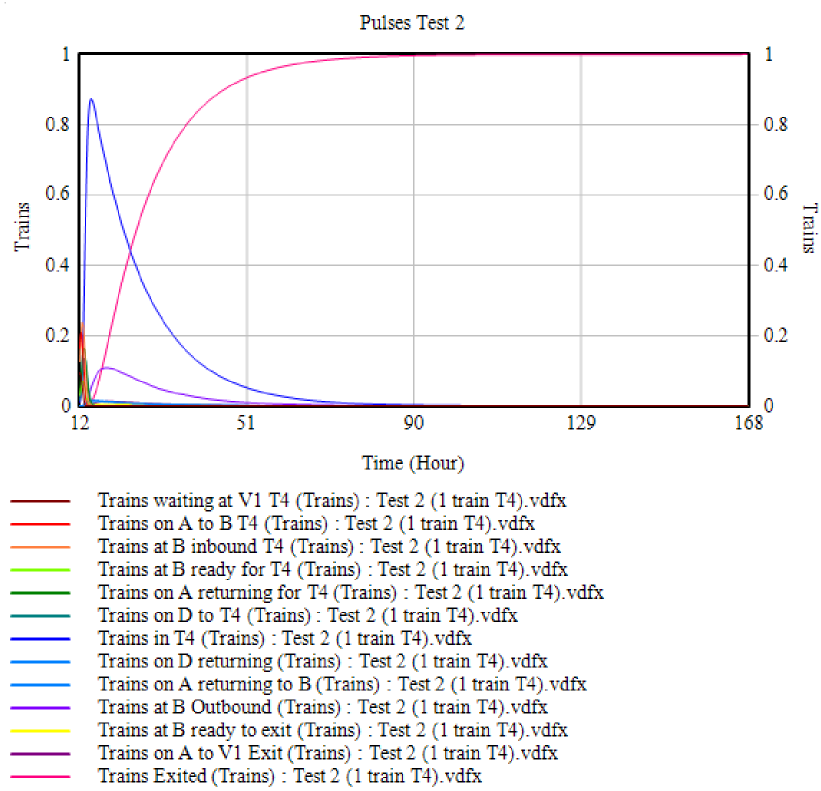

Figure 20: Pulses for journey of terminal 1 for test 2

- **Test 3 - 1 train on T5**

The third test, applied on terminal 5, allowed to view interesting insights, due to the fact that it has a shared inbound path with terminal 4, but has different operational characteristics, making it have a significantly shorter time, for which it could be said that trains transit time if empty, takes around 42 hours, significantly shorter than for terminal 4 due to the shorter dwell time in terminal.
As further tests are performed, the model's sensitivity to the dwell time in the terminals is confirmed.

- **Test 4 - 1 train on T7**

The fourth test examined the path towards terminal 7, which structurally changes with respect to the first tests, as for moving from hub B to the terminal the segment A is not used. The results show that at around hour 75, the train leaves fully, making a total of 63 hours of transit time.
This duration is significant and is again associated with the dwell time in the terminal which is also slightly high.

- **Test 5 - 1 train on T8**

Corresponding to the last individual test, this terminal shares the same path as terminal 8, but has faster dwell times in the terminal, which makes it a lot faster. This is why; at around hour 50 trains fully leave the system.
In this case, and in the cases where the dwell time in terminals was shorter, it's possible to observe pulses of closer magnitude across the process, than when the dwell time is long. Across all, and again in this test, it is possible to identify how the trains in the terminal present an extended wave, due to it being a significant and dominant time from the total transit time.

- **Test 6 – one train at hour 12 on each terminal**

The final test had the goal to analyze the response of the system when having a pressure from arrivals for all terminals at the same time, and to understand how the system prioritizes shared resources. This test goes beyond the determination of individual baselines, to actually identify bottlenecks that occur when resources are common and are under a selection case.
An important finding is that when observing the pulses for each of the journeys, it can be seen how the queue at V1 access points accentuates, which makes sense as it now has 5 trains competing for segment A that has only capacity for 1 train entering. This initial delay creates a cascading effect

that propagates along the whole system, increasing the transit time of the trains inside the system. From this test an important conclusion is therefore made, associated with the fact that segment A is a bottleneck possibility in the system, as it is a critical resource needed by all terminals at access, by some during the path to the terminal, and again by all during the exit.

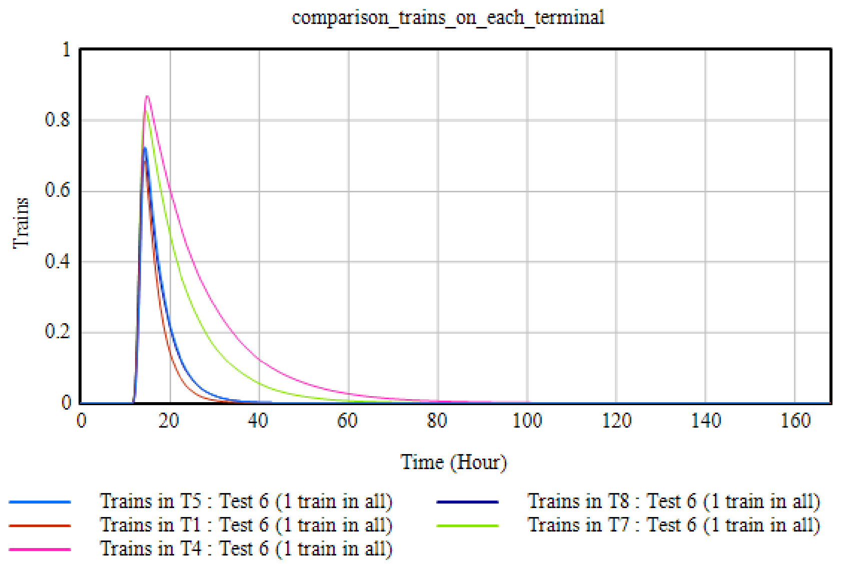

Figure 21: Comparison of trains on each terminal for test 6

By comparing the trains on each terminal on Figure 21, it is possible to get a comparative view on how the system prioritizes trains when they arrive all at once the staggered peaks of the pulses are a hint of the consequence of the queue generated at the entrance, and the width of the peaks reflects the dwell time differences previously discussed.

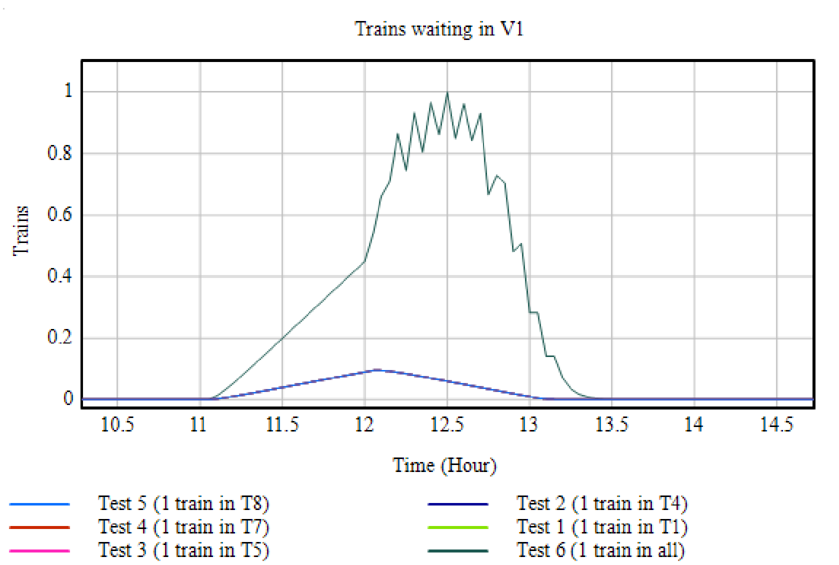

Figure 22: Comparison of trains waiting in the access point for all tests

By taking a look to Figure 22, it is possible to see that small queues of around 0.1 fractions of a train generate when one train only enters to the non-saturated system, as it is clear to pass through any of the segments succeeding such as shared segment A, which is the case of scenarios 1 to 5. Meanwhile, for scenario 6, it can be seen how a larger queue forms of nearly 1, as 5 trains arrive at once per terminal, and their queues accumulate at once reaching therefore this value, as not all can pass through immediately as A's capacity is only 2.

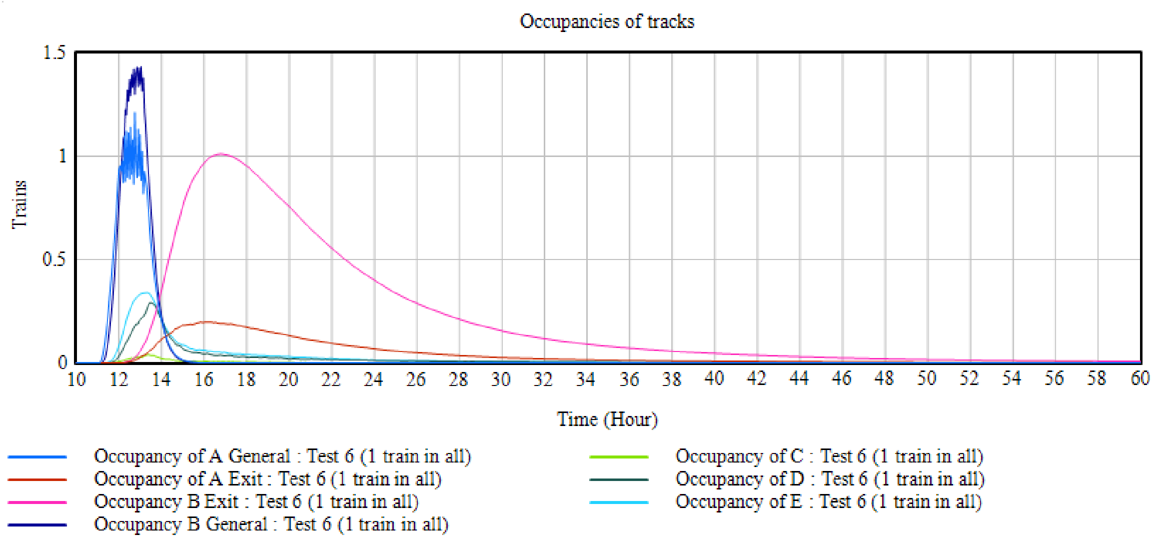

Figure 23: Occupancy of tracks for test 6

Then, when observing the occupancies of the tracks and of hub B on Figure 23, it is possible to get a dynamic view on how the shared resources of the port are being used, confirming a sharp bottleneck at A immediately after the trains arrive. A queue in B starts to form as there is clear way for trains to go to the terminals, especially for using C and D, as they are accessed through A, while E is used almost immediately.

These tests successfully highlight the model's capability of simulating the interactions between all terminals, and not only each individual path. Some additional tests were performed by putting the system under extreme flows at a pulse, to check that capacities were not being overpassed. It can be seen for example, for a case of overloading, regarding the occupancy of segment A, that it slightly overpasses the capacity of 1 for entrance that it has. This is a classic behavior of continuous simulation, and it is a phenomenon called overshoot. In this case, the capacity is not actually being physically overrun, since it is the process of calculation of the software, in which it immediately reacts to it and corrects it in the following time step. If time steps are shorter this is less likely to happen but will demand more computational power.

Finally, another insight is gotten by comparing the occupancy of A for all scenarios, where it is reflected that terminals 7 and 8 have a lower usage of A, which will was expected to be convenient for their functioning when running the base scenario or the other scenarios, as it allows them to have better flows and less dependance on the availability of A which is a complex bottleneck. This can be seen on the graph below (Figure 32).

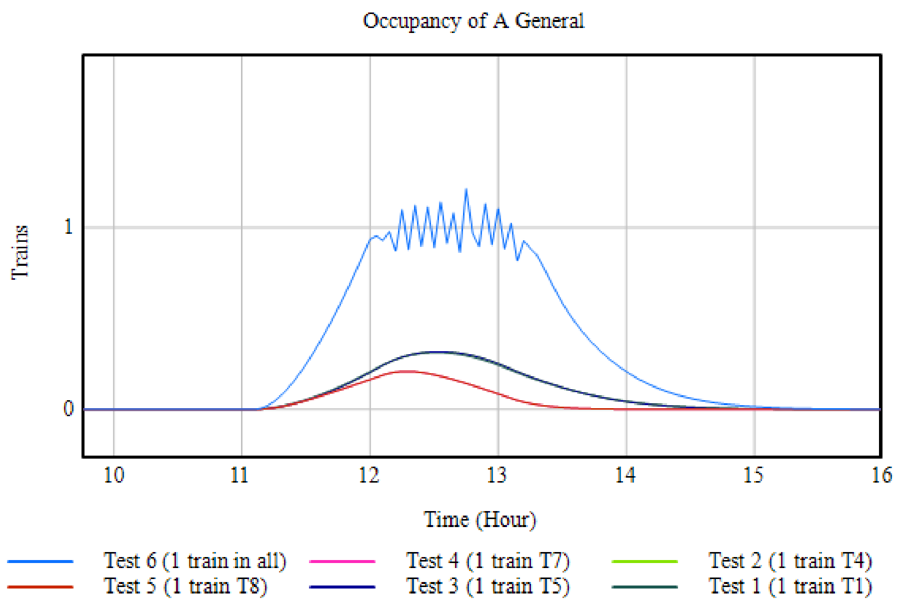

Figure 24: Occupancy of A general in all tests

After conducting all tests, several conclusions may be drawn besides proving the viability of the model. On one hand, tests 1 to 5 suggested that in an uncongested system the most dominant activity is an operational factor tied to cargo type, being the train's dwell time at its destination terminal, as the tendency is it requires long times. However, test 6, that simulated multiple simultaneous arrivals to all terminals, immediately shifted the primary constraint from the terminal operational times to shared infrastructure capacity, which may be evidenced in the queue formed at the V1 entry point, proving that segment A acts as the system's main gatekeeper, that generates bottlenecks even before trains reach their destination terminals. This highlights a key insight, as improving dwell time may sound like an attractive intervention, when in fact its impact is constrained by the congestion of the network and its segment capacities.

4.2. *Rail network results*

4.2.1. Aggregated and disaggregated models

As mentioned earlier, data may be retrieved in different ways according to the availability. The first analysis consisted of comparing a probabilistic model based on general data of entrances to the port and probabilities of entering each terminal, with the base model which has specific data on entrances to each of the terminals of the port. The aggregate model simplifies the system by treating all incoming trains as a single flow that is distributed onto the terminals based on known probabilities as multiplication factors.

Despite the significant difference between the formulation of both models, both throw high degree of similarity in the results, which can be reflected in the total trains inside the system (Figure 25), and in the overall congestion patterns across the different common variables of the models. It can be seen that inside the system trains follow the same patterns of congestion, have the same peaks and troughs, and have similar patterns in bottlenecks.

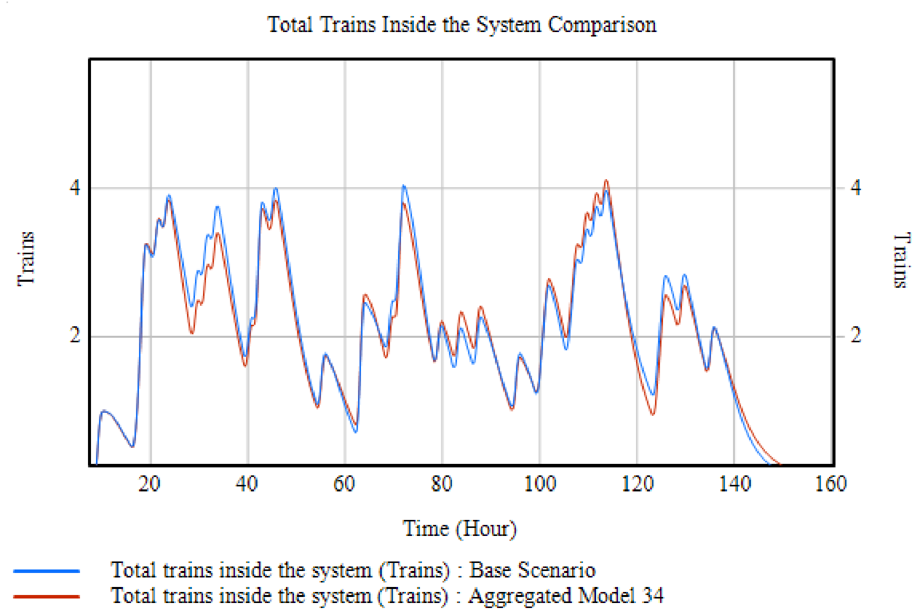

Figure 25: Total trains inside the system comparison between aggregated and disaggregated train model

The exit rate also has a strong correlation between the two models, suggesting that the system's throughput is the same through both representations.

An additional analysis was done by comparing both under a higher level of traffic as seen in Figure 26, selecting the highest scenario initially defined, meaning 68 trains during the week. In this case, the results show that the aggregated scenario (red line) consistently shows diverse peaks of congestion, approaching sometimes more and sometimes less trains inside the system, with respect to the base scenario (blue line) for 68 trains. This difference could mainly be caused by the aggregated inflow that is combined into a single stream and considers a more intense pattern of trains entering the port as every arrival is always divided into multiple terminals, making use of all resources at similar times. In such scenario, the disaggregated model shows a more realistic approach to the data collected.

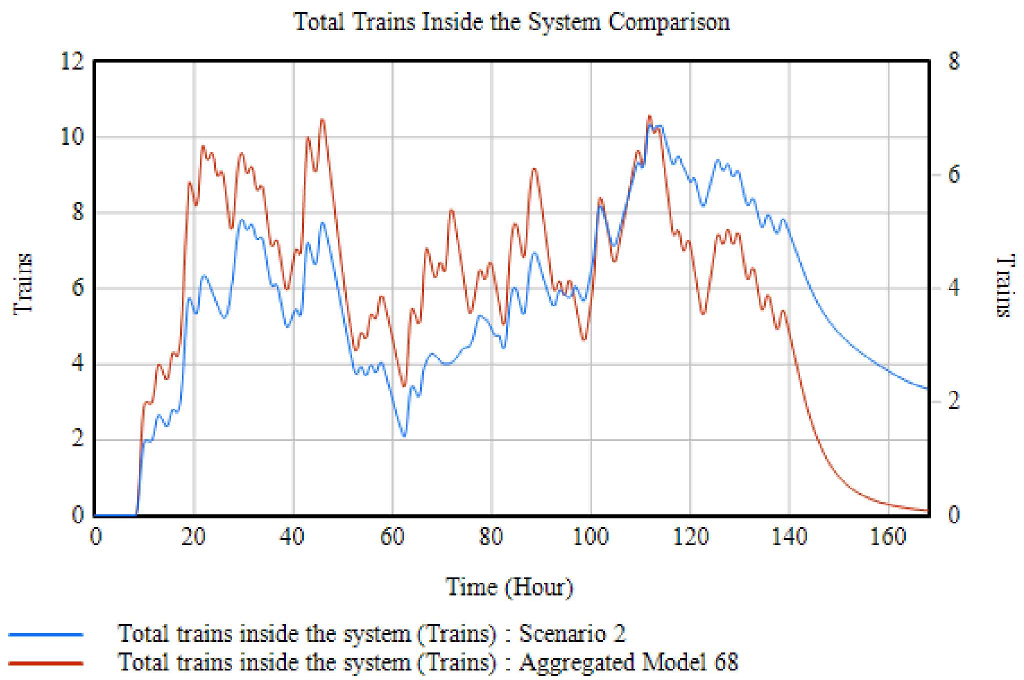

Figure 26: Total trains inside the system comparison for demand increment in the aggregated model

This means that the simplified model could also be a very valid and accurate tool, with certain strengths and weaknesses:

- As strengths, the aggregated or probabilistic approach presents a strategic insight into the key congestion points, bottlenecks, and queues inside the system, and it does it in a less data-intensive way, as it only requires total trains expected, and percentage destined for each terminal, making it easier to adapt the model when evaluating scenarios of growth, as only one flow has to be changed, and not a flow for each terminal.
- Nevertheless, as a weakness, this system has a loss of operational specificity, which is a drawback, as it is unable to model scenarios related to specific arrival patters, as it softens the distribution of trains across the terminals in an agglomerated way, rather than maintaining the specificity of arrivals at certain times to each terminal, which may greatly

affect the system, specifically under very congested conditions. Another drawback is that it is not possible to model targeted interventions, such as arriving train priority in the main entrance, as the model does not distinguish between them.

It could be said therefore, that the aggregated or probabilistic approach is more sensitive to the total volume of traffic and the timing and concentration of traffic than the more realistic, disaggregate model.

In such way, this analysis provides insight into a trade-off between data requirements and predictive accuracy for port planning. Under strategic planning (long-term with low demand and high-capacity) it is appropriate enough to use a probabilistic aggregated approach, while for high demand and low-capacity scenarios (tactical or short-term planning) a more disaggregated model is needed to approach reality better and successfully capture sharp localized peaks in congestion caused by clustered arrival schedules.

4.2.2. Demand growth scenarios

Scenario	Demand	Description	Percentage of trains processed	System gridlock	Maximum trains inside the system
0	Base demand	Flow of entrance according to base conditions	100%	No	3.7
1	+30% demand	Flow of entrance is incremented by 30% respect base conditions	100%	No	5.5
2	+100% demand	Flow of entrance is incremented by 100% respect base conditions	94%	No	10.3
2a	+100% demand and 1 binary less in track A	Flow of entrance is incremented by 100% respect base conditions, and the capacity of track A is decreased by 1	11.9%	Yes	19.0

Table L: Results by demand growth scenario in railway network

To assess the port's resilience and identify its operational limits under the 168 hours of operation, the model was subjected to scenarios of demand growth. The base scenario was compared against a 30% (Scenario 1) and 100% (Scenario 2) increase. They revealed how the port network has a non-linear performance degradation, as it operates near a critical tipping point, after which it fails. From the comparative table of trains that exited the system in Figure 27, it is possible to observe the direct measure of the train stress. Base scenario, on pink, shows how all 34 trains are processed in less than 168 hours, as well as the red line that represents the 30% increase, for which 45 out of 45 trains were processed on time. On the contrary, for scenario 2 in blue the system suffers from blockage and does not process all trains but 64 out of 68, meaning 94% of them.

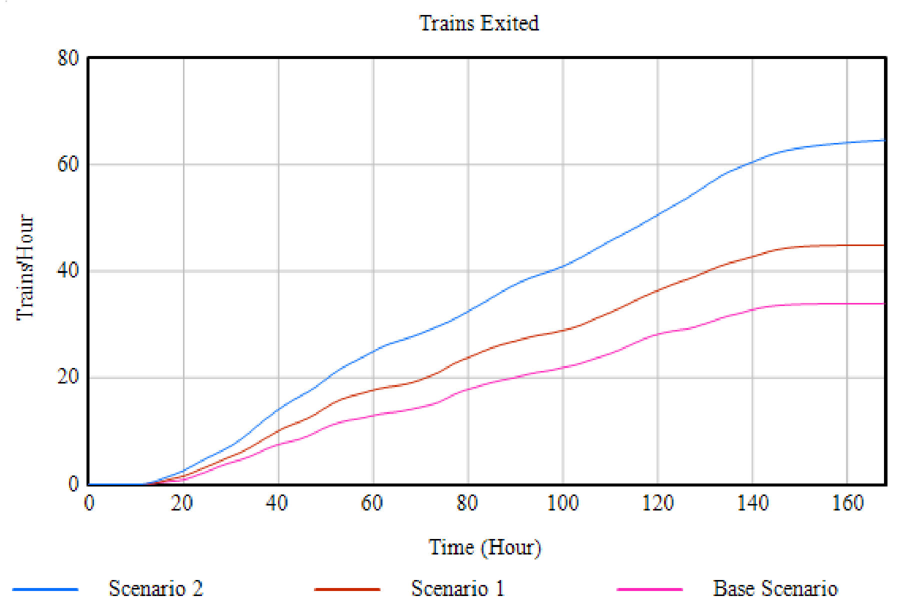

Figure 27: Total trains leaving the system on demand growth scenarios

Internal congestion and bottlenecks may be identified through Figure 28. On the base scenario, the occupancy of the tracks has a typical behavior in which occupancy raises and decreases in pulses while trains are being processed. Due to low demand, no tracks are saturated, and only get occupied while trains are being processed, but no significant queues form, as seen in the occupancy graph below (Figure 38).

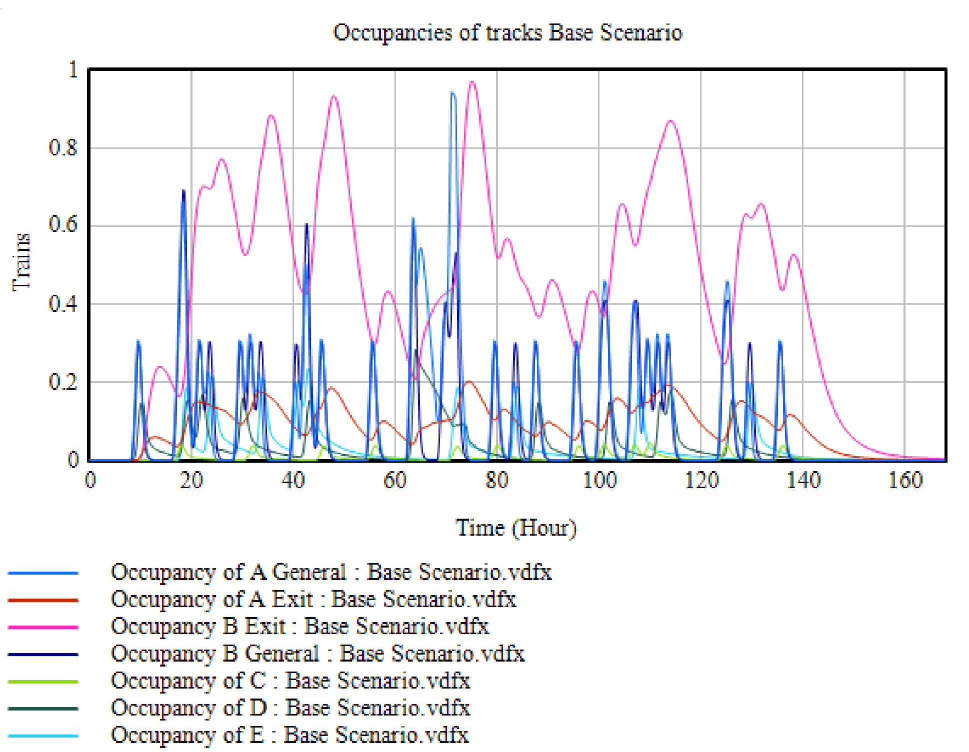

Figure 28: Occupancies of tracks on the base scenario

On scenario 1, larger occupancies are seen, but still a similar behavior, as it is still a manageable demand. It can be observed in Figure 29, thanks to correct model functioning, that no capacities are exceeded. Meanwhile, on scenario 2, where demand exceeds capacity, it can be seen how segment E spends has a sustained maximum occupancy from around hour 85, meaning that from Thursday at midday this track is at sustained maximum occupancy, which affects terminals 7 and 8.

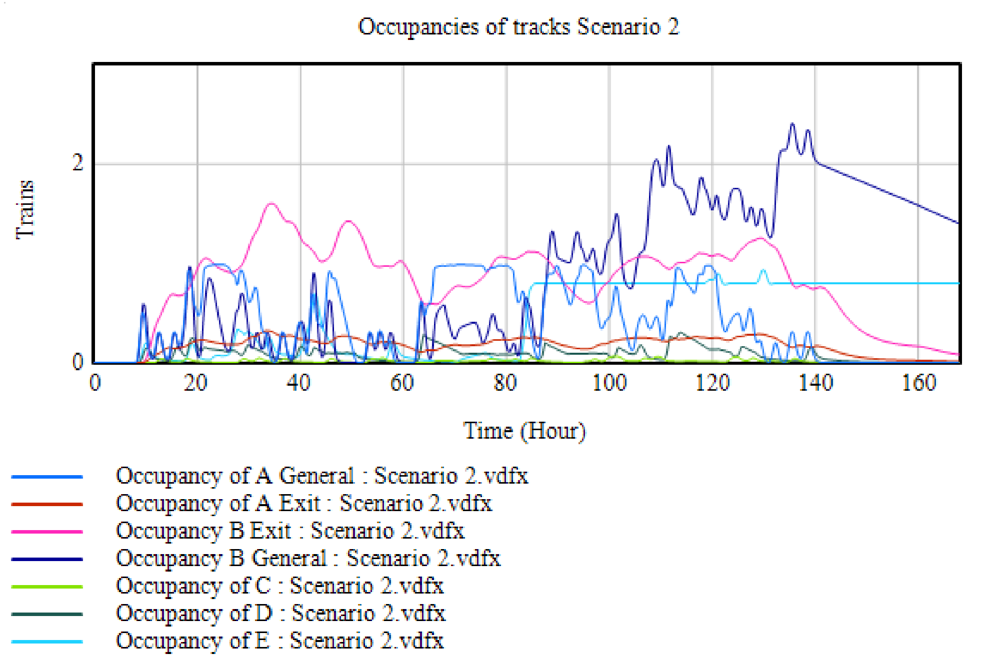

Figure 29: Occupancies of tracks on scenario 2

To understand if it is blocked or if it is just working at the maximum occupancy, a further analysis is done. What is seen is that the system is not actually blocked: during the week only a total of 64 trains is processed but it keeps constantly processing trains until the very end. Therefore, the sustained occupancy only suggests that the segment is being constantly used, but trains are constantly moving and not blocked.

It was speculated from the beginning that segment A would probably be a bottleneck as well as hub B. It was possible to confirm it by running an additional alternative scenario with respect to scenario 2 (Figure 30), in which the capacity of A was not 2, but 1. This allowed to observe how sensitive the network capacity is to the shared resource A, as by decreasing the number of binaries available on it, the system gets blocked very early, and leads also to the blockage of B as trains queue on it to wait for space to transit A. This is a clear example of gridlock of the system, in which under such high demand and low capacity of A, the system is victim of a bottleneck from which it cannot recover:

- The occupancy of B, destined for both entry and exit, reaches the maximum capacity of 6 at around hour 60 sustained for the rest of the simulation, meaning hub B fills completely and never gets to clear its queue.
- The occupancy of A stays at its capacity of 1 for the entire simulation after several time in the initial period. This means that as this track is occupied, and B is occupied trains may not advance and the port fails, as it can no longer accept new trains, and trains that are in are locked or moving at a drastically reduced rate.

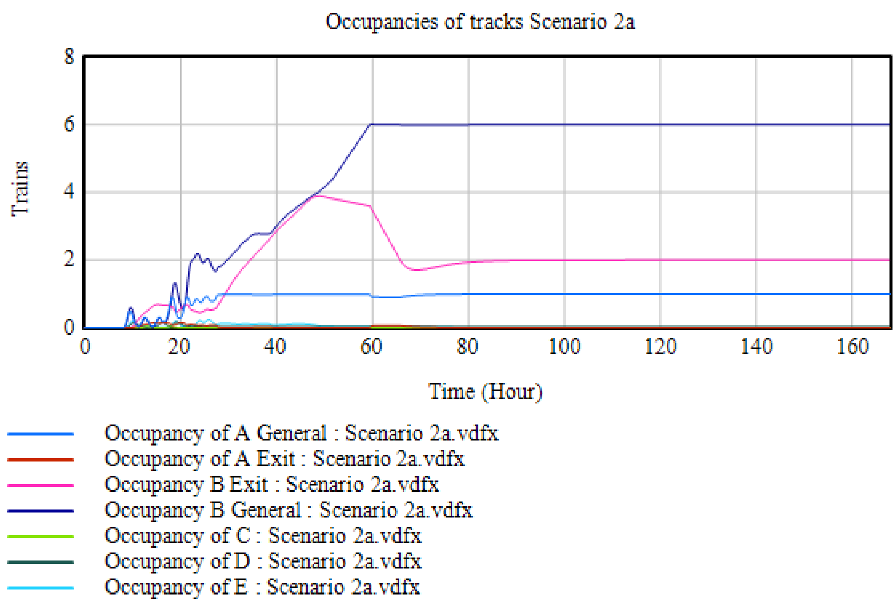

Figure 30: Occupancies of tracks on scenario 2 with reduction of capacity of track A to 1.

In such way, it is possible to identify the operational limits of the port's rail network. While the system can absorb a 30% increase in traffic pointing an elastic behavior, doubling the demand slightly pushes the system outside of capacity without generating a blockage but without being able to process all trains withing the week, demonstrating the elasticity of the system is limited. This suggests the non-linear behavior of the system, as it doesn't just gradually get slower, but has a breakpoint at which it exceeds capacity, and the efficiency deteriorates drastically. The analysis of internal occupancies also allowed to confirm that the main bottlenecks under high demand conditions are the shared entry track (A) and the processing hub (B), especially at outbound service due to its long duration of 2 hours. Through the supplementary test in which the capacity of segment A was reduced to a single track it was possible to prove that it is fundamental for the functioning of the system and suggests big impacts if completely closed temporarily. Therefore, these are the areas that would require infrastructural or operational interventions to improve the port's capacity for future growth of demand.

4.2.3. Disruption scenarios

For the disruption scenarios, the goal is to isolate the specific impact of each disruption to compare it directly to the normal operation of the base scenario in normal conditions. It allows to map the vulnerability of the system, concluding that the vulnerability of a disruption is related to the centrality of the component affected.

Scenario	Disruptions	Description	Percentage of trains processed			Max trains inside the system	
			Base demand	+30% demand	+100% demand	Base demand	+100% demand
0	None	Flow of all segments according to base conditions	100%	100%	94%	3.9	10.2
3	At terminal 5	Closure of T5 during Wednesday from 10:00 to 18:00	100%	100%	94%	4.1	11.3
4	At segment A	Closure of segment A all days during 20:00 to 4:00	100%	100%	90%	5.0	8.34
5	At segment E	Closure of segment E all days during 20:00 to 4:00	100%	93%	60%	4.3	15.6
6	Adverse weather	Decrease in speed of trains.	92%	87%	29,4%	6.8	13.0

Table M: Results by disruption scenario in railway network

- **Scenario 3**

For Scenario 3 (displayed in blue in the graph below, in Figure 31), which simulates the closure of terminal 5, it can be observed that for a traffic of 34 trains during the week, even if it delays the access of trains between hours 58 and 66, the system is able to recover itself and continue the same trend that the base scenario (in red) has. This is due to the low traffic conditions of this scenario with respect to the system's capacity, as no segment or terminal collapses in capacity. Trains wait in segments before advancing to terminal 5 and wait for it to be open again.

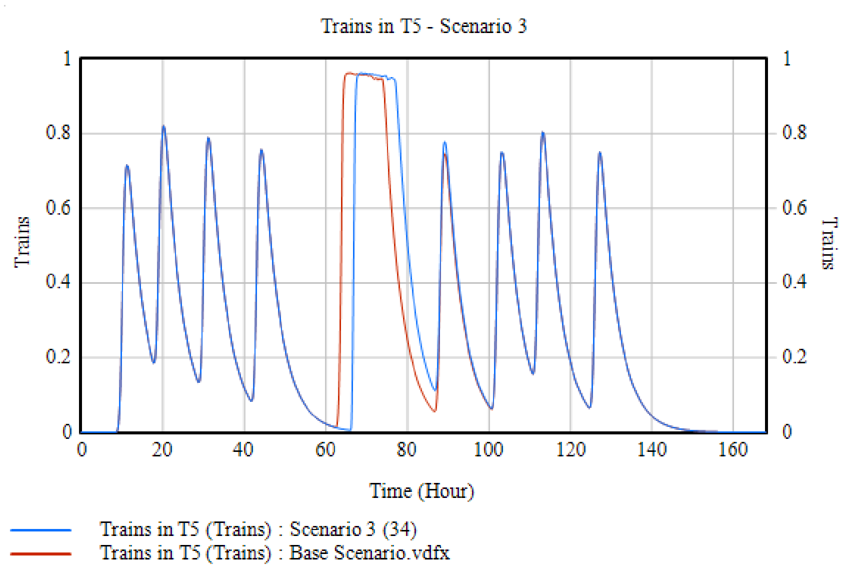

Figure 31: Occupancies of terminal 5 on the scenario 3

This scenario was then also evaluated under the demand growth conditions, and for traffic of 45 trains and 68 trains the system does not fully recover but is still able to manage the departure of all trains in the same amount as if T5 stayed open, but with a slight delay with respect to normal conditions. The total trains that exited respect normal conditions are shown in the Figure 32 below.

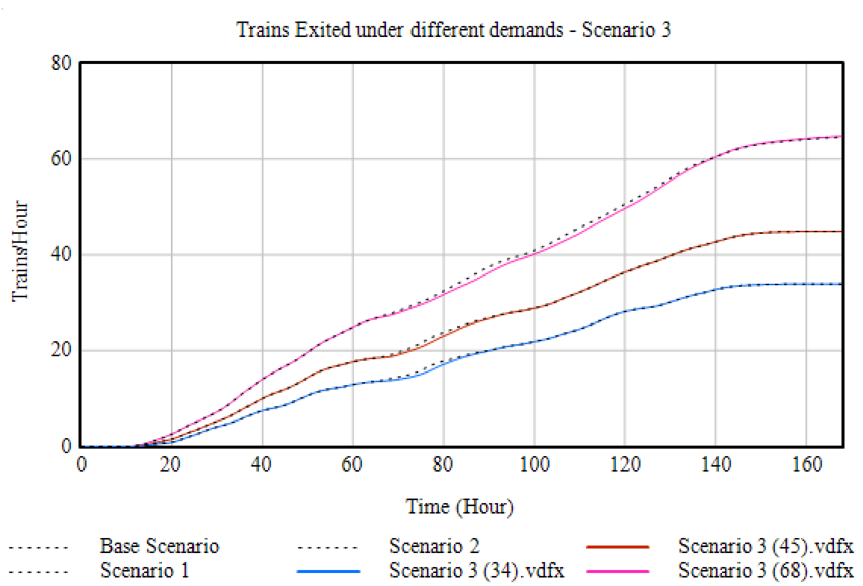

Figure 32: Comparison of trains leaving under base scenarios and disruptions

- **Scenario 4**

This scenario involved the closure of segment A from 10:00pm and 4:00am everyday simulating the possible maintenance of the segment. This had a greater impact, as segment A is a critical point of the network as previously explained. The impact was specially seen in the number of trains inside the system, while for the amount of trains processed it didn't have such a great impact.

It is possible to observe in Figure 33 how the occupancy is interrupted as the capacity becomes zero both at entry and an exit in segment A, except for a section evaluated in between hours 70 and 76, in which a small flow is found. This was revised, and after analyzing the other flows, it was observed that it corresponds to trains that were already inside A when the closure occurred, and that is why there is no increment in the trains inside A during that time, but there is a residual inside due to the functioning of the model. In real life, if the closure is due to an unexpected event this could happen, as the closure traps the train inside temporarily until it's possible to move forward, but if it is a scheduled repair or maintenance procedure, trains would know beforehand not to enter if they do not have enough time to cross before the closure, and the repairs would begin when the segment is empty.

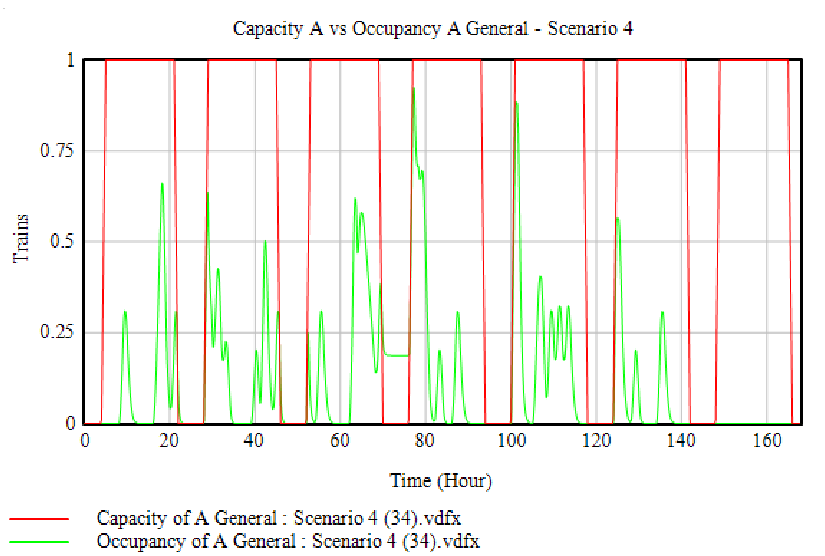

Figure 33: Occupancies of A on scenario 4

This scenario was also run under the different demands previously evaluated, to see how the system is stressed under more extreme conditions. It can be seen in Figure 34 that in lower demand conditions, such as 34 trains and 45 trains, there is delay with respect to the base scenario on when the trains leave the system.

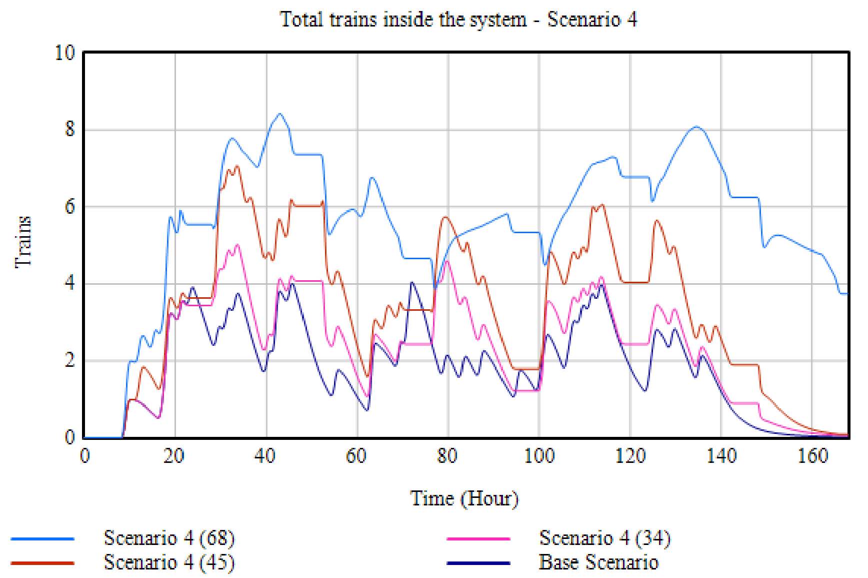

Figure 34: Total trains inside the system in scenario 4

On the other hand, when the system is under major flow conditions, such as 68 trains per week, not all trains leave the system. As shown on Figure 35 for 68 trains a slightly smaller amount of trains remain in the system without being processed in comparison to normal conditions (around 61 against 64 trains are processed). This means, that the closure of A has an impact specially on a stressed system, which matches the expectations and the observations drawn from previous scenarios, reaffirming the criticity of segment A.

It was noted, when comparing to other scenarios, that closing segment A causes a significant traffic inside the system, but it can be relatively held back as alternative options may be chosen by trains, such as waiting at V1, at the terminals or at segments before. In fact, the criticity of these closure lies on segments A and hub B, in which limit capacities are achieved and the system blocks, confirming again that these shared zone of the system is a bottleneck source, sensitive to closures or effects around all the network.

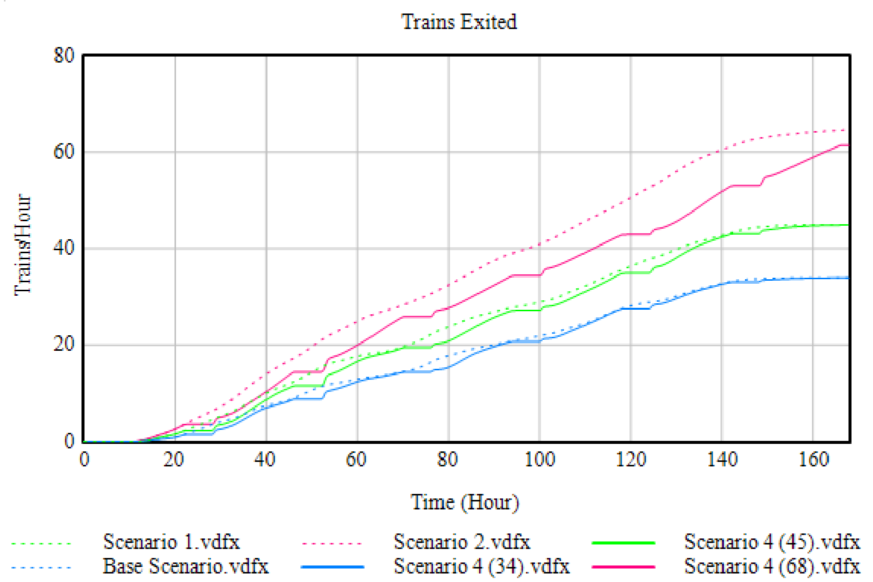

Figure 35: Total trains exited in scenario 4

- **Scenario 5**

This scenario also consists on closing a track for 6 hours every day during the same schedule as before, but in this case closing track E, which connects hub B with terminals 7 and 8. In this case, as for the one before, the occupancy of E effectively turns to zero during the hours of closure.

The constraint succesfully closes traffic on the segment, and leads to a concentrated workload in bursts right after re opening the track just like the previous scenario, this cerates a less efficient and more volatile flow for both terminals 7 and 8, nevertheless under low traffic conditions the effect is contained and does not negatively impact in a severe way the rail network performance.

Scenario 5 was also run under the different demands evaluated, observing that even for demand of 45 trains, the system fails to process all trains with a remainder of aproximately 3 trains inside the system after one week of operation, and in the case of 68 trains a remainder of 11. (Figure 36

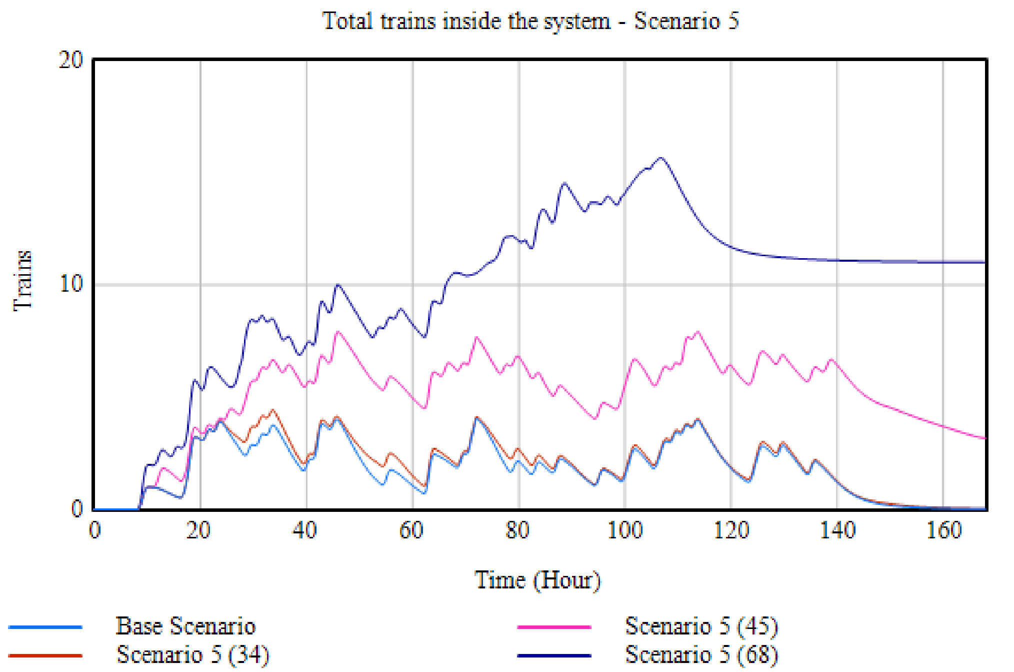

Figure 36: Total trains inside the system in scenario 5

Nevertheless, after a thourough verification, it is found on Figure 37 that the only scenario that actually has a blockage is under 68 trains, as the departures and arrivals for both terminals 7 and 8 stop at around hour 40, meaning there is a real block end in segment E where both segment E and T7 – T8 are on maximum capacity and remain blocked as no trains may enter or exit as can be seen below, where three trains block terminal 8, one blocks terminal 7, and another one blocks segment E.

This reveals that closing segments that connect critical parts of the network, much more at the deadends of it, may generate a higher impact as it shuts down the only access for certain terminals, and some of the trains remain in certain way trapped in the system. Trains arriving to terminals 7 and 8 remain trapped in hub B waiting for the segment to be opened, causing disproprotionally large and rapid system failure.

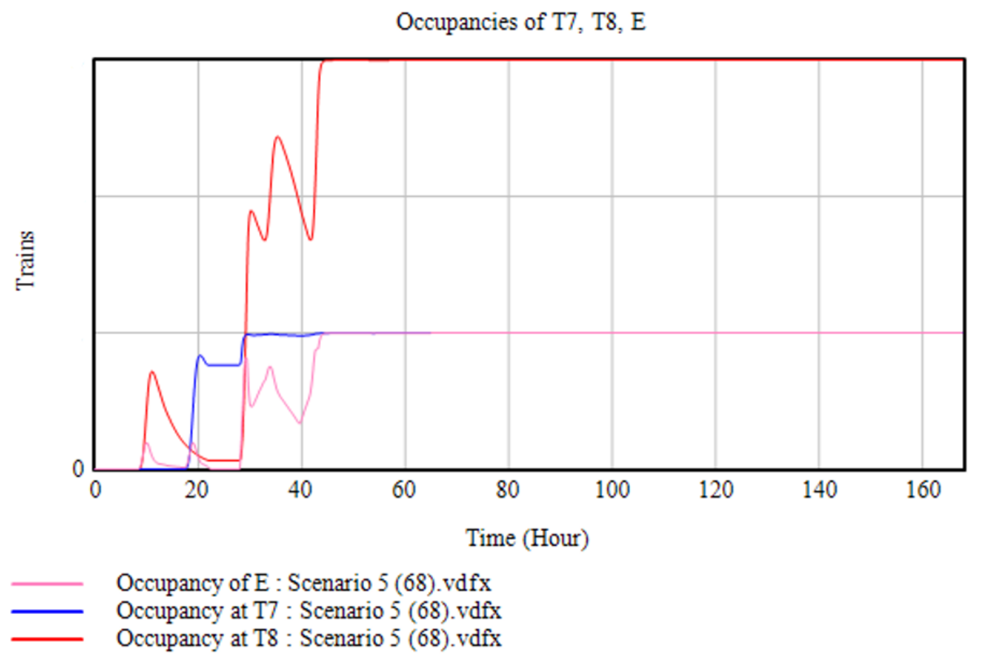

Figure 37: Scenario 5 occupancy disruption on terminals and track E

- **Scenario 6**

The sixth scenario consisted of slowing down all trains inside the terminal due to bad weather conditions that reduce visibility, which may be a common real-life occurrence in a port. Total entrances and exits may be seen in Figure 38. This scenario was performed under a flow of 34 trains throughout the week (blue line), from which approximately 31 were processed out of the system as shown in the red continuous line, with respect to normal conditions in which all trains are processed as displayed in the red dotted line. This means that bad weather conditions, or any condition that causes trains to go slower, may cause a decrease in the throughput of the system. In this case the system never got to blockage, but it wasn't able to process all trains.

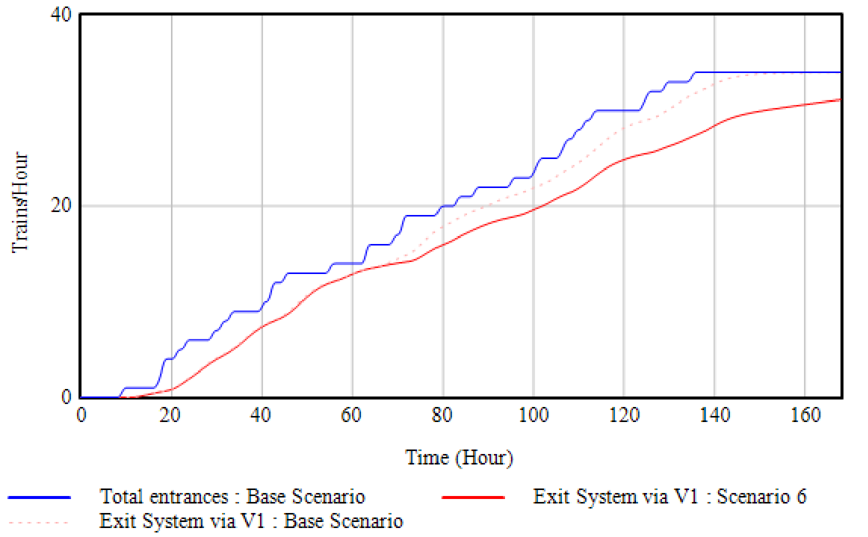

Figure 38: Total entrances and exits for scenario 6

When simulating these conditions for a traffic of 68 trains, it is possible to observe that the system gets blocked, and only around 20 trains can be dispatched. This happens because of the increased times in each of the segments affected, which increase their occupancy duration, and therefore collapse the system. It was observed that the system may handle around 7 to 10 trains at the time during the adverse weather conditions, but more than 10 start to lead to its collapse as seen in Figure 39 below.

Figure 39: Total trains inside the system for scenario 6 against 68 trains

- **Comparison of disruption scenarios**

A comparative analysis was performed to determine which closure had the greatest impact between. The graph below (Figure 40) plots the total number of trains inside the system throughout the week for the base scenario, along with scenarios 3, 4 and 5. The results evidence a more severe impact for the closure of segment E corresponding to scenario 5, as the congestion level is greater than the rest, even if A is a main artery of the system, as segment E is more deep into the branches of the system and leaves less options for trains to queue while they wait for the terminal opening. Meanwhile for scenario 3 in which terminal 5 is termporarily closed, an acute temporary congestion is caused as trains wait for T5 to reopen and the system recovers, making this impact severe but short. Finally, regarding the amount of trains inside the system, the least impact is observed, since the closure of track E (presented in blue) ends up having a neglegible effect on the overall congestion of the port, creating short delays but with no impact on the throughput.

On another hand, it is possible to evidence how impactful a widespread disrpution may be, such as the case of severe weather, as low-level inefficiencies erode the entire network's capacity simultaneously, an ended up causing a stronger effect on the network's efficiency.

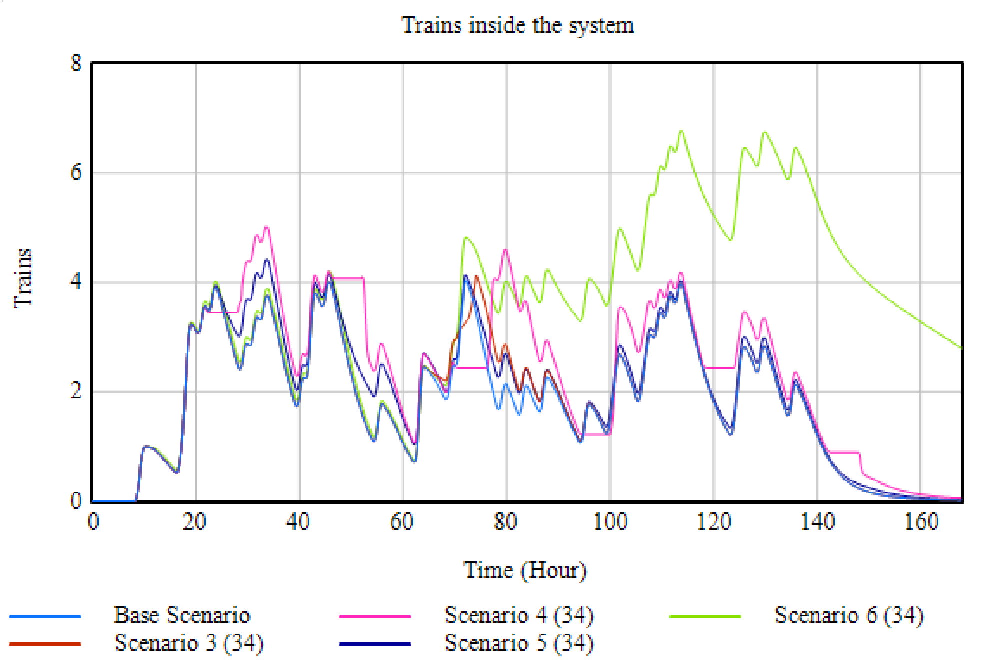

Figure 40: Total trains inside the system among the disruption scenarios

4.3. Crossing between network results

Developed in collaboration with Sara Cardinale

The scenarios ran are summarized in the table below:

Scenario	Case	Description	Trucks processed	Max number of trucks at gate V2	Max number of trucks at gate V3
Version 1	Road only	Base demand for only road	100%	2	8
Scenario 1	Road + Rail	Base demand for road interrupted by train's flow.	83%	6	1609
Scenario 2	Road + Rail (adverse weather)	Base demand for road interrupted by train's flow under adverse weather conditions	54%	7	742

Table N: Results by scenario in crossings between road-rail networks [made by author]

4.3.1. Baseline performance scenario

For Scenario 1, the analysis focused on quantifying the impact of normal train traffic on the road network's throughput and congestion levels. The results of this scenario are compared directly against "Version 1" of the road network model in which Sara Cardinale developed the road network under normal operation conditions, which represents the ideal state with no rail interference.

The primary finding of the integrated model is that even under normal conditions, the priority given to rail traffic causes a significant reduction in the road network's overall efficiency. The graph below (Figure 41) compares the cumulative number of trucks exiting the port in the integrated model against the standalone road model.

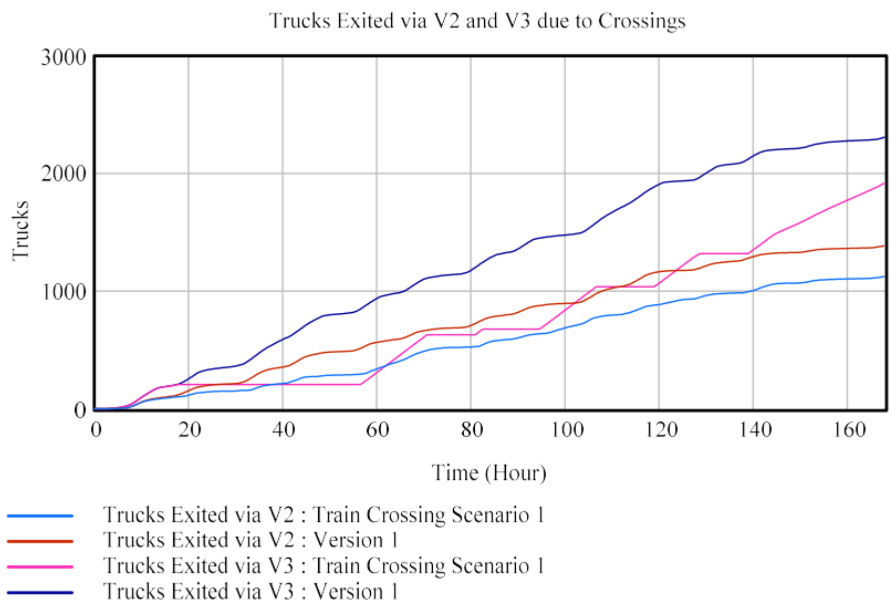

Figure 41: Trucks exited via V2 and V3 for crossings

The road network's total throughput is reduced by approximately 25%, from almost 3700 trucks to almost 2800 trucks over the week. The interference from train crossings prevents the road system from ever catching up, resulting in an important loss of capacity of processing.

The closures at Crossing X1 create observable but manageable disruptions. The graph in Figure 42 shows the "Trucks Permission to Cross" variable (dotted red line) dropping to zero when a train is present, which momentarily alters the corresponding inbound and outbound truck flows (blue and pink lines).

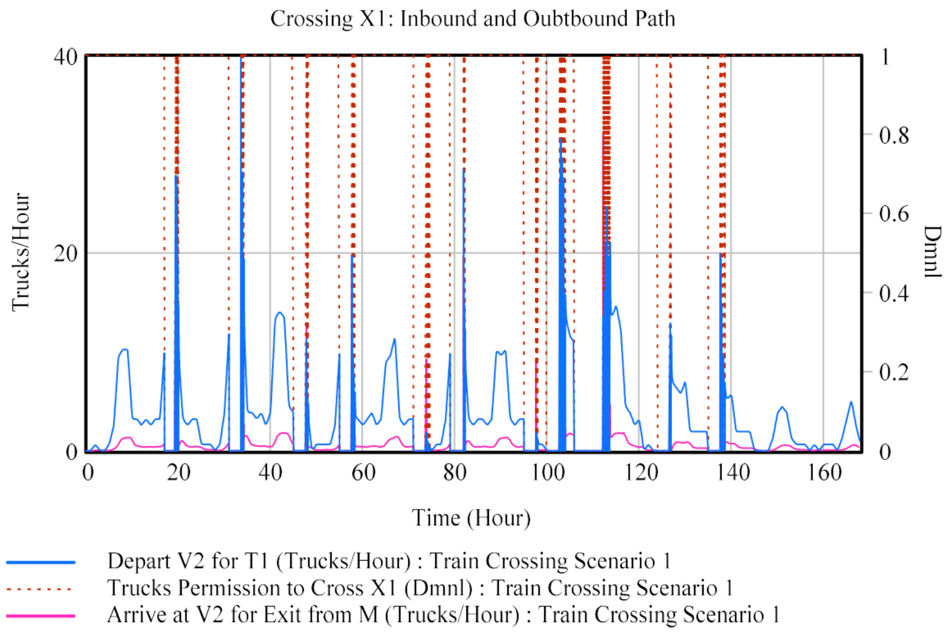

Figure 42: Crossing X1 - Inbound and outbound path

These interruptions cause minor, localized increases in queue lengths at the preceding segments. However, Figure 43 shows that the overall impact on the queue at Gate V2 is minimal when compared to the baseline, indicating that the network has sufficient capacity to absorb these short delays.

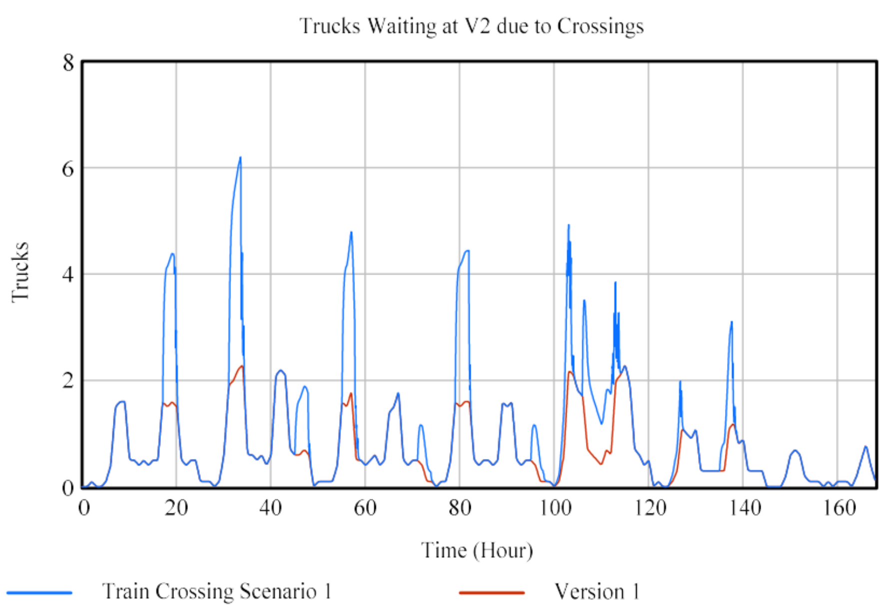

Figure 43: Trucks waiting at V2 for crossings model

The same does not apply to Gate V3, which was previously identified as one of the most concerning points of the road network and now is characterized by an enormous queue of over 600 vehicles. (Figure 44)

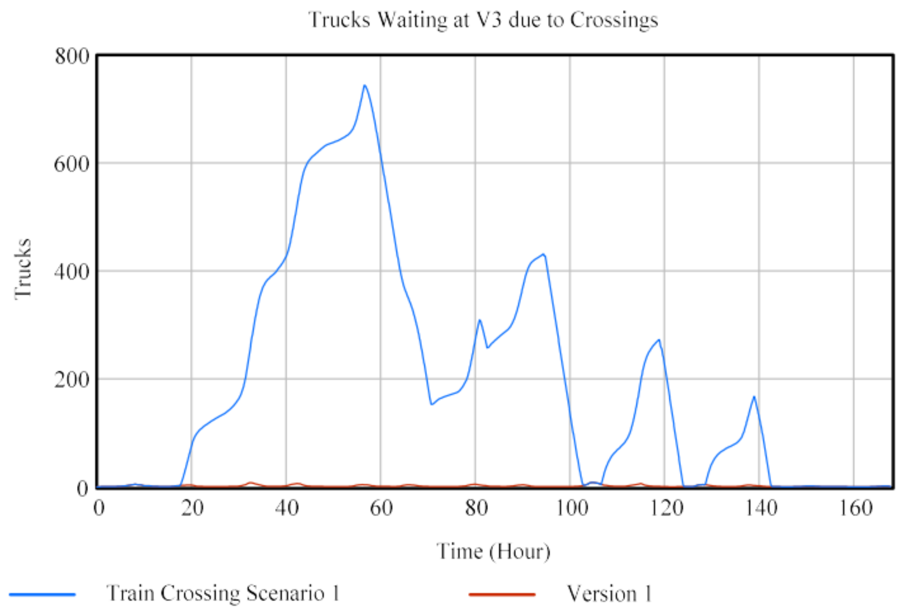

Figure 44: Trucks waiting at V3 for crossings model

Gate V3 is highly influenced by Crossing X3, that appears to be a critical point of failure for the entire network, being occupied by trains for the majority of the simulation, as abstracted from Figure 45.

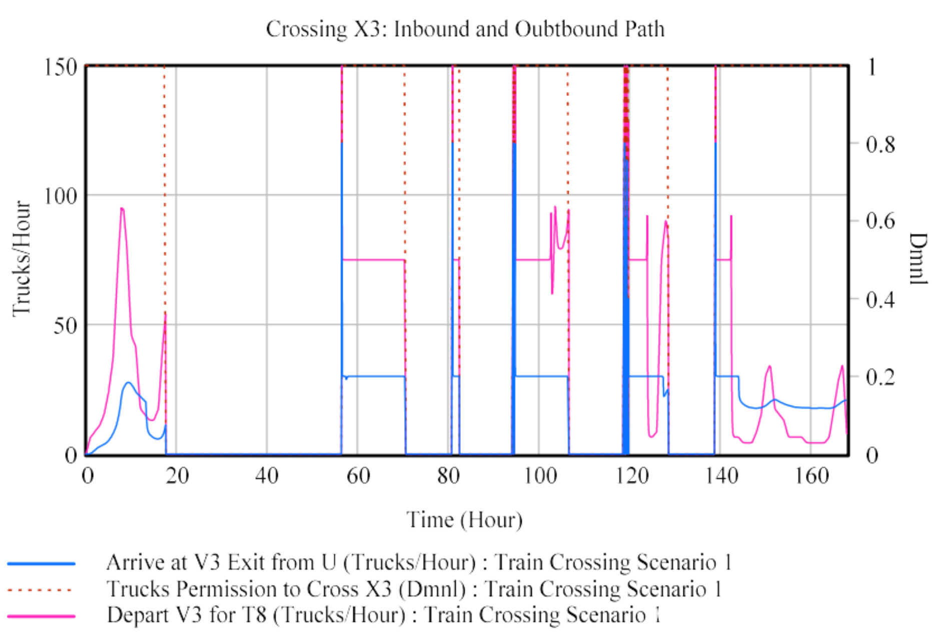

Figure 45: Crossing X3 - Inbound and outbound path

This integrated model demonstrates that the interaction with the rail network is the single most significant constraint on the port's landside performance under normal conditions. The analysis reveals a critical vulnerability that is not apparent when studying the road network in isolation.

4.3.1. Slow-down scenario

When analyzing the scenario in which both rail and road systems are under adverse weather conditions, the system starts from a heavier occupation of the facilities, which as one could expect, leads to greater occupancy of the shared system and a decrease in its throughput or capacity. The following graph (Figure 46) shows how scenario 2 has a great impact on the total trucks that are available to exit the system (in continues lines) with respect to a scenario where no trains disrupt the crossings in normal weather conditions (dashed lines), and a scenario where trains disrupt the crossings in normal weather conditions (dotted lines).

It can be seen in Figure 46 that in the case of V2 the impact is slightly lower than for the case of V3, which reaffirms what was mentioned earlier regarding the vulnerability of access point 3, presenting an additional reduction in capacity of processing of 24% and 40% respectively against the previous scenario.

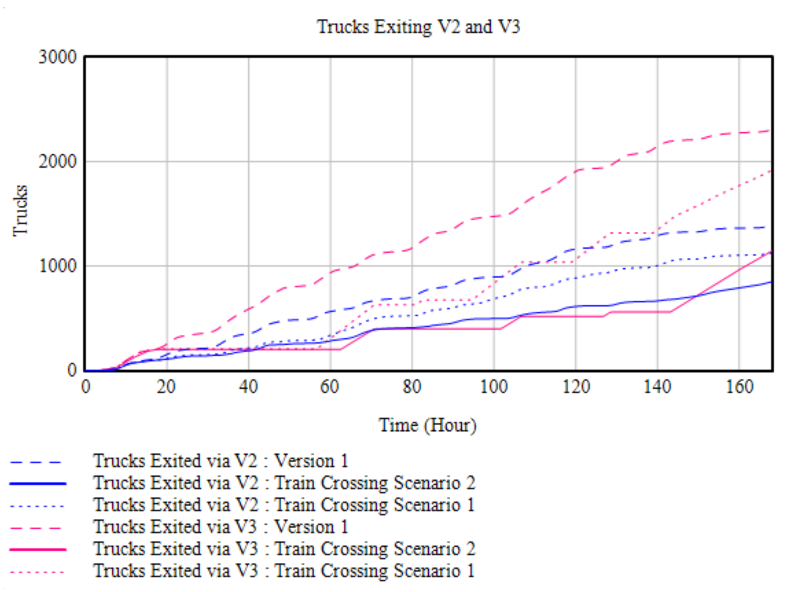

Figure 46: trucks exiting V2 and V3 under scenarios 1 and 2 for crossings model

To further understand the impact, the queues generated around the crossings were observed just like in the previous scenario, in which only slight increments were observed in crossings 1 and 2, and a greater impact in crossing 3, which confirms previous results that associate V3 to a critical point.

Finally, by analyzing the number of trucks waiting at both access points through Figure 47, it was visible that for V2 the results remained relatively similar with slightly higher queues, while for the case of V3 queues more than 1600 vehicles waiting to pass due to the presence of trains in crossings in adverse weather conditions.

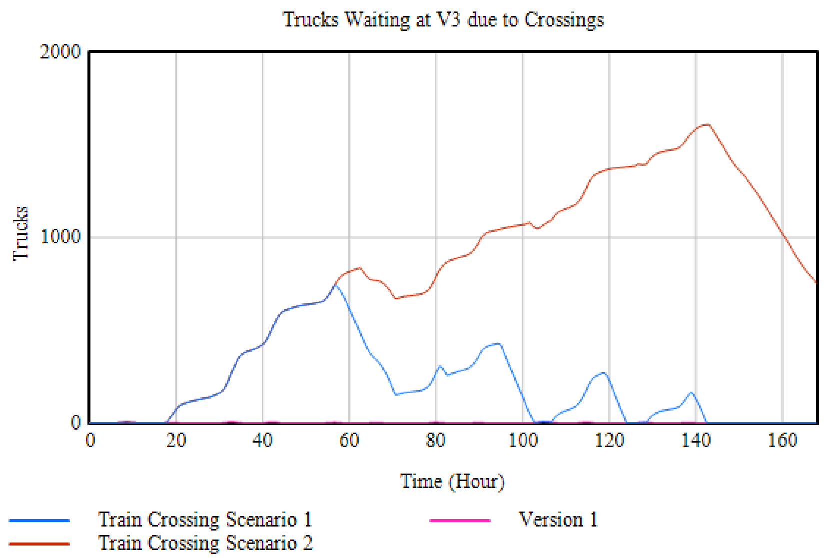

Figure 47: trucks waiting at V3 under scenarios 1 and 2 for crossings model

These two scenarios of the crossings allow to understand the sensitivity of the road network to the presence of trains, and to speed and occupation of both the tracks and the road system. An important and key aspect to take into consideration is that for all scenarios that considered adverse weather conditions, only internal impacts were evaluated, but in real life the impact is widespread throughout the entire network inside and outside of the port and actual impacts are expected to be greater. Nevertheless, the scenarios simulated give an insight into internal disruption.

5. Conclusions

Through this thesis it was possible to analyze a port node, focusing on the interaction between the road and railway network, to assess critical bottleneck points and potential impact of different strategic interventions in the rail network. This analysis was supported by a case study of a port in Italy, as well as its impact when intersecting the road network. By implementing multiple scenarios, it was possible to understand the network's dynamics, and to establish a base for future traffic management of the studied port's infrastructure vital for its development and effective operations.

The port's rail network offered a simplified yet realistic view of the real network. An initial comparison was made to understand the use an aggregated against a disaggregated simulation, concluding that the selection would depend on the use, the data availability, and the level of detail needed for the operational planning.

When using the disaggregated model and bringing it under pressure several behaviors were observed. A 30% increase in demand resulted in manageable delays, as the system was able to absorb the additional traffic. However, by doubling the traffic, the system was pushed beyond its saturation point, being unable to process all trains within the operational, though avoiding gridlock. Regarding vulnerability, the model demonstrated that disruptions affect the most central and shared components of the network generate greater impacts, as was the case with track E and A closure which may lead to blocking the system in such way that no trains are able to exit or move. In contrast, the temporary closure of terminal 5 caused sharp spikes in congestion due to backpressure, but the system proved resilient and was able to recover once the terminal reopened, particularly under lower traffic conditions. When closing a specialized track like segment E, as the only segment that serves a set of terminals, the effect was very localized and led to system-wide delays. Finally, it was possible to understand how wider disruptions, even without closure but only with performance reduction, have a high impact on the networks efficiency and reduce the system's capacity to process trains, especially under stressed conditions.

The analysis consistently exhibited that bottlenecks primarily form at segment A, as it is a shared track for entry, exit and for access into multiple terminals. This primary constraint results in long queues in the processing hub B, which consequently reaches its capacity limit under high-demand and disruption scenarios.

A detailed analysis of the road-rail crossings provided a crucial explanation of the network sensitivity, pertinent to the port of study which, like many ports in Italy, presents a limited space condition that leads to a complex interaction between the modes of transport present. The model demonstrated that these intersections are the primary points where operational friction occurs; each time a train passed, all road traffic was forced to a temporary stop.

The analysis quantified in certain way the cost of coexistence of both networks. Under normal operating conditions, the rail priority generates a significant impact reducing the road's network total throughput by around 25%. This is not a disruption but a permanent inefficiency result of the port. The simulation then quantified a critical secondary effect: the massive queue of waiting trucks would often grow so long that it physically blocked other key intersections behind it. This is a very important insight, because it proves that a brief event on the rail network can trigger a lasting and widespread traffic jam on the road network, inside and outside the port.

The analysis indicated that crossing X3 and its associated gate V3 is the most critical point of failure, as even under normal conditions the prolonged presence of trains in the crossing leads to greater queues at the gate reaching over 600 vehicles under normal weather conditions, meaning it propagates backward, transforming a localized traffic intersection issue into a major strategic capacity constraint. The vulnerability was further amplified in the slow-down scenario, where adverse weather conditions caused queues at V3 to grow to over 1600, further reducing the gate's throughput by an additional 40%. This proves the network has poor residual capacity to absorb even moderate, widespread disruptions.

Infrastructural intervention should be done strategically, as apparent improvements may be limited by other vulnerable sections. For instance, crossing 3 reveals as a top priority for future improvement, which could be done through a complete physical separation of the road and rail networks (for example an overpass or underpass) to decouple the two systems, since the current at-grade crossings significantly reduces the road's network total throughput.

This work was able to demonstrate how the efficiency of a port doesn't depend only on its individual network's capacity and functioning, but how their individual behavior is interdependent as they intersect and interact. Therefore, not only the critical points of each network were identified, but also bottlenecks were found in intersections and in the shared infrastructure.

It was also found that key points such as segment A and hub B have great sensitivity to disruptions due to their frequent usage, and result as sources of operational friction and congestion. It is noted that bottlenecks follow a certain hierarchy, and as the network divides in branches the pressure decreases as it arrives to a more specific and less shared segment.

The study demonstrated that the resilience of the port is sensitive to disruptions in this shared intersections and in the critical segments of the rail network, but that the port behaved with a non-linear performance when pressured, as it was able to absorb slight demand increases with moderate delays, but was pushed by higher demand scenarios into cascading effects and potential gridlock when demand exceeded capacity.

In such way, this critical point identification serves as tool to understand where to focus the interventions and for possible future operational and strategic improvements that improve the competitiveness and resilience of the port.

6. *Scope and limitations*

The simulation serves as a powerful tool to identify bottlenecks and throughput of the port's network under several scenarios. However, its utility is a direct result of design choices that prioritize computer efficiency over granular detail, and therefore its effectiveness is balanced by two key limitations.

On one hand, it was developed under a defined scope, in which a boundary was set to account only for internal or endogenous dynamics and not external factors such as highway congestion, national line delays, adverse weather or accidents that could significantly impact the system's performance outside the port and drag delays inside the port.

Secondly, as a simulation model, it was developed under a simplification of reality, which implies making some assumptions and simplifying complex operations and parameters. For instance, flows were aggregated, and dwell times were fixed, which don't completely reflect real world variability. This model meets its primary objective, but future enhancements could be developed and focus in incorporating a higher level of detail in procedures and a more powerful traffic management logic that approaches real-world conditions.

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