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D3.3 CONCEPTS FOR IMPROVED PORT CARGO HANDLING THROUGH AUTOMATED PORT INTERFACES

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EXECUTIVE SUMMARY

This deliverable, part of the SEAMLESS project, presents innovative concepts for improving port cargo handling through automated port interfaces, focusing on efficiency, digitalization, and sustainability in short-sea and inland waterway transport. The document provides an in-depth analysis of current maritime and logistic-port processes and explores areas for enhancement via automation and digital integration.

The document covers some of the operational aspects, including terminal handling equipment, vessel-port-terminal communications, cargo operations, and hinterland connections. It examines the role of digital solutions such as Terminal Operating Systems (TOS), Electronic Data Interchange (EDI), and automation technologies to streamline port operations. Various cargo handling systems, including berth and yard equipment, automated guided vehicles, and real-time data exchange platforms, are analysed for their impact on efficiency, safety, and environmental performance.

Furthermore, the document evaluates the integration of hinterland transport systems, highlighting the role of rail, road, and inland waterways in optimizing cargo movement beyond port terminals. It also assesses some of the autonomous processes included in SEAMLESS, such as autonomous vessels, ship management systems, automated mooring, and terminal automation with autonomous cranes and equipment. Additionally, some recommendations are included on standardizing communication protocols, implementing smart cargo tracking, and enhancing coordination among stakeholders.

By identifying key technological advancements and process improvements, this deliverable aims to contribute to a more efficient, seamless, and sustainable port logistics ecosystem, aligning with European transport policies and the global push for greener, automated supply chain solutions.

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List of Abbreviations

AGS	Automatic Gate System
AGV	Automated Guided Vehicle
AIDC	Automatic Identification and Data Collection
AIS	Automatic Identification System
API	Application programming interface
ASC	Automatic Stacking Cranes
BAPLIE	Bay Plan Including Empties
CANBUS	Controller Area Network Bus
CCS	Cargo Community System
CHE	Container Handling Equipment
CODIS	Central Organising, Dispatching and Information System
DCSA	Digital Container Shipping Association
DGPS	Differential Global Positioning System
EC	European Commission
ECTM	European Container Traffic Model
ECU	Electronic Control Units
ECS	Equipment Control System
EDI	Electronic Data Interchange
EDIFACT	Electronic Data Interchange For Administration, Commerce, and Transport
EMSWe	European Maritime Single Window environment
ERP	Enterprise Resource Planning
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
EU	European Union
GPS	Global Positioning System
HM	Harbour Master
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IM	Infrastructure Managers
IoT	Internet of Things
ISPS	International Ship and Port Facility Security
IWW	Inland WaterWay
JSON	JavaScript Object Notation
Lolo	Lift-on/Lift-off
LPR	License Plate Recognition
MES	Manufacturing Execution System
MMS	Management Systems
MQTT	Message Queuing Telemetry Transport

NUTS	Nomenclature of Territorial Units for Statistics regions from EC
OCR	Optical Character Recognition
OPC-UA	Open Platform Communications Unified Architecture
PCS	Port Community System
PLC	Programmable Logic Controller
Port CDM	Port Collaborative Decision Making
PRINOS	Port Railway Information and Operation System
PROFINET	PROcess FIeld NETwork
RFID	Radio Frequency Identification
RMG	Rail-Mounted Gantry crane
ROC	Remote Operation Centre
RoRo	Roll-on/Roll-off
RTLS	Real-time locating system
RTG	Rubber-Tyred Gantry Crane
RU	Railway Undertakings
SaaS	Software as a Service
SC	Straddle Carrier
SSS	Short Sea Shipping
STS	Ship To Shore crane
TAF-TSI	Technical Specification for Interoperability relating to Telematics Applications for Freight
TAS/SBS	Truck Appointment / Slot Booking Systems
TEU	Twenty Equivalent Unit
TIC4.0	Terminal Industry Committee 4.0
TOS	Terminal Operational System
UN	United Nations
ULCV	Ultra Large Container Vessels
UML	Unified Modelling Language
VMT	Vehicle Mount Terminals
VNF	Voies Navigables de France
VTS	Vessel traffic services
Wi-Fi	Wireless Fidelity
WSV	Waterways and Shipping Administration
XML	Extensible Markup Language

1. Introduction

SEAMLESS main objective is to develop and adapt the missing technological components to create a fully automated and economically viable freight transport service that can be applied in both short sea shipping (SSS) and inland waterway transport (IWW). The project focuses on developing and adapting the basic elements and enablers needed to successfully implement the service. One of the main objectives of SEAMLESS is to shift road freight transport to inland waterways while improving the performance of the TEN-T network, through the development and integration of autonomous systems.

The purpose of this deliverable is to explain the maritime and port-logistic processes that are currently carried out and which of them are going to be improved in the SEAMLESS project (through digitalization and/or automation).

Nowadays there are a high number of events and messages that are required to successfully complete the operation of a vessel call request, with the consequent docking of the vessel in port, discharging/loading of goods and its subsequent departure to the next port.

The scope of SEAMLESS within the supply chain includes:

1) Cargo handling, from ship-shore and within the port, at intermodal SSS and IWW ports with other maritime and hinterland connections (i.e., trucks and rail)
2) Loop transportation of various cargoes (including containers with RoRo and LoLo, bulk cargo, etc.) between SSS-IWW or IWW-IWW ports
3) Information flow throughout the supply chain with respect to the transportation means, the cargoes, and the supporting shore-side infrastructure.

The processes defined in this document are manly focused on the container transport and container vessels. The main reason is that the container is the most common element used to transport goods and the one that will be used in the SEAMLESS project. In any case, most of the processes are common to the different types of vessels.

1.1. Links to other WPs and deliverables

This deliverable extends the initial definition of processes in the vessel arrival and cargo operations defined in the deliverable D2.2 (SEAMLESS reference logistics architecture, standards, and simplified administrational procedures) [1] and D2.3 (Concept of operations and requirements for SEAMLESS building blocks) [2].

This document focuses on the equipment, systems, and communications in the processes in the port area, from the time the vessel arrives until the goods are distributed in the hinterland. Moreover, the previous deliverables (D2.2 and D2.3) focus on the general transport processes and the processes related to the building blocks.

2. Description of port operations linked to the cargo

Within its scope, SEAMLESS will develop innovations towards minimizing bottlenecks and delays in the following three interconnected layers:

- Physical Assets
- Logistics System
- Digital Assets

Nowadays, a container terminal is an essential piece of infrastructure for global supply chains. A vital function of the container terminal in seaports is to connect maritime transport and other modes of transportation, such as river, road, or rail. The role of the container terminal has become increasingly important as globalization has led to more international trade.

Container terminals can be located inside a port (maritime container terminals or river terminals for inland waterway) or inland (intermodal terminals, also called dry ports). The main activity of a container terminal is to transfer of cargo units from one transport modality to another (vessels, trucks, barges, or rail); auxiliary activities include the temporary storage of containers and value-added services, such as cargo units' maintenance and repair, and sometimes cargo consolidation and deconsolidation activities, performed in dedicated areas known as Container Freight Stations (Figure 1).

Terminals act as an interface between countries or between cities inside the same country (Short Sea Shipping) or nearby areas. They are part of the supply chain, acting as an important distribution node for cargo. From this node, goods can be moved via vessel, rail, road, and canals to their final destination.

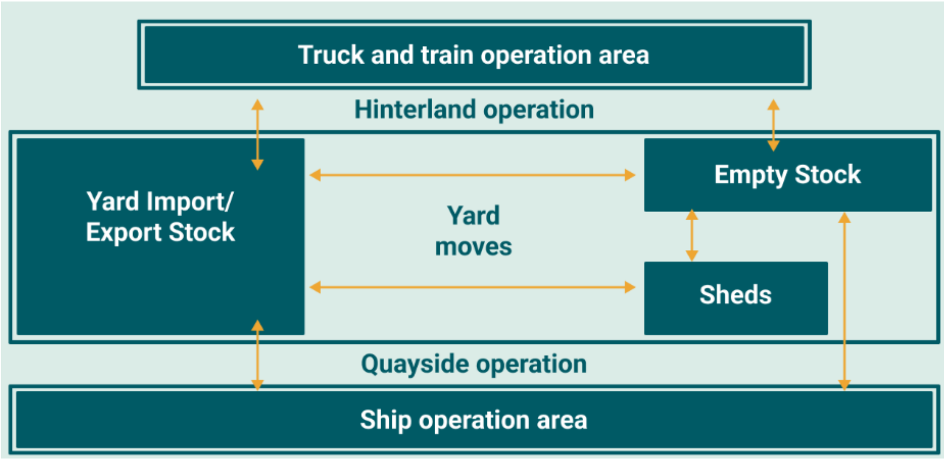

Figure 1. Operation areas of a seaport container terminal and flow of transports

A key challenge for terminals is meeting the demands of different stakeholders while still being efficient and profitable. Stakeholders include ship owners, shipping lines or ship agents, freight forwarders, importers, exporters, shippers, port workers, and government agencies. Each stakeholder has its objectives and priorities, which can conflict with each other.

In this section, it is presented in a generic way how each one of the processes that are carried out in a terminal. Beginning from the moment the ship leaves a port informing of the next call, going through the whole process of call request, berthing, work in the terminal with the discharged goods and the subsequent departure of the goods to the final consignee.

To provide more clarity to the process, following sections are considered to describe the activities regarding this deliverable.

I. Vessel
II. Vessel – Terminal
III. Terminal
IV. Terminal – Land Transport
V. Expedition of cargo to hinterland
VI. Vessel departure

To be more specific, the two first sections are described together.

I. Vessel
II. Vessel – Terminal

Communications exchange vessel-port-terminal

2.1. Terminal handling equipment

Container terminals are the most common and specialized infrastructures for loading and discharging containers, achieving a high level of automation due to the standardization in the transport and port handling of containers.

Within a container terminal, a diverse set of handling equipment is used, each selected to fit the unique operational requirements of the terminal. The equipment depends on the size and type of container terminal and the operations performed within it. That is why the same container transport operations are done with different handling equipment depending on the terminal.

Being fundamental infrastructures for international trade, container terminals must have robust infrastructure and resources to facilitate seamless 24/7 cargo handling and exchange.

Because of their high level of systematization, container terminals necessitate a greater degree of specialization among their employees, resulting in a reduction in the overall workforce. Additionally, these terminals must possess specialized facilities tailored to their capacity for handling various types of containers.

The main elements for the proper functioning of container terminals are:

- Maritime infrastructures and berthing and mooring facilities to receive the different types of vessels (e.g. berths, bollards, bunkering, shore power).
- Land areas or infrastructures that allow the development of port operations such as loading, discharging, storage, reception, and classification of cargo, among others (e.g. quays, yard, gates, etc.).
- Availability of the equipment and machinery required to perform the operations involved in port services (e.g. cranes, reach stackers, terminal tractors, etc.).
- Human resources (e.g. stevedores, mooring, terminal staff, etc.) and information technology (e.g. Terminal Operating System, Gates System, etc.) are essential to manage all activities properly.

At the same time the terminal areas can be commonly divided in different zones:

- Container loading-discharging zone: This is the area of operations between the ship and the quay.
- Inland receiving and delivery area: This is the horizontal transport area that includes the inland gates and facilities for truck and rail, streamlining the handling of the high volume of containers received.
- Container storage area: This is the largest part of the terminal area, where containers are properly stored and organized to facilitate their movement.
- Internal connection area: It ensures the horizontal transport of containers between the vessel and the inland receiving and delivery area. It includes control offices, parking space, customs, repair shops, among others.

The following sections focuses on the equipment and machinery needed for handling containers, which can be divided into berth equipment, yard equipment, and distribution equipment inside the terminal.

2.1.1. Berth Equipment

Ship-to-Shore (STS) cranes

STS cranes — sometimes referred to as quay cranes — are typically the largest port gantry cranes and are used to load and discharge containers from ships to the quay. This limits its installation along the water's edge on rails that extend the length of the berth.

There are two main types of ship-to-shore cranes: low profile and high profile. Low profile STS cranes have a non-pivoting telescopic boom that extends out from the crane and over ships, where it’s used to load and discharge the vessels. High profile STS cranes have a hinged boom that makes navigation easier for ships during berthing.

STS cranes consist of a supporting framework that can traverse the length of a quay or yard. They attach to containers by using spreaders. The spreader can be lowered on top of a container and locks onto the container’s four locking points using a twist-lock mechanism. Cranes usually transport a single container at once, but newer cranes can pick up two twenty TEUs at once. One TEU (Twenty Equivalent Unit) is a container of 20 feet long, 8'0" wide and usually 8'6" high. In metric terms, a TEU is 6.10 metres long, 2.44 metres wide and 2.59 metres high.

Crane on-board

In certain terminals, particularly those designated for general cargo or located in remote areas with limited infrastructure, the absence of specialized equipment for container handling poses a logistical challenge. In these instances, vessels arriving at such terminals must rely on alternative methods to discharge their cargo efficiently.

In the absence of dedicated container handling equipment at the terminal, vessels are often equipped with their own onboard cranes, specially designed to facilitate the discharge of containers. These ship-mounted cranes, equipped with impressive lifting capacities and manoeuvrability, play a key role in the vessel's ability to offload containers directly onto the dock.

After the vessel is safely moored, its onboard crane springs into action, hoisting containers from the cargo hold and carefully manoeuvring them to the designated drop-off points on the quay side. Through precise coordination and skilled operation, the vessel's crew orchestrates a seamless transfer of containers from ship to shore, ensuring the timely and efficient discharging of cargo.

While this approach may require additional resources and expertise onboard the vessel, it serves as a vital workaround in terminals where dedicated container handling equipment is lacking. By leveraging the versatility and capabilities of onboard cranes, vessels can navigate and operate in diverse port environments, facilitating trade and connectivity even in remote or less-equipped terminals.

2.1.2. Yard equipment

Gantry crane

Crane that consists of an elevated bridge or gantry supported by two legs in the form of an angled arch, with the capacity to move containers in the three possible directions (vertically, horizontally, and laterally), manoeuvring on rails (Rail Gantry Crane or Transtainer) or on tires (Rubber Tire Gantry, RTG) in a limited space.

They usually have a straight-line route, defining its work area and allowing other machinery to work underneath. Those cranes, inside a container terminal, are in the yard area, where the containers wait for the next step in their logistic chain. We can say that main task of a gantry crane is to manage the input / output flow of containers in the yard.

Rubber-Tired Gantry (RTG) cranes

RTG’s are gantry cranes outfitted with rubber tires for unimpeded movement around the container yard. They primarily move and stack containers throughout the port after the containers have been unloaded from ships or to stage containers in preparation of loading operations. Power is provided typically with a diesel engine, although fully electric versions are becoming common.

Rail-Mounted Gantry (RMG) cranes

RMG’s are very similar to RTG’s, with the biggest difference being the use of rails for movement rather than free movement with tires. Non-cantilever (without extended arm or structure that protrudes beyond the main frame), single and double cantilever options are all possible. They’re often larger than RTG cranes and require more robust data communication capabilities due to additional onboard equipment and automation functionality.

Automatic Stacking Cranes (ASC)

ASCs are essentially fully automated RMG’s without an operator. They’re both gantry cranes that utilize rail mounted movement and are available in similar sizes. The major difference between the two is that ASCs are fully automated, improving their efficiency and overall productivity.

Straddle Carrier (SC)

A SC is an equipment that can be used for all intermodal operations, such as loading/discharging railcars and trucks and stacking containers up to three in height, depending on whether the straddle carrier is a 3-high or 4-high.

SCs are equipment that carry its load underneath by "straddling" it. The advantage of the straddle carriers is their ability to load and unload containers without the assistance of cranes or forklifts. There are SCs able to stack containers up to 1 over 3, so they are able to store containers in the yard and also move containers between berth and yard, therefore they belong both to the yard sub-system and horizontal sub-system. The Straddle Carriers can also be used to load or unload containers on trucks, so they are very versatile machines but not very specialized in any task, making them less efficient than others.

These machines are usually quite large, but smaller versions of straddle carriers (Mini Straddle Carriers) have been developed for end users who need to move containers around their yard or depot.

Reach stacker

Reach Stackers, also known as a side loader, are another type of truck yard stacking equipment widely used in small port container terminals. Although they are also present as auxiliary machinery in big installations developing a wide variety of operations (empty container stacking, delivery and reception of containers for external trucks, loading/discharging of containers for trains, etc.). This machine is composed by a mechanical arm and a spreader which fix the container by its top side. A Reach Stackers is mainly used in the yard, however it is a very flexible machine and can be used in other sub-systems like the horizontal transport and the delivery/reception sub-systems. They have a relevant role in loading/discharging operations with trains and in the transport of occasional containers within the terminal (such as positioning for inspection, repair or re-stowed).

Since reach stackers are limited to stacks of three full containers (five or six empty), they can support a stacking density of 500 TEU per hectare. It can lift 20´- 40´ empty and full containers from 10 to 45 tons up to 6 containers high in the first row. It can even load and unload containers in the second and in the third row. They are often used in intermodal rail terminals and maritime terminals for specialized moves (e.g. reefers).

As reach stackers offer a more efficient and economical solution than any other type of container-handling machine and don´t take up too much space they are widely in operation in many ports and container terminals. Modern reach stackers have an elevating cabin in order to improve the visibility of the driver.

Empty container handlers

Empty container handlers, also known as container lifters, are mainly used in terminals and depots to handle, transfer and stack empty containers of various specifications. There are several types depending on the needs, for 8 to 11 tonnes lifting capacity or a range of stacking heights from 4 to 8-high. Double container stackers (two 20 feet containers) are also available with 10 and 11 tonnes lifting capacities.

Forklift

Forklift trucks are the most basic piece of intermodal equipment but has limitations and can handle only loaded 20-foot containers or empty containers of other dimensions. This is not a piece of equipment suitable for intermodal operations but can be occasionally used.

2.1.3. Distribution equipment

Terminal tractors

Terminal tractors, also known as yard trucks or shunt trucks, play a crucial role in transportation and logistics, especially in freight terminals, ports, and distribution centres.

This vehicle goes along with a container platform, that are used to transport standard containers within the terminal. Here, the containers are lowered by crane from the ship onto the platform, which is coupled to a terminal tractor. The containers are then distributed or reloaded in the port terminal.

This type of equipment is also used in Ro/Ro terminals, where the cargo is stored in rolling merchandise (tarpaulin-type trailers, tank trailers, container trailers etc.). The Terminal tractor or Tug Master hooks to the trailer to move it from the yard to the vessel or vice versa.

Automatic Guided Vehicle (AGV)

AGV is fully automatic non-articulated platform used to transport containers between the quay and the container yard. It has a load capacity that is normally for 20', 40', 45' containers.

The speeds that these platforms reach is reduced, which, together with the limitations due to the necessary traffic rules, cause the performance to depend on the ASC and STS cranes, since a delay in any of these operations will cause waiting times for the AGVs, which will negatively affect the global operations.

Sidelifter

This unit involves the skills and knowledge required to operate a container side lifter (swing lifter, side loader), to load a container from the ground onto a vehicle, unload a container from vehicle to ground, and transfer a container from one vehicle to another. It also includes systematic and efficient control of all functions, management of side lifter condition and performance, and effective management of hazardous situations whilst operating a container side lifter.

2.2. Communications exchange vessel-port-terminal

The six process activities described in section 2 are divided into different main tasks, so that a first study can be made of the processes currently being carried out in any port in Europe. This description is also explained in D2.2 [2] (section 2.2.3).

If we try to create an imaginary route for a ship that must sail from port A to port B, we must take into account the following first steps in order to better understand and be aware of the whole spectrum of activities it covers.

Firstly, 12 hours before the ship's departure, customs and dangerous goods authorities must authorize the transport of the consignments by SSS or IWW. This might require the reporting of some formalities before the loading of these consignments. That depends on the specific regulations for this type of transport. Customs authorities must ensure that the consignments to be sent comply with the customs rules applicable in the area. The hazardous service authorities must be informed about dangerous and/or polluting substances being transported for safety and environmental protection reasons, for example, if explosive substances are transported.

After that, the rest of the steps involved in a common cargo transport operation involving a container ship are described.

Firstly, incoming vessels request a berth from the port and the terminal they wish to visit and plan their voyage after the terminal's confirmation. Before the vessel departs from its origin, there are some formalities for notifying the departure and the arrival, to the port and maritime/IWW authorities (i.e. the Harbour Master (HM) office). Once it is approved by the HM, the pilot organization, tugboat company, and mooring crew organization receive the vessel's Estimated Time of Arrival (ETA) and Estimated Time of Departure (ETD) so that they can plan accordingly.

During the sea voyage, the destination port needs to confirm the berth allocation according with the information shared by the vessel about dimensions, number of containers to load/discharge and their locations inside the vessel.

Figure 2. Vessel operations at port

Upon the vessel's approach to the port, the captain communicates with the Harbor Master (HM) to obtain operational clearance, ensuring compliance with port regulations and safety protocols. Once the traffic conditions within the port allows the authorization, the vessel, guided by the expertise of the HM, proceeds to receive the pilot on board. The pilot, with their specialized knowledge of the local waters, assumes command of the vessel, orchestrating its navigation through the channels and/or port waters.

In instances where manoeuvring assistance is deemed necessary, the pilot coordinates with tugboat operators, to tow or push the vessel, guiding it smoothly to its designated berth.

Upon reaching its assigned docking location, the vessel's crew stands ready, prepared to execute the mooring process. Working in tandem with the mooring crew, lines are expertly secured, ensuring the vessel is safely and securely anchored at its berth.

With the vessel now firmly moored, the terminal can start the cargo handling operations, for the seamless transition from ship to shore.

While this process typically unfolds as described, there are exceptions that may apply. These exceptions often stem from the captain's experience and the vessel's dimensions. In certain circumstances, captains with extensive knowledge of the local waters may navigate without the assistance of a pilot, while vessels of smaller dimensions may renounce the need for tugboat support, relying instead on their manoeuvrability and the expertise of their crew.

2.3. General overview of discharge/load operations from/to the ship

This section describes the process from when the vessel is moored and the discharging/loading process can start, to the final process when the vessel has all containers loaded and the HM has provided the authorization to departure to next port call.

When vessel and mooring crew has confirmed that vessel is moored, the process for unlashing all containers to be discharged can start. Before this step, the terminal received the vessel´s stowage and with that they can schedule better how to proceed the work inside the vessel and in the terminal (hands, handling equipment, time windows, etc.)

2.3.1. Cargo information exchange

The terminal receives the vessel's stowage information to begin the discharge/loading plan and yard planning before the vessel arrives at the terminal.

In this process, several messages and formalities across the process can be found. The detailed characteristics and specifications of the messages sent by the Ship Agent are:

- **BAPLIE:** Bayplan/stowage plan with occupied and empty locations, which includes the containers' location.
- **COPRAR:** List of containers to be loaded and discharged.
- **MOVINS:** Instructions regarding the loading, discharging and re-stowage of equipment and/or cargoes and the location on the means of transport where the operation must take place

2.3.2. Mooring and terminal equipment & information preparations

When the vessel is moored at the berth, it allows subsequent unstowage/stowage operations with terminal equipment and also acquirement for all requirements requested by the vessel (bunkering, deadlines, etc.).

First, the terminal checks if information sent in the COPRAR message matches with the information stored in the TOS.

In this stage, the main message provided is the NOR (Notice of Readiness), a document sent by Captain´s vessel confirming the stowage operations can start.

2.3.3. Lashing - unlashing and cargo preparation inside of the vessel

The next step is to prepare the cargo to be discharged/load from/to the vessel. The orders are submitted through the Terminal Operational System (TOS) and are received by stevedores in the on-board equipment devices.

Before starting the discharging of containers, they need to be unlashed. A similar process will be done after loading the last container for lashing the needed containers on the deck.

After the unlashing process, the next step followed by terminals and shipping lines is to discharge all import containers from the vessel. To schedule the process, the Ship Agent has informed about the sequence of the discharging cargo from the vessel (MOVINS) and the captain have confirmed the sequence. During the import container discharge process, to ensure vessel stability, one container in one side of the vessel and another in the other side of the vessel are usually discharged at the same time. Sometimes big container vessels can combine the process for discharging import containers and loading export container simultaneously.

Usually the use of STS cranes is based on the concept of “hands”, where a group of stevedores work together using different terminal equipment (STS, RTG, etc.). So, when a vessel has three hands it means that three STS cranes are working in that shift.

In Figure 3, the three main zones inside the terminal can be found:

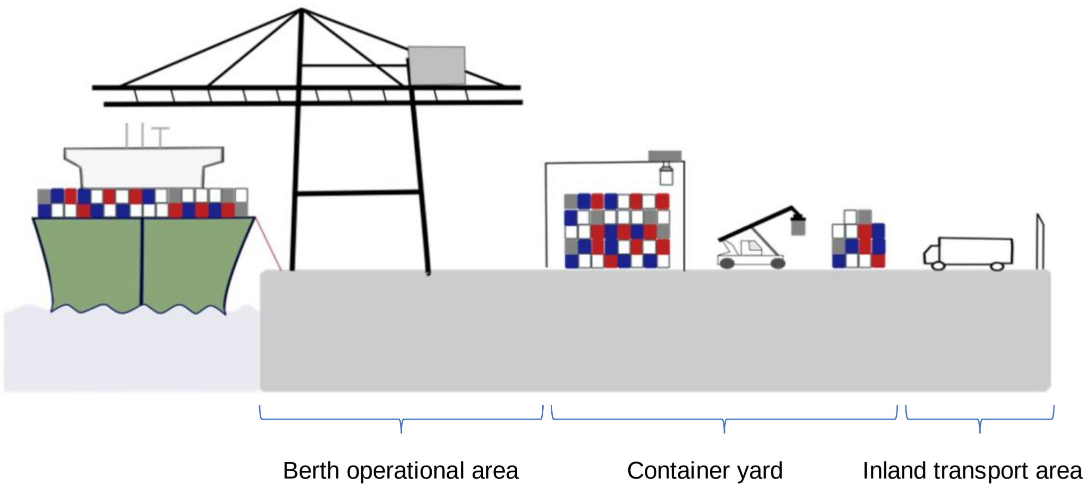

Figure 3. Main zones in a container port terminal

When the process of discharging begins, all the orders about how the discharging/loading plan must be sent from TOS to the stevedores and all handling equipment. This sequence should be as fast as possible to avoid time and decrease the productivity for the global process.

The whole process that follows one container since it´s taken from the vessel with the spreader of the STS crane to the final destination in the stack of the container yard is the following.

1) The STS crane grabs the container with its spreader, lift it, and moves it from vessel to the quay side.
2) The container is then placed in the container chassis of the terminal tractor or AGV, and the STS crane disconnects its spreader. In terminals with straddle carriers, the container is placed on the ground and picked up with a straddle carrier.
3) The terminal tractor, AGV, or straddle carrier moves inside the terminal until it reaches the location where the stack of containers on which the container is going to be placed.
4) With the Cargo Handling Equipment (reach stacker, RTG or RMG) the container is moved from the terminal tractor and lifted into the correct spot ordered by TOS. In terminals with straddle carriers, the container is directly located in the location by the straddle carrier.

2.3.4. Other cargo operations

In a container terminal, the flow of containers is diverse and dynamic, reflecting a variety of logistical considerations and destination requirements. While a significant portion of containers discharged at the terminal are indeed import containers destined for temporary storage in the yard until a truck picks it up, the operational landscape encompasses a variety of alternative scenarios tailored to the specific needs of cargo and its ultimate journey.

Regular maritime lines call only in the main ports, which are called hub ports. In these ports, a part of the cargo operations is for containers with origin and/or destination outside the hinterland of the port. For these cases, transhipment containers discharged from the vessel are then loaded in a feeder vessel or a barge, extending the reach of maritime transportation networks to more remote destinations.

Furthermore, modern container terminals are not only confined to maritime interfaces; they often include integrated rail facilities within their own premises. This strategic inclusion allows for the seamless movement of large volumes of containers to distant destinations via rail, offering an efficient and environmentally friendly transport solution. Containers designated for rail transport bypass traditional yard storage, heading directly to the railway terminal for onward journeying, streamlining the logistical process and reducing handling time.

Additionally, stringent safety regulations dictate special handling procedures for containers carrying hazardous materials. Containers classified as such are swiftly moved out of the terminal confines upon discharge, bypassing yard storage altogether. Instead, they are directly transferred to external trucks for immediate departure, ensuring compliance with safety protocols and minimizing potential risks within the terminal environment.

2.4. Cargo operations at the Terminal

Once containers are discharged from the vessel, the container terminal operator has to manage the yard which includes several processes.

2.4.1. Main elements in operations planning

Operations planning within a container terminal is a multifaceted process essential for optimizing the utilization of space and resources while ensuring smooth container movements. At the core of this intricate orchestration lies the vital role of the Operations Planner, whose responsibilities extend far beyond mere logistics coordination.

At the core of the Operations Planner's mandate lies the strategic optimization of vessel and yard activities, aimed at achieving productivity targets. Focused on efficiency, the Operations Planner meticulously maps out the flow of containers within the terminal, orchestrating a synchronized movement of inbound and outbound cargo movements.

The Operations Planner's role is the oversight of the Cargo Control Process, encompassing the end-to-end management of container handling operations. From the moment a vessel docks at the terminal to the final dispatch of containers to their respective destinations, the Operations Planner assumes responsibility for ensuring seamless execution and adherence to operational protocols.

Once the Operations Planner creates a plan, it is shared with the terminal staff and other stakeholders to ensure everyone works coordinated.

As a summary, the Operations Planner coordinate and control all container terminal activities to achieve efficient and effective operations (Figure 4), and to be able to achieve the terminal goals. These are the main coordination activities:

- <u>Berth allocation</u> is the process of determining which vessel will use which berth and for how long. The decision is based on a number of factors, including the vessel's size, draft, and cargo type.
- <u>Stowage planning</u> is the process of determining how containers will be discharged, restowed and loaded from the vessel. The goal is to optimize the use of space and ensure that the vessel is adequately balanced. Stowage planning is a responsibility of the master of 1st officer onboard. They are making sure that also the stowage plans in following ports are meeting stability and efficiency requirements.
- <u>Quay crane assignment</u> is the process of allocating quay cranes to vessels. The number of quay cranes needed depends on the size of the vessel and the crane's lifting capacity. Quay crane scheduling is the process of determining when each quay crane will be used. The schedule must consider the time needed to load and discharge the vessel and any maintenance or repair needs.
- <u>Yard management</u> is the process of coordinating the movement of containers within the terminal's yard. This includes deciding where to place each container and how to move it between different locations.
- <u>Yard crane scheduling</u> is the process of determining when each yard crane will be used. The schedule must consider the time needed to load and unload containers and any maintenance or repair needs. The stevedores receive the work orders based on the containers and cranes scheduling.
- <u>Yard transportation</u> is responsible for moving containers around the terminal yard. This includes using trucks, AGVs, or other vehicles to transport containers from one location to another.

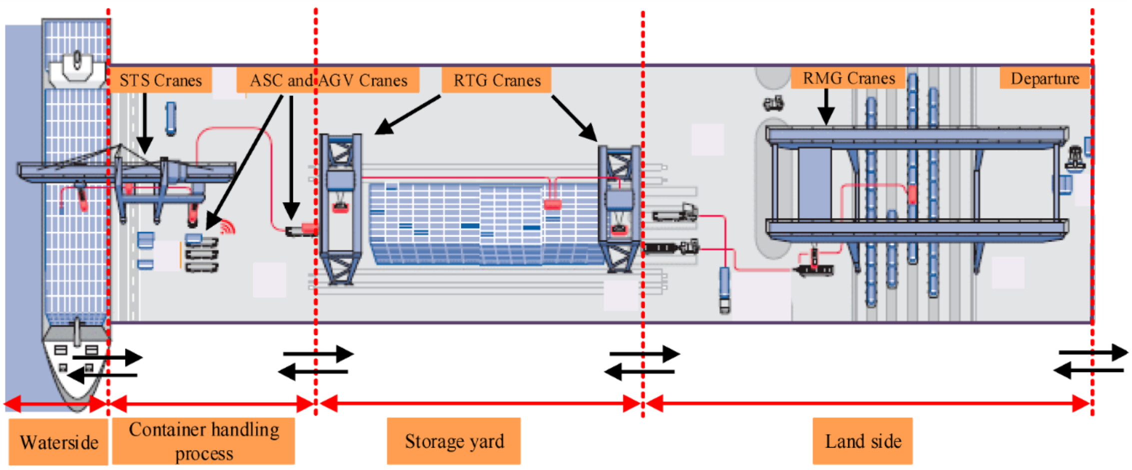

Figure 4. Perspective plan of a container terminal

2.4.2. Terminal Operation System (TOS)

Due to the growing complexity in port terminal operations, caused by the global growth of cargo transportation, the increase in administrative tasks and security, it has been necessary to gradually incorporate support tools to face these new challenges. It is in this context that digital solutions such as Terminal Operating Systems (TOS) emerge. They were initially oriented towards a function of control and management of administrative processes and compliance, which however has been incorporating important functionalities aimed at management, operational, control and analysis of productivity.

It is important in this section to be able to describe the main functions that the TOS currently performs, what is its scope and what are the systems with which it interacts. It must be considered that there are multiple providers that offer a wide range of solutions using different technologies and with different approaches. This is why this section will seek to describe the most extended version of a TOS from which to understand within the project how a TOS would coexist within the design of the systems architecture.

2.4.2.1. TOS Definition, Modules and Functions

Port terminals, regardless of their size and its main function, have the four traditional activities that could be subdivided into four main areas: Berth, Transfer Zone, Yard and Gates. It is in these four systems where the main processes of a terminal occur, which are: Loading/Discharging, Horizontal Transportation, Storage and Reception/Delivery. The TOS will come into contact with these fourth subsystems through the two main functions that a TOS must perform, which are planning and management operations.

Regarding the services provided by a Terminal Operating System (TOS) to a terminal, it can be understood as encompassing modules oriented towards planning, as well as those designed for the control and monitoring of operations. These operations are aimed at adhering to the planned activities and furnishing support to the terminal's remaining processes and subsystems.

Numerous versions of a TOS exist, depending on the type of terminal and the unique perspectives of different developers. Among the various definitions examined, the following one is most closely aligned with the study's purpose due to its emphasis on centralizing the definition around processes both physical and administrative related to cargo handling.

"A terminal operating system (TOS) is referred to as a computer system that is designed to plan, track, and manage the movement and storage of all cargo, the use of assets, and the deployment of people in and around the seaport terminal of the port (including the hinterland) on a real-time basis." [3].

In addition, discussing the different modules, it is crucial to highlight the primary functions of the Terminal Operating System (TOS). In this context, it delves into how the TOS interfaces with terminal operations, encompassing stages ranging from the pre-arrival phase, where it undertakes planning tasks, to its role in the execution phase, ensuring effective management and control while monitoring adherence to the pre-established plans. Furthermore, the TOS concludes its vital functions by generating the necessary reports to facilitate comprehensive analysis of operational outcomes.

The TOS is a critical component in the efficient management of a terminal's operations. Its functions are multi-faceted, covering various key phases in the operational process.

- Firstly, in the pre-arrival stage, the TOS plays an integral role in the **planning** process. It is responsible for tasks related to scheduling and organizing operations, ensuring that resources are allocated optimally, and that the terminal is prepared to receive incoming vessels.
- Moving on to the **execution** phase, the TOS continues to be a linchpin in the smooth functioning of the terminal. During this stage, it actively manages and oversees the execution of operations, ensuring that they align with the previously established plans. It constantly monitors the progress of activities, enabling real-time adjustments if necessary to maintain operational efficiency and productivity.
- Lastly, the TOS provides a crucial component for **post-operation analysis**. It generates detailed reports that offer insights into the terminal's performance, allowing for a comprehensive evaluation of results. These reports are invaluable for making data-driven decisions, optimizing processes, and identifying areas for improvement.

Figure 5. TOS Key Modules [4]

In summary, the TOS is not just a passive observer in the terminal's activities; it is an active and essential participant in various operational phases, from planning to execution and post-operation analysis. Its ability to facilitate efficient coordination, control, and analysis of terminal operations is paramount to achieving optimal performance and productivity in a complex logistical environment. Below is the description of the TOS key modules (Figure 5):

- Berth: the planning and management of the berth should be considered as the first step in establishing an operational strategy. It is crucial to take into account variables such as the size, type, and number of docks. Additionally, obtaining a general overview of the expected vessel arrivals in the near future is essential to evaluate the potential dock occupancy. Information about schedules is fundamental for estimating the use of terminal resources. Properly projecting dock utilization is essential for planning operational activities based on the infrastructure capabilities and dock equipment of the terminals. Currently, there are various Terminal Operating Systems (TOS) capable of planning operations according to expected schedules, vessel specifications, and the needs of the port itself.
- Vessel: once there's a clear understanding of the scheduled vessel arrivals at the terminal and the anticipated dock utilization, the next step is to conduct vessel planning. This aspect, as seen in section 2.3, relies on the communications between Shipping Lines and Terminals. These communications are facilitated through EDIFACT messaging in a Port Community System (PCS). Often, these messages are automatically integrated into the Terminal Operating System (TOS). Depending on the sophistication of the TOS, one of the primary features available in the market is the automatic planning of loading and discharging operations. This automatic planning is validated by a Vessel Planner, who assesses the relevance of the proposal and makes necessary modifications based on requirements.
- Yard: similarly to vessel planning, yard planning is carried out through the TOS. Sometimes, depending on the type of TOS, it's done automatically, while in other cases, it's done manually. Unlike vessel planning, yard planning involves two main points of analysis: the loading and discharging operations at the dock, and those at the gates. These two sources of movement flow determine yard operations as it's necessary to accommodate all containers passing through the terminal. The importance of this stage lies in the need for a powerful system capable of managing a high volume of information while ensuring that operations proceed as planned. Difficulties in yard operations can lead to decreased productivity levels at both the gates and the dock, causing operational bottlenecks.
- Gates: in the case of gate management, similar to vessel management, it serves as another point of contact with the external environment. Therefore, the system must interact with different parts of the port system that need to be aware of how cargo will be received or dispatched to and from the hinterland. All operations in this regard are primarily managed by the TOS through EDIFACT messages responsible for notifying and reporting movements. Messages such as CODECO, COARRI, and COPINO facilitate advanced knowledge of the flow that gate operations will face, thus providing insight into the potential workload intensity and its impact on the yard, vessel, and berth.

In addition to the main modules that plan and control operations, we find interactions with other internal systems that allow feeding information to the TOS to better understand reality, improve processes, and thereby increase productivity. The following are examples of tools that contribute to enhancing the performance of a TOS:

- Gate System: While previously mentioned that TOS have a gate management module, one activity for which the TOS is not equipped is the execution of entry and exit operations. Instead, a system known as the Gate System communicates with the

TOS to obtain authorizations and communicate the entries and exits of each container passing through the terminal. These services can be either in manual format, where a person interacts with the transport to carry out the movement, or it can be carried out through Automatic Gate management Systems (AGS), in which necessary information for authorization is identified through sensing and monitoring without the need for personnel intervention.

- Optical Character Recognition (OCR): The Container Number OCR framework automatically recognizes information and verifies both set and moving situations with the Container Id number. The system is designed to ensure precise container movement for effective container loading and discharging. The system facilitates efficient gate, yard, and load & unload zone management and operations for modern ports and terminals. OCR systems are increasingly being utilized in terminals due to their growing reliability. Coupled with License Plate Recognition (LPR), automatic data capture has become a reality, enabling terminals to design automatic and autonomous processes that were previously impossible. Both systems are usually part of the AGS.
- RFID: Radio Frequency Identification is an Automatic Identification and Data Collection (AIDC) technology, or, as it is more generally known, RFID. RFID has become an omnipresent, indispensable part of our everyday lives at work as well as at home, from access cards to passports to toll tags. For the identification and monitoring of persons, assets and inventory, RFID provides unique benefits.
- Reefer monitoring system: Operating a container terminal involves managing diverse cargo types, including refrigerated or frozen shipments that require meticulous temperature control. Integrating reefer monitoring into Terminal Operating Systems (TOS) facilitates this process, offering comprehensive insights into temperature-sensitive freight. Further exploration of cold chain logistics and effective management strategies is available in our specialized post.

Regarding the connections between the TOS and the external environment of the terminal, including port authorities, customs, clients, and transportation companies, there are various systems and communications that the TOS must manage to harmonize operations according to the interests of each involved party. Regardless of the terminal's size and other variables, current TOS are equipped with the same capabilities and technologies to operate in different environments. The following list will detail some of the most important communication and connection capabilities with the most common environment:

- Electronic Data Interchange (EDI): EDI messaging is one of the primary methods of communication between terminals, particularly through EDIFACT messages specifically designed for transportation. For several decades, EDIFACT messages have served as the standard for transferring information between terminals and shipping lines, port authorities, and transportation companies, usually using the PCS as communication channel. TOS are equipped with the capability to incorporate these EDIFACT messages seamlessly into their operations. They can receive, interpret, and transmit EDIFACT messages to relevant stakeholders, facilitating smooth coordination and efficient data exchange in the logistics process. This integration ensures that essential information, such as cargo manifests, bookings, and status updates, are accurately communicated between parties, contributing to the overall efficiency and effectiveness of terminal operations.
- Application programming interface (API): Due to the need to continue advancing towards digitization and in order to keep pace with the rest of the industry, TOSs have

been endowed with the ability to connect via REST API. These systems support messaging formats such as JSON, XML, among others. Participants in port logistics such as port authorities and shipping lines are beginning to utilize these technologies to transmit information.

	Type of freight	Number of installations	On-premises/ cloud hosting	Short description and special features
Navis (Octopi, N4, N4 SaaS, Master Terminal)	containers and general cargo	around 300	both	A recognized world-leading provider with a variety of products for different needs
CARGOES (TOS+, GC+, IOT+, AVA+)	containers and general cargo (different products)	70+	both	Solutions with heavy usage of innovative ML techniques and IoT devices
CATOS	containers	70	On-premises	All-in-one TOS with planning, operation, and management modules and a user-friendly interface
TBA Group (Autostore, CommTrac)	containers and general cargo (different products)	30+	both	Full-fledged platform with seamless ERP integration
RBS (TOPS Expert, TOPS Expert Cloud)	containers	around 30	both	A comprehensive base solution with a choice of optional modules

Figure 6. TOS TOP providers compared [4]

Regarding the main developers of TOS, Figure 6 shows who the main developers are and what their main solutions are in broad terms. The market is primarily concentrated in no more than five companies, among which NAVIS stands out as the main developer. NAVIS offers solutions with high levels of customization, making it possible for them to be implemented in all types of container terminals regardless of their size. This figure not only shows how the market is distributed but also indicates the existence of multiple functionalities within the existing offerings. As mentioned, container terminals must have some type of terminal management system. Currently, there are adaptable solutions according to the terminal's possibilities; however, it still represents an investment that, despite the significant reduction in costs in recent years, can be high if the terminal does not have a minimum volume of movements to amortize and obtain results from these systems.

2.4.2.2. Communication between TOS and handling equipment used

In the previous section, we discussed the main internal and external systems that interact with the TOS in various scenarios where operations require information. This section will present how the TOS governs operations at the execution level to coordinate resources as operations unfold. We have seen that a TOS fulfils the functions of planning operations; the next step is to execute the plan. Within the process of executing operations, the primary tool for coordinating activities is job instructions. These job instructions are sequenced by the TOS through the work of the Vessel Planner in collaboration with the Yard Planner to determine an optimal sequence. This sequence is then transmitted to terminal equipment operators to carry out the job instructions.

There are three main systems through which the TOS is capable of executing operations. Firstly, communication systems for job instructions are needed so that the equipment operator effectively has information on what tasks to perform in case operations are manual or to transmit to an autonomous team. Another system that allows the TOS to execute the plan is knowing the real-time positioning of the equipment, and finally, knowing the status of the equipment enables knowing its availability. Next, these tasks will be explained in more detail.

- Transmission of job instructions: Once again, the method through which the TOS, or operations department, communicates instructions to operators regarding container movements depends on operational complexity and terminal size. While small terminals nowadays may have complex processes, some still rely on radio frequency communications, where a person communicates via radio to an operator to provide information - a method typically used in low-volume movement operations.

  The most common system in the sector, especially in manual terminal setups, are Vehicle Mount Terminals (VMT). These are computer devices that can either be affixed to equipment or mobile. They offer wireless connectivity features such as Wi-Fi, Bluetooth, and cellular data, facilitating seamless communication between drivers, dispatchers, and vehicles. This enables real-time data exchange, a crucial element for maximizing operational efficiency.

- Real-time locating system (RTLS): To monitor terminal handling equipment, various technologies like GPS, DGPS, RFID, Bluetooth, among others, are employed. Real-Time Location Systems (RTLS) consist of a network of tags or wireless transponders affixed to equipment units, alongside readers strategically placed across terminal premises to capture tag signals and ascertain their whereabouts. This information is seamlessly integrated into the Terminal Operating System (TOS), allowing it to adapt the execution of operations, validate planning, and provide suggestions for any necessary changes.

- Status monitoring: The real-time monitoring of the status of equipment is relevant to determine if there is any impediment preventing the equipment from performing the tasks that have been assigned or will be assigned. Currently, equipment such as yard, horizontal transportation, or dock equipment are equipped with IoT sensors centralized in a Programmable Logic Controller (PLC) for equipment such as STSs, RTGs, RMG, among others. The PLCs should be equipped with Ethernet connectivity, allowing between the equipment and other device with wireless communication to send the data to the TOS. This data is collected by the TOS, analysed, and based on the provided information, necessary variations in operations can be made to fulfil the planned tasks.

  When it comes to terminal tractors or reach stackers, as they typically lack a PLC, the most common method for capturing information is through systems like CANBUS. CANBUS is a communication protocol used in vehicles, particularly in commercial vehicles for connecting various Electronic Control Units (ECUs) and sensors. It allows for data exchange and control signals between different components of the vehicle. Through converters of communication protocols, terminal tractors equipped with CANBUS systems can communicate with the TOS. These converters facilitate the translation of data between the CANBUS protocol used by the terminal tractor and the communication protocol understood by the TOS, enabling seamless integration and information exchange between the two systems.

2.5. Overview of vessel and cargo processes

This section provides an overview of the processes detailed below, accompanied by flow diagrams that visually represent each stage. These processes are also explained in detail in D2.2 [2] (section 2.2.3). The processes are divided into three main categories: port call (Figure 7), cargo operations (Figure 8), and land transport (Figure 9), each with its own dedicated flow diagram to clarify steps and interactions within these distinct phases.

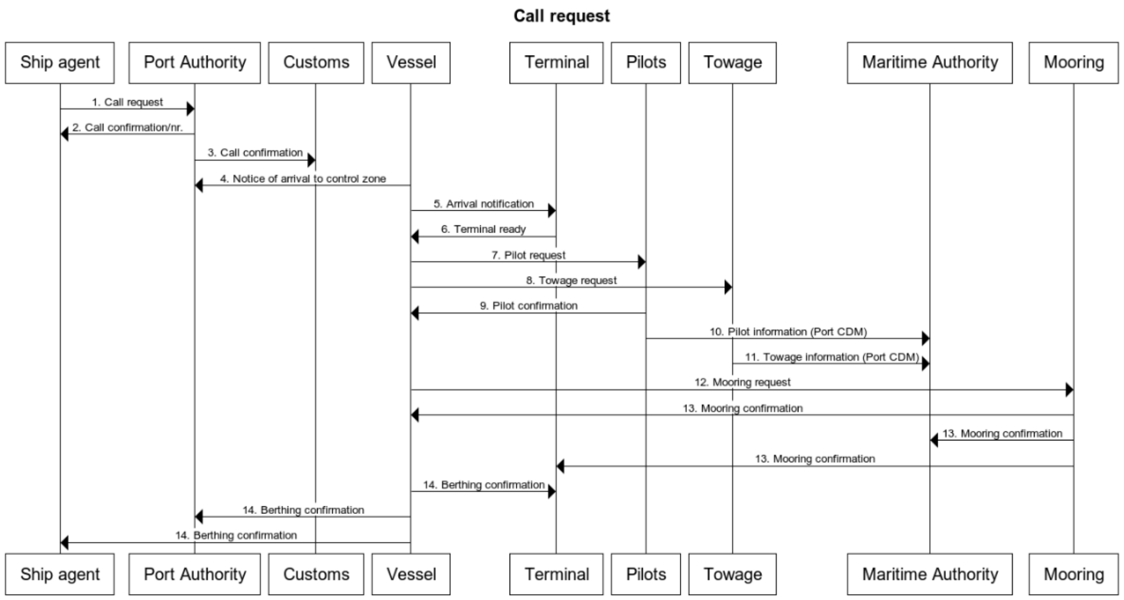

Figure 7. Flow diagram of the processes in the port call request

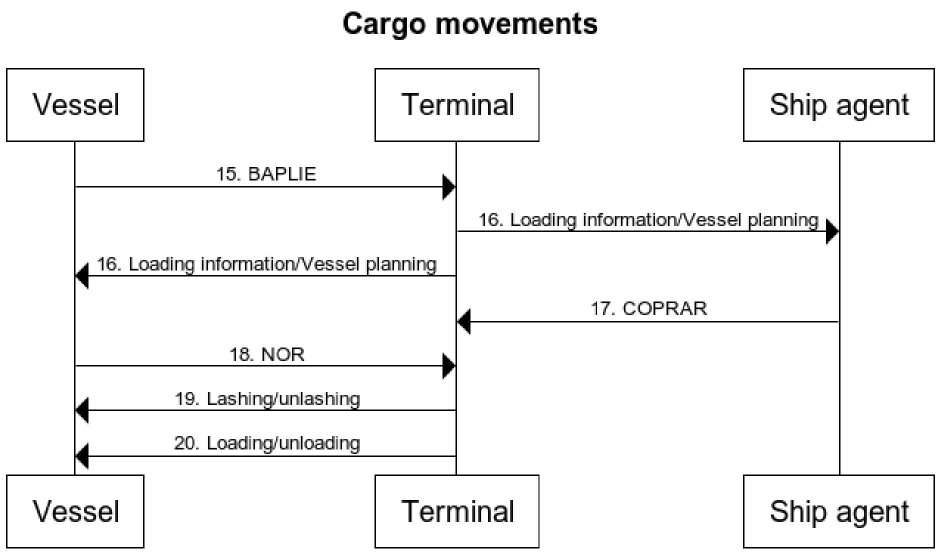

Figure 8. Flow diagram of the processes in the cargo operations

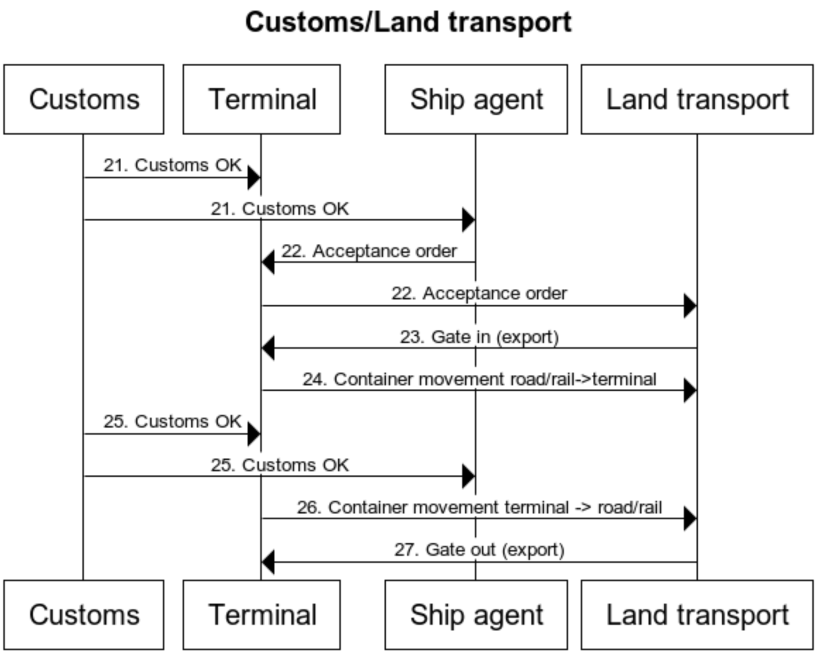

Figure 9. Flow diagram of the processes in the land transport

Table 1 provides a comprehensive description of all processes represented in the flow diagrams. Each process is grouped according to its relevant operational interface (whether is vessel, vessel-terminal, terminal-land transport, etc.) to clearly distinguish each stage of the overall workflow. For each process, the table outlines the information flow exchanged, detailing the data types and communication protocols used to support efficient interactions between systems and stakeholders.

Additionally, the table specifies the systems involved in transmitting and receiving this information, highlighting essential tools such as Terminal Operating Systems (TOS), Electronic Data Interchange (EDI) platforms, and Customs Systems, among others. These systems enable real-time updates, monitoring, and decision-making, fostering seamless connectivity throughout the operational chain.

The table also identifies opportunities for process automation, accompanied by detailed justifications. Each automation opportunity is evaluated based on factors like process efficiency, operational safety, resource optimization, and the potential for minimizing human intervention in repetitive or hazardous tasks. The reasons for automation are explained, such as reducing manual handling errors, increasing process speed, and improving data accuracy, ensuring a smoother and more reliable workflow from port entry to cargo departure.

Table 1. Port processes description

	Phases	BRIEF DESCRIPTION	INFORMATION FLOWS RECEIVED/SENT	SYSTEMS USED TO EXCHANGE INFORMATION	POTENTIAL AUTOMATION	DETAILED REASONS
1-Vessel	1. Call Request - Planning activities	Vessel, through the consignee/shipping line, will request to call at the port and terminal indicated, being approved by the Port Authority and allowing the vessel to call at port. This process activates berthing planning activities to properly prepare the berthing for the future arrival of the vessel. And Customs also opens a "summary statement" folder.		Port System EMSWe TOS	HIGH	-
	2. Vessel arrival to the port's control zone	Vessel requests entry authorisation and this event generates all messages to the port services agents	**Vessel clearance** **IALA S2011** or **DCSA** (semantic)	AIS-VTS PortCDM ROC	HIGH	In this process we need to maintain the international processes informing via AIS-VTS (VHF message).
	2.1 Pilotage request and service	Pilotage	**IALA S2011** or **DCSA** (semantic)	VHFs VHF Radio PortCDM	MEDIUM	Pilotage may not be required if the vessel has a recurring call at the same terminal (similar case like ferries). In this step the ROC need to be aligned with vessel captain, and this one must confirm is he agree with the port passage plan.
	2.2 Towage request and service	Towage	**IALA S2011** or **DCSA** (semantic)	VHFs VHF Radio PortCDM	MEDIUM	Considering that there is some automated solution related to Tug navigation, human intervention is still needed to connect the Vessel to the Tug by doing it by manual tasks.
	2.3 Mooring request and service	Mooring	**IALA S2011** or **DCSA** (semantic)	VHFs VHF Radio PortCDM	MEDIUM	There are various proven and implemented automated mooring systems in the industry including large scale container terminals. The barrier is the high cost of infrastructure for implementation.
2-Vessel - Terminal	1. Cargo information exchange	The terminal receives the vessel's stowage information to begin the discharging/loading plan and yard planning before the vessel arrives at the terminal.	**BAPLIE** (sent by vessel planner - Bayplan/stowage plan occupied and empty locations) **COPRAR** (sent by consignee/shipping line for load and discharge) **MOVINS** (sent by yard planner where we can find the load data and location inside the vessel)	TOS	HIGH	The current solution favours the terminal operator, whereas it is of shipping lines responsibility to meet stability and efficiency criteria also in forthcoming ports.

	2. Mooring and terminal equipment & information preparations	Vessel is moored to the berth, allowing subsequent unstowage/stowage operations terminal equipment and also procurement for all requirements requested by the vessel. Terminal can check if information sent with the COPRAR match with the information showed in the TOS.	**NOR** (Document sent by Captain´s vessel confirming the stowage operations can start)	VHF Radio VHFs TOS AIS-VTS	HIGH	-
	3. Lashing-unlashing and cargo preparation inside of the vessel	Lashing-Unlashing Prepare the cargo to be load/unload from/to the vessel.	Electronic messages TOS<->stevedoring personnel Vessel plan either physical or digital	TOS	LOW	The existing solution includes only the automatic twist locks, but there are no alternatives to lashing bars. Hyundai shipyard's lashing-free container ship secures design approval from international societies
3-Terminal	1. Vessel to yard movement, import	Container movements from vessel to yard (import). Through work instruction the TOS gives specification about container movement	Electronic messages TOS<->Crane COARRI Container Discharge and Loading Confirmation	TOS	HIGH	-
	2. Yard to Vessel movement, export	Container movements from yard to vessel (export). Through work instruction the TOS gives specification about container movement	Electronic messages TOS<->Crane COARRI Container Discharge and Loading Confirmation	TOS	HIGH	-
	3. Vessel to vessel movements, transshipment	Container movements from vessel to vessel (transhipment). Through work instruction the TOS gives specification about container movement	Electronic messages TOS<->Crane COARRI Container Discharge and Loading Confirmation	TOS	HIGH	-
4-Terminal - Land transport	1. Crane movements to load cargo onto land transport vehicles	Crane movements to load cargo onto/from train/trucks	**COPINO** (Container pre-notification message)	TOS PCS	HIGH	-
	2. Intraport transportation of containers via land vehicles	Intraport container transportation to/from terminals to other terminals for transit containers	**IFTMIN** (International Forwarding and Transport Message – Instructions) **COPARN** (Container announcement message) **COPINO** (Container pre-notification message) **CODECO** (Container gate-in/gate-out report message)	TOS PCS	HIGH	-
	3. Gate in/out operations by rail	**GATE IN/GATE OUT** By rail operation	**IFCSUM** (International Forwarding and consolidation summary message) **IFTMIN** (International Forwarding and Transport Message – Instructions) **COPRAR** (Container discharge/loading order message) **COPINO** (message by which an inland carrier notifies of the delivery or pick-up of containers) **CODECO** (message by which a terminal, depot, etc. confirms that the containers specified have been delivered or picked up by the inland carrier)	TOS PCS	MEDIUM	All digital processes are automated, cargo handling as well, the only one that is not fully automated is seal number verification.
	4. Gate in/out operations for export/import via land transport	**GATE OUT (IMPORT)** Truck transportation inside/outside of the terminal	**<u>Green Routing</u>**: Goods are released straightaway (Automated customs clearance) **<u>Orange Routing</u>**: All documents provided have to be checked and compared to confirm them	TOS PCS	HIGH	The only issue is the impossibility of automatically checking the seal number

		Delivery orders sent by consignee (or forwarder) via PCS to free up the container Admission orders requested via PCS by the shipper (or forwarder) when they want to get in in Terminal their container	**Red Routing:** Goods have to be inspected physically and their documents reviewed (Veterinary, Pharmaceutical, Phytosanitary and SOIVRE)	TOS PCS	HIGH	The only issue is the impossibility of automatically checking the seal number
		GATE IN (EXPORT) Truck transportation inside/outside of the terminal Delivery orders sent by consignee (or forwarder) via PCS to free up the container Admission orders requested via PCS by the shipper (or forwarder) when they want to get in in Terminal their container	IFCSUM DUA (CUSRES - Customs Response message) VGM (VERMAS) - EDI/XML message	TOS PCS	HIGH	The only issue is the impossibility of automatically checking the seal number
5-Expedition of cargo to hinterland	1. Movement of goods to inland transport depots	Movement of goods under the customs transit process, when the customs are still not declared (for example - container deconsolidated in Temporary Storage Warehouse)	Non-Union goods transported by a vessel in a regular authorized maritime service must be placed under a T1 transit procedure. Applies to goods of the Union: - Moving from a special tax territory to another part of the customs territory of the Union which is not a special tax territory; - When such movement ends at a place outside the Member State where they entered the customs territory of the Union.	PCS Customer system EMSWEs TOS	MEDIUM	At this point the challenge lies in the possibility of transferring data between TOS and customs to effectively prepare the container at the right place and time that the customs officer needs. Cargo handle is easily automated.
6-Vessel Departure	1. Vessel departure process	Cargo operations are complete and all required services have been notified to support the departure process.	**Cargo manifest** (EDI) **IFTDGN** (Dangerous goods notification message) - EDIFACT message	Port System EMSWe TOS	MEDIUM	Same challenges that inbound vessel processes have

3. Analysis of systems for handling cargo

In order to understand the interactions between the systems that manage automatic or autonomous cargo handling operations, it will be necessary to first understand the particularities and scope of the existing tools, identifying possible gaps and needs to adapt to new operational types.

The relevant points of analysis have been defined differentiating the loading and discharging operations related to the vessel, processes that happen inside the terminal, and finally the communication between the systems and the autonomous handling equipment.

3.1. Ship management system

The first system to analyse is related to the monitoring and management of the ship once docked at the berth. Although the type of operations proposed does not exclude the presence of a crew, more precisely the figure of a captain, it is necessary to consider the operations contemplating the scenario in which there is no human intervention in the processes. This consideration requires the autonomous vessel to be equipped with all the necessary sensors and IoT to know the conditions in real time, the activities that are being carried out and the way in which the vessel is affected. Aspects such as the physical efforts to which the ship is being subjected, stability, loading and discharging situation, services provided and its condition, among others.

Ship management continuously monitor important parameters of the ship, namely hull integrity, maintenance schedules, crewing, procurement, quality control and even dry-docking activities. From the autonomous' ship point of view, the most important aspects are those related to operations which can be carried out during the call: refuelling, unplanned and planned maintenance, etc. During a fully autonomous procedure, these shall be requested by the ship before arriving to the port to plan them accordingly and reduce delays and berth occupation.

Although the development and implementation of autonomous ships in real and regular operations has not so far been widespread except on rare occasions and in very controlled environments, ship management systems do have a certain level of maturity and are intended to support the people interested in and responsible for controlling operations.

Through a bibliographic search, systems have been found that offer different possibilities depending on the level of information needed. The following paragraphs describe the functionalities of the options currently on the market:

K-Load (Kongsberg) [5]

Enhancing cargo operations, Kongsberg Maritime and Consultas have joined forces to enhance their range of products and system solutions, with particular emphasis on the loading computer system solution. By bringing the two organisations together, they have created a centre of excellence to provide existing and new customers with products and services that deliver the optimum in operational safety and efficiency.

Kongsberg takes K-Load a step further. It utilises a 3D model of the vessels' hydrostatic – a full geometric definition of the vessels – as the basis for the calculation of loading conditions, floating position and stability, and longitudinal strength. This creates a precise description of the actual loading conditions, dispensing with the need to rely on precomputed tables, simplifications, or assumptions. The result avoids dead freight or overload. By utilising the full geometrical definition of the vessel as the basis for the computation, additional applications have been developed to improve the load planning and condition handling.

K-Load is always connected to the tank gauging system, giving the operator full control of the cargo, ballast, and fuel flow. The loading computer is online in the Online Condition mode and the operator can also choose to work offline in the Planning Condition mode to carry out simulations or planning. The operator can easily transfer data between the two modes.

This system provides the necessary characteristics for the management of the ship in port. Although the development of this application is aimed at bulk operations, more precisely liquid bulk, its adaptation to both container and RO-RO operating environments is not considered a barrier.

Aries Marine [6]

Aries Marine offers specialized ship loading software designed to provide an integrated, user-friendly system for load planning and loading calculations, ensuring safe and efficient vessel operations.

The software features a comprehensive range of modules tailored for both onboard and office use, operating within an interactive graphical environment. Users work directly with an accurate vessel plan, with intuitive, self-explanatory screens that maintain a consistent format, enabling quick access to essential information for seamless task execution. It functions as both an onboard tool and a standalone office system.

Approved by all major classification societies, the ship loading software includes various modules that meet statutory requirements while addressing key operational and safety aspects, including emergency response. Specialized versions are available for different vessel types, each customized to handle the unique loading and stability challenges of bulk carriers and dry cargo ships, tankers including LNG carriers, offshore support vessels, Ro-Ro and passenger ships, chemical tankers, LPG carriers, and container ships.

This advanced solution enhances operational efficiency, compliance, and safety across a wide range of maritime applications.

3.2. Vessel Stowage System

In this section, the analysis is focused on the systems involved in the stowage planning from the perspective of a Shipping Line.

The bay planning systems on container ships (Figure 10) are fundamental elements for optimizing efficiency and cargo capacity in maritime logistics. These systems, based on advanced algorithms and cutting-edge technologies, play a crucial role in the optimal organization of containers in the different bays of a vessel. Efficient planning is essential to maximize the ship's capacity, reduce waiting times at container terminals, and decrease costs associated with maritime freight.

These advanced systems do not operate in isolation; they are intrinsically linked to the activities and processes taking place in container terminals. In terminals, efficiency in loading and discharging is crucial to minimize waiting times and optimize operational capacity. The seamless integration between bay planning systems on ships and terminal management platforms allows for more effective coordination. Real-time communication about planned cargo and space availability on ships facilitates a more efficient distribution of cargo at the terminal, improving synchronization between operations on land and at sea.

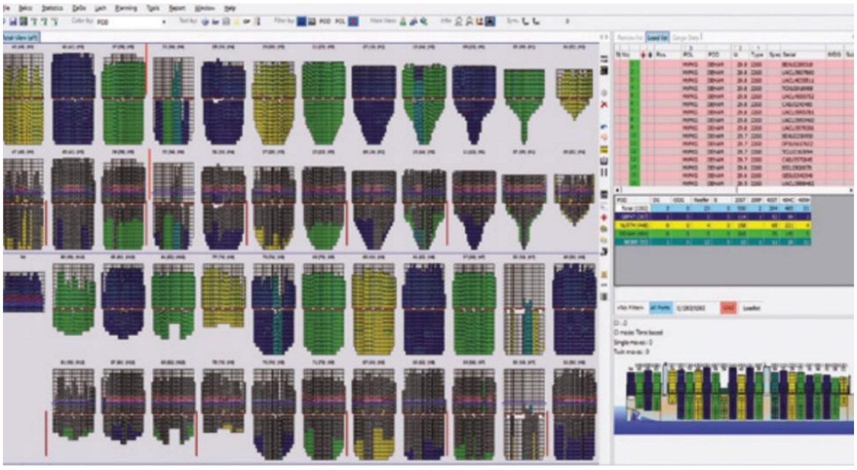

Figure 10. Example of a container vessel bay planning [7]

This connection between bay planning systems and activities in terminals not only benefits shipping companies but also has a positive impact on the supply chain. The continuous optimization of algorithms contributes to a more efficient distribution of cargo on the ship, facilitating terminal operations by receiving containers in a more organized and optimized manner. Furthermore, efficiency in loading and discharging not only reduces transit times but also lowers logistics costs, thus contributing to a more agile and sustainable supply chain.

In broader terms, the implementation of advanced bay planning systems and their integration with terminal operations not only improves profitability and operational efficiency but also contributes to sustainability by optimizing resource use and reducing emissions associated with maritime transport. The ongoing evolution of these technologies promises to further drive efficiency and sustainability in global logistics, establishing a vital synergy between high seas planning and onshore operations.

Stowman DS [8]

Stowman DS, the Navis software for the vessel management, offers highly accurate and flexible stowage planning with multi-port views for voyage planning, condition and checks for on board and load list cargo. The solution is enabled to integrate stowage optimisation and to analyse business intelligence data.

Stowman DS is able to minimise incident risks by automatically taking into account loading computer operational data like most up-to-date approved lashing calculations, stability and stress, segregation, tank situation and trim already in the planning stage.

It offers advanced planning functionality like e.g. restows and shift moves, crane split and advanced crane operation functionality to minimise cargo operation times in port and is saving time and reducing costs by managing up-to-date ship profiles flexibly through the Vessel Pool.

It also allows an easy and fast distribution of workload across various planners and teams and is increasing visibility across stakeholders and various workstations. It provides full visibility for the assigned responsible voyages to every user and offers an import and export function of standardised cargo data formats that are also used by terminals, agencies, and partner liners.

OPUS Stowage [9]

OPUS Stowage, from Cyberlogitec, is an advanced vessel stowage planning solution designed to optimize container loading and unloading operations for shipping companies, enhancing efficiency and profitability. The system manages stowage data, including loading requests connected to terminal operations, ensuring seamless coordination between shipping lines and port facilities.

The stowage planning engine, developed from extensive stowage experience and cargo pattern analysis automatically generates optimized stowage plans. It considers critical factors such as space utilization, vessel stability, weight distribution, and ballast calculation, while enabling planners to maximize productivity under planning constraints.

Developed on a Java-based platform with a centralized database, OPUS Stowage offers high scalability and reduced maintenance costs. As a next-generation solution, it streamlines planning processes, improves operational efficiency, and supports shipping carriers in achieving greater profitability through precise and optimized cargo management.

Autoship Stowage Planning [10]

Autoship Systems Corporation Stowage Planning Systems go beyond simple cargo modelling by providing a comprehensive solution for managing all cargo types, voyages, ports, and vessels within a fully integrated global information system. These systems facilitate both long-term strategic planning and real-time operational adjustments, seamlessly incorporating existing booking databases and integrating shipping operations into broader supply chain management.

At the core of this solution is the electronic stowage plan, or Stowage Plan File, which serves as a centralized repository for all voyage-related data. This includes graphical stowage representations, cargo booking details, real-time cargo location and status, and vessel hydrostatic conditions. The system enables seamless data transfer and is equipped with Autoload®, a cutting-edge hydrostatics analysis engine.

Each system is customized to match the specific needs of shipping lines, cargo types, and vessel configurations. However, the core planning modules cover a broad range of vessel types, including Ro-Ro, breakbulk, container, bulk cargo, tanker, and heavy lift vessels. This tailored approach ensures optimized stowage planning, improved efficiency, and enhanced cargo management across diverse shipping operations.

4. Analysis of the links with hinterland and their systems

4.1. Introduction of Hinterland Links

This chapter considers the operational links and interfaces of ports and their respective hinterland transportation systems. The term “hinterland” in this context is understood as the “effective market or the geo-economic space in which the seaport sells its services” [11, p. 75]. Scientific inquiries suggest that hinterland transportation may account for 40-80 % percent of the costs in maritime transport and logistics chains [12, p. 122]. In the remainder of this study, the hinterland concept will be applied not only to seaports but inland ports as well. As in the previous chapters, the focus will be placed on container transportation.

Sea as well as inland ports play a crucial role within the overall transport chain and serve as hubs for consolidation and distribution of cargo. While inbound and outbound transport often do not link immediately, ports also represent a logistical buffer. Hence, establishing efficient links and accessibility to the hinterland not only affects the performance of port operations but the performance of transport and logistic chains as a whole.

One critical issue for port operations is uncertainty with regards to the arrival of inbound and outbound hinterland flows. For import cargo, terminal operators often lack certainty about the onward hinterland mode. Depending on the individual setting, hinterland transportation can be carried out by means of scheduled modes such as rail and inland waterway transport or by road transportation. Due to its non-scheduled nature, terminal operators often lack information about arrival patterns throughout the days. For rail and inland waterway transportation, arrival delays may distort capacity planning. This situation significantly reduces efficiency in the system, as terminal operators face problems to balance the workloads of berth, yard and landside resources.

The issue increases with the event of Ultra Large Container Vessels (ULCV) which accommodate up to 24.000 TEU. For illustration, [12] calculate a required yard area of around 8 ha for a port call with 8,000 TEU. Given a modal distribution of 70% transported by road and 30 % by rail they assume up to 2,800 trucks carrying a capacity of 2 TEU each and 30 trains with a capacity of 80 TEU [12, p. 119]. However, storage space as well as the human (employees), infrastructural capacity (railway tracks, roads, gates) and equipment availability (cranes, straddle carriers) at the terminal remains limited due to spatial and economic constraints.

Given the described circumstances, efficient coordination and exchange of goods between ports and their hinterland links is of critical importance for the performance of transport and logistics chains.

Modal-Split and Modal-Shift are two key concepts in transportation planning that play a critical role in shaping efficient, sustainable, and well-balanced transport systems. Modal-Split refers to the distribution of transport demand across different modes of transportation, such as road, rail, air, and water. It represents the percentage share of each mode in the total movement of goods or passengers within a specific region or along a particular route.

When determining the modal split, several factors must be considered, many of which are not always reflected in official statistics, making it challenging to accurately assess the modal distribution. For instance, feeder transport, which involves the movement of goods or passengers from smaller hubs to major transport nodes, often complicates the calculation. Additionally, local traffic, which refers to short-distance movements within a region, also affects the overall modal split [13]. In seaport-hinterland transport for example, the modal split is typically calculated by considering the volume of goods transhipped minus the traffic attributed to feeder services and local deliveries. However, due to the lack of precise statistical data on local traffic, estimating the exact modal split can be difficult.

Observing the modal split of containerised hinterland transport on the example of the three largest ports in container throughput in Europe, namely Rotterdam, Antwerp and Hamburg, the difference in distribution on the different modes of transport for the three ports becomes evident. While all three ports have a very similar share of road transport ranging from 53.3 % for Rotterdam to 55.6 % for Hamburg in 2015, the share of rail and IWW are very different, at least for the port of Hamburg. Whereas for Hamburg, the IWW share of 2,1 % is negligible, Rotterdam and Antwerp have a very low share of rail transportation [14].

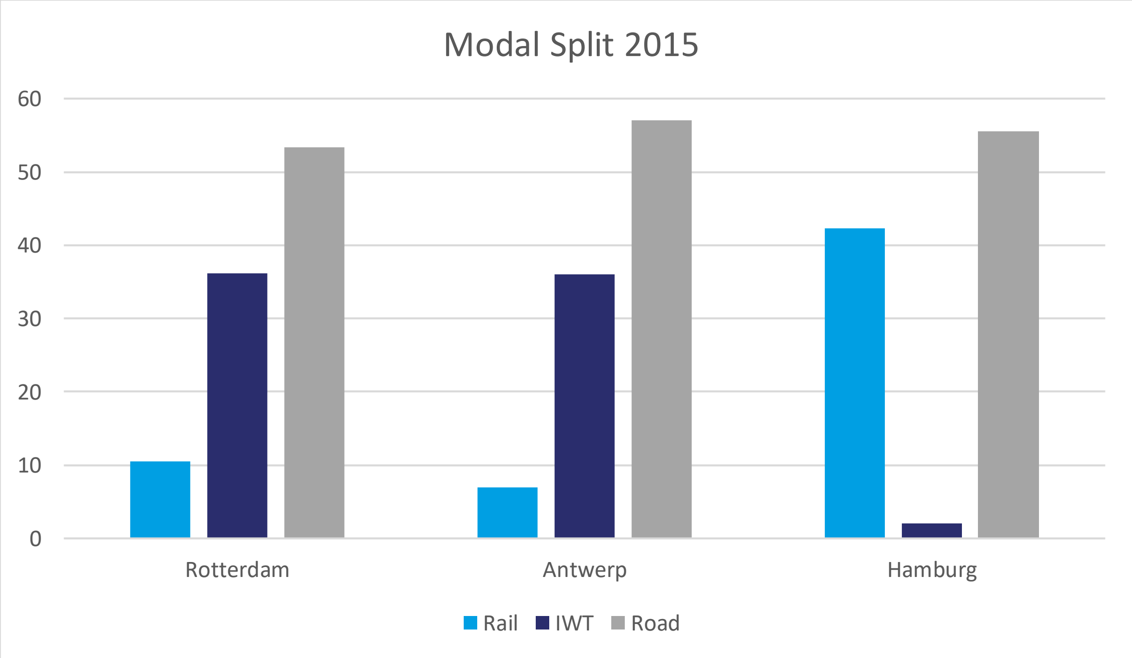

Figure 11. Modal Split Rotterdam, Antwerp, Hamburg 2015 [Based on [14]]

While Figure 11 shows the modal split of the three different ports for 2015, the individual split can vary significantly depending on the transport distance and specific transport relations. For longer distances, the share of transport modes can shift dramatically, making general modal split statistics less meaningful for analysing specific routes or regions [13]. SEAMLESS partner ISL has developed the European Container Traffic Model (ECTM) to close this gap. Among other things, the model provides an insight into container-based hinterland traffic at the main European container ports. Using Antwerp as an example in Figure 12, it becomes possible to investigate how Antwerp's maritime hinterland traffic is distributed across the individual NUTS 2 regions (Nomenclature of Territorial Units for Statistics regions from EC) and what the modal split looks like for each region. It can be seen that the modal split of different regions varies significantly. The figure shows cumulative import and export container volumes. A separate breakdown between import and export container volumes would again show a completely different picture of the modal split.

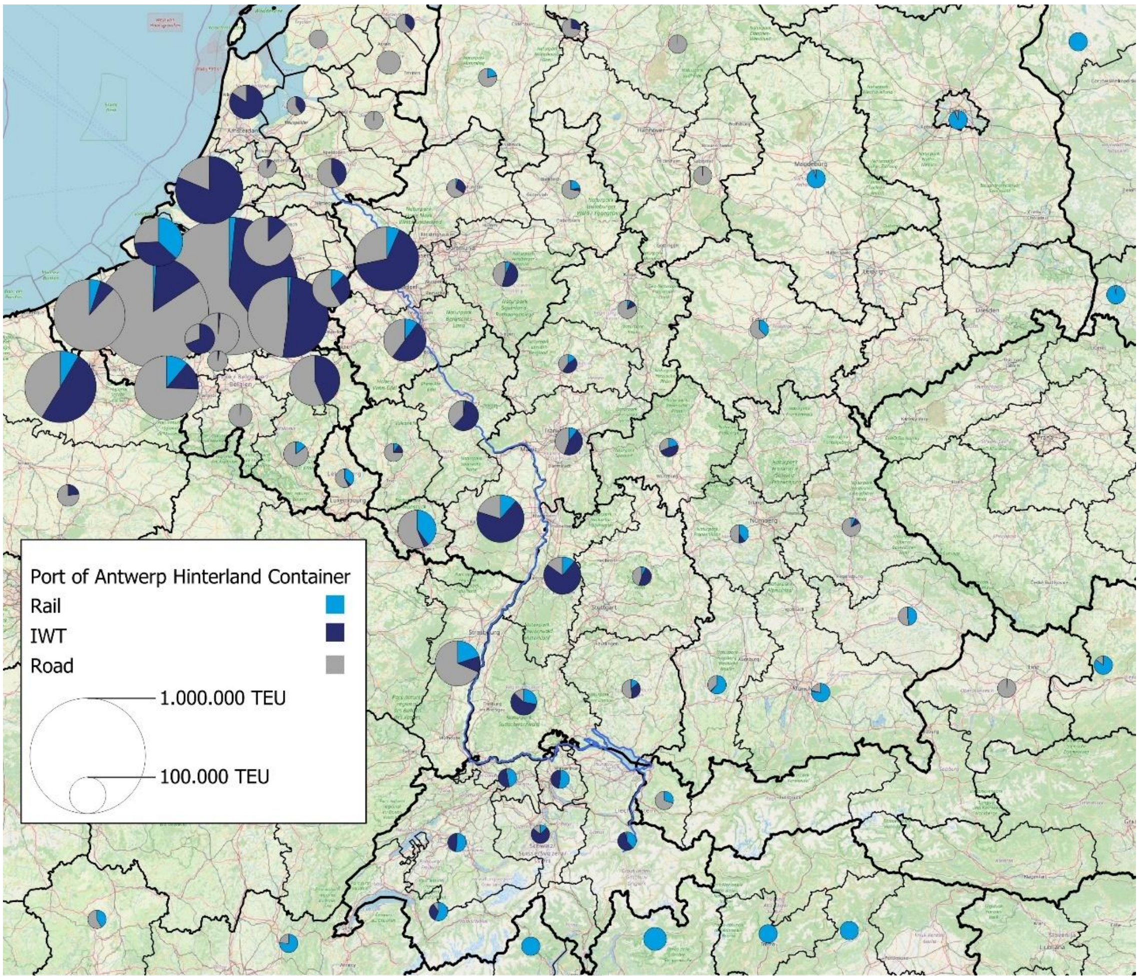

Figure 12. Modal Split of Antwerp's Maritime Hinterland Container Traffic for 2022

Source: ISL based on ECTM
Note: Only NUTS-2 regions with 500 TEU or higher; small diagrams not proportionally scaled.
Source: ISL European Container Traffic Model (ECTM)

The concept of modal shift usually refers to the transition of transport demand from one mode of transportation to another, typically from less sustainable modes, such as road transport, to more sustainable ones, such as rail or water. The goal of modal-shift strategies is often to reduce the environmental impact of transportation, alleviate congestion on roads, and optimize the overall efficiency of the transport network [15].

Again, looking at the modal shift ambitions of the three above mentioned ports (Figure 13), one can observe that Antwerp and Rotterdam aim to shift their road share in favour of rail, but also to a large extent in favour of IWW. Hamburg already has a large rail share and a rather poor IWW network, so the possibilities for a modal shift are much more limited here than in the other ports [14].

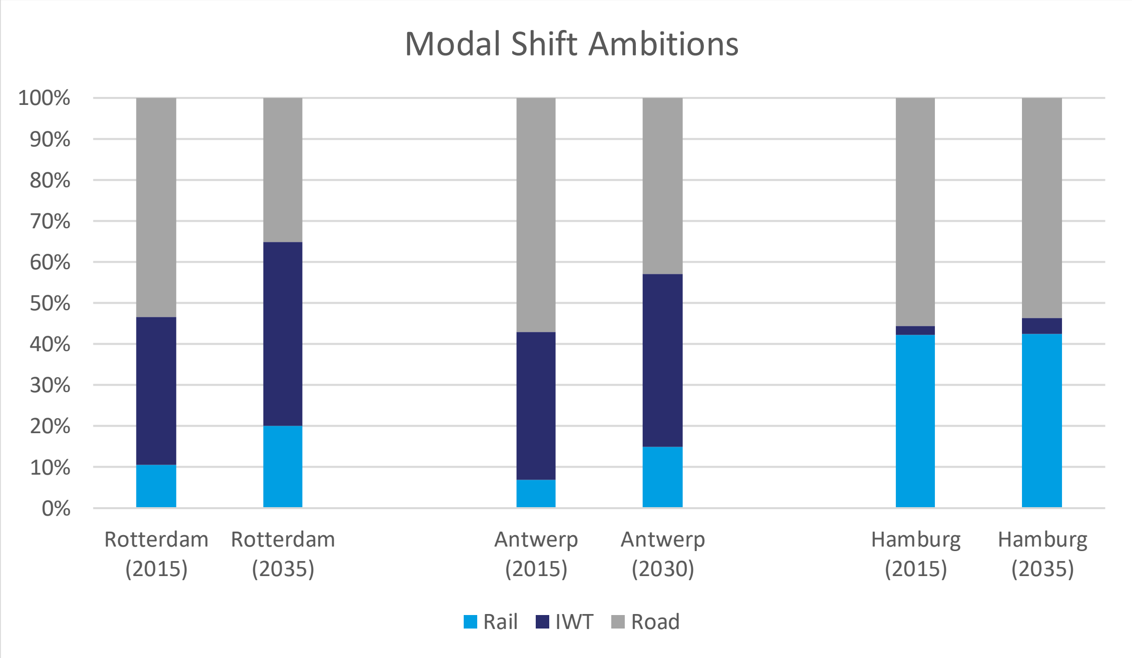

Figure 13. Modal Shift Ambitions [14]

In summary, understanding Modal-Split and Modal-Shift is crucial for developing transport systems that are both efficient and sustainable. While the modal split provides insight into the current distribution of transport demand across different modes, modal-shift strategies are essential for driving the transition towards more sustainable and balanced transportation networks.

The rail mode of transport is particularly emphasised here, as on the one hand there is greater complexity in the interaction patterns and on the other hand IWW functions are very similar to maritime shipping processes (see section 2).

4.2. Road Hinterland Link

Road transportation (also referred to as "trucking") represents the most prominent means of containerized hinterland transportation and thus relevant at almost every port terminal (see also Figure 12). Road transportation services and production systems can be differentiated according to the transport distances to be covered. On short distances, trucks are used to connect seaports and close hinterland destinations or logistics centres. In the case of very short distances, e.g., for inter-terminal transport, the production system is also referred to as "drayage". In the case of these short distances, road transport is often the only economical and technically possible alternative. On the opposite side of the spectrum, road transportation is also used for long haul connections, especially in the case of perishable or time-critical goods.

Trucking offers the advantage to provide high flexibility for customers, as containers can be picked up or dropped off in a responsive and non-scheduled fashion. Furthermore, it is considered a relatively fast way of transportation and can be used to complete door-to-door transport without the need for further transhipment. On the downside, road transportation carries higher direct as well as external costs [16] (such as pollution or accident-related costs). Especially in cases of highly frequented terminals and ports or hinterlands with poor or insufficient infrastructure, road transportation may also suffer from congestion and thus unreliability.

The physical interface between a terminal and the road transportation system is generally represented by truck gates, which ensure ISPS as well as transport contractual compliance. Entry to the terminal is granted based on the respective authorization to pick up or drop off containers. While this process used to be reliant on terminal personnel, more and more terminals utilize automated authorization mechanisms that make use of optical character recognition (OCR) technology (as discussed in section 2.4.2.1). A visualization of a state-of-the-art gate can be seen in Figure 14. The transfer of cargo from and to the truck's chassis is typically carried out at assigned interchange areas and by means of the existing yard equipment (see section 2.1.2).

Figure 14. Automated truck gate at container termina in Valencia

Even though some cargo owners operate own trucks, the majority of truck transportation is carried out by specialized container trucking operators that are hired by the shipper or an assigned party. This poses the problem of "intermodal disintegration" [17, p. 731], as terminal operators and truck operators have an operational but no contractual relationship. Due to the limited exchange of information and accountability, this may lead to uncertainty and missing coordination at the road hinterland link.

In order to improve coordination with truck operators, some port terminals have adopted organisational or IT-based measures. Organisational measures include financial incentives for truck operators to visit terminals outside of traffic peaks. One of the first initiatives of this kind is the OffPeak program at Long Beach, USA [18].

More commonly used are IT-based measures, such as electronic truck announcements that require truck operators to announce the drop of or pickup of cargo prior to the actual arrival. In combination with automated truck gates, this enables to exchange and check relevant information in advance and thus speed up the entrance and exits of trucks. One step further is the implementation of Truck Appointment / Slot Booking Systems (TAS/SBS) which mandate the determination of specific operational slots at the terminal. This way, the terminal is able to synchronize available equipment and landside handling capacity with actual truck arrivals. While first implementations of TAS/SBS relied on fixed time windows, more dynamic and flexible schemes (automated and short-term rebooking, swapping of slots) are increasingly being acknowledged as beneficial [19].

4.3. Inland Waterway Hinterland Link

While most ports worldwide are accessible via the road and rail transportation system, the handling of inland vessels is dependent on the geographical location and thus access to an inland waterway network. Within Europe, most inland waterway traffic relates to the Rhine corridor, which connects North Sea ports such as Antwerp and Rotterdam with inland ports in the Netherlands, Germany, France and Switzerland.

In inland waterway transport, the waterway infrastructure, such as rivers, canals, locks, and ports, is managed by entities known as waterway authorities or agencies. These authorities are typically government-operated and responsible for maintaining navigable waterways, ensuring safety standards, and facilitating the smooth movement of vessels. Key examples of waterway authorities in Europe include Voies Navigables de France (VNF) in France, the German Federal Waterways and Shipping Administration (WSV), and the Danube Commission for countries along the Danube River. The inland waterways are largely public assets, meaning their use is often less commercially segregated and more integrated into regional and national transport strategies.

The companies that operate the vessels and transport goods via inland waterways are known as inland shipping operators or carriers. These can be privately owned, publicly owned, or a combination of both. Inland shipping operators typically own or lease their vessels, which range from barges to more specialised ships for bulk goods, containers, or hazardous materials. These companies are responsible for providing the necessary services to transport goods along inland waterways, linking them with other transport modes such as rail or road at inland terminals.

One important characteristic of inland waterway transport is that it is often used in combination with other forms of transport, making it a key part of intermodal transport chains. Logistic service providers, freight forwarders, and intermodal operators play a crucial role in coordinating inland waterway transport with other modes, ensuring efficient and seamless transitions between ship, rail, or road.

Inland waterway transportation can be regarded as especially beneficial in terms of its energy consumption per tonne-kilometre as well transportation costs. On the downside, it is limited in speed as well as in its geographical scope which is defined by the existing and navigable inland waterway network. Also, as origins and destinations are not always located directly at inland waterways, an additional transport leg by truck is often required. Lastly, given limited routing possibilities, IWW is vulnerable to obstructions in the waterway network, e.g., outage or maintenance of locks or low and high-water conditions.

On the physical side, most seaport terminals handle inland vessels at the same berths and with the same equipment as deep-sea vessels [20]. Thus, transhipment procedures in general can be regarded as similar to deep-sea vessels (see 2.3) but are carried out on a smaller scale. Compared to seagoing vessels, different vessel types and combinations can become subject to port operations. Self-propelled motor cargo vessels are capable of independent navigation, allowing for relatively straightforward handling at seaports. In contrast, coupled convoys, consisting of a push boat and one or multiple barges, may require more complex planning and execution. Barges can be either processed separately from the push boat, which allows for flexible operations, such as staggered discharging or loading (Figure 15). However, this also necessitates additional coordination to manage berthing schedules and optimize terminal space. The decoupling of push boats and barges can increase operational efficiency but may also introduce additional handling time and resource allocation.

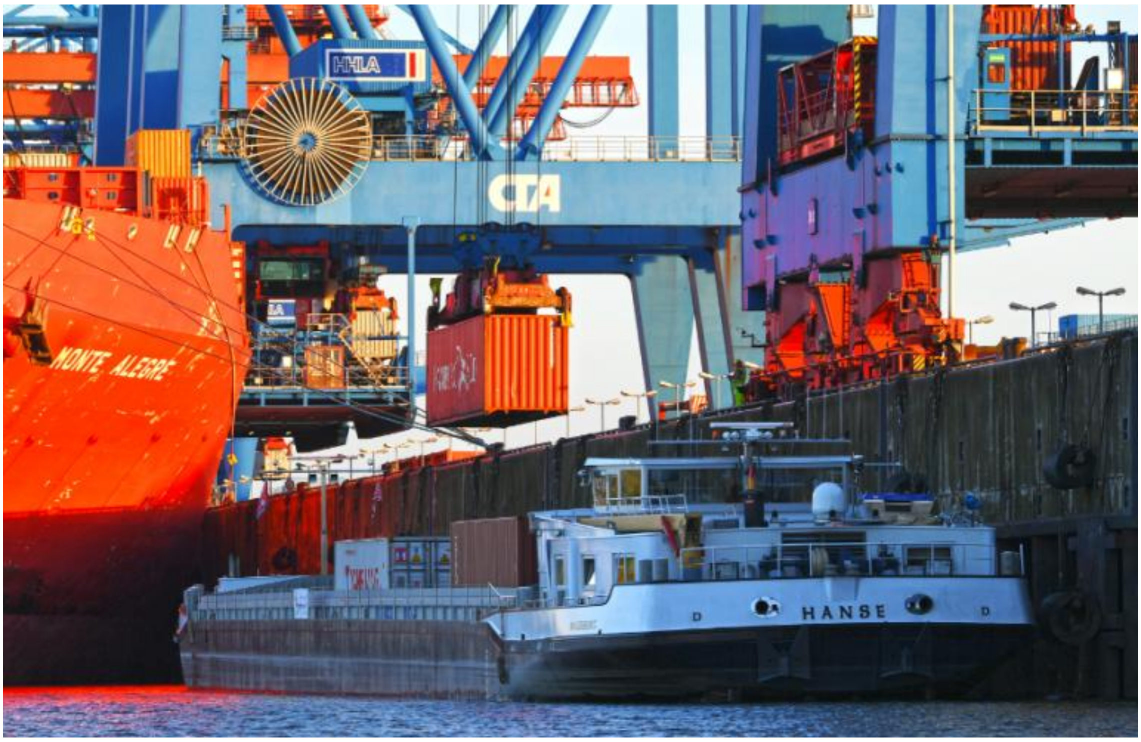

Figure 15. Handling operations on inland vessel at seaport

The common use of maritime and inland vessels combined with arrival uncertainty can pose significant problems. As deep-sea vessels occupy more space as well as handling equipment and work under tighter nautical restrictions, they are handled with highest priority. This is also due to the fact, that ocean carriers represent the main customers of terminal operators, leaving inland vessel operators in a weaker bargaining position [20]. The lack of dedicated equipment to serve inland vessels in combination with low transhipment volumes and call sizes also leads to poor use of waterside handling equipment and thus low berth productivity of the terminal. From the perspective of inland vessel operators, waiting times may result as a consequence. In cases of multi-terminal visits, delays may also affect subsequent calls, causing a “domino-effect” [20]. As longer port turnaround times and unreliability lead to reduced inland vessel performance, this situation may weaken the competitiveness of inland waterway transport.

An organisational measure to increase the amount of cargo to be handled during deep sea terminal call is the use of consolidation hubs that bundle containers per terminal. However, while this may improve the situation for terminals and increase reliability, additional transhipment leads to higher costs and transport duration. Another structural approach which focusses on the improvement of reliability is the provision of “fixed time windows" for inland vessels at seaport terminals as well as dedicated berths and crane equipment to handle inland barges [21].

Technical solutions to improve coordination and provide for better flexibility in case of delays in multi-terminal scenarios is the use of centralized integral rotation planning systems, such as NextLogic in the Port of Rotterdam [22]. This is in line with digital solutions for data exchange (e.g., electronic port call and lockage announcements), booking of port services, passage planning as well as real-time tracking of inland vessels as provided by the APICS platform in the Port of Antwerp [23].

4.4. Rail Hinterland Link

4.4.1. Rail Freight in Europe

Rail connections are crucial for container terminals due to their role in enhancing efficiency, reducing costs, and supporting sustainable transportation. This mode of transport plays a particularly important role over long distances and offers advantages in various segments of the transport chain, economically and ecologically. Rail connections contribute to increased capacity and throughput at ports. By handling higher volumes of cargo, rail-connected terminals can manage growing trade volumes without overwhelming local road networks. Moreover, rail systems help to optimize space within ports, allowing for better planning and management of cargo flows.

Compared to trucks, transport by rail is more cost-efficient, as economies of scale can be used very effectively. A much larger number of containers can be transported per trip by rail than by truck, which can drastically reduce transport costs per unit. The longer the route, the more this effect comes into play. In addition, direct rail links to container terminals often reduce the need for multiple handling operations, thereby lowering overall logistics costs. On the downside, rail transport is not as flexible as road transport. It requires a considerable amount of coordination and communication between the involved parties: cargo owner, railway operator, railway infrastructure manager, harbour railway operator, shunting service provider, and terminal. In order to ensure safe and efficient rail operation in the port, most of the involved processes have been digitalised and in parts automated.

From an environmental perspective, rail transport is generally more fuel-efficient and produces fewer emissions per ton-mile than road transport, at least if you only consider the primary energy consumption. If the emissions from energy generation are included or if diesel-powered locomotives are involved, the question of sustainability can be answered less clearly. Nevertheless, as renewable energy sources become an increasingly important part of the electricity mix in Europe and ports seek to reduce their carbon footprint, intermodal rail transport will also play an increasingly important role [24].

The organisational structure of rail freight in Europe is profoundly different from inland shipping or road, especially when it comes to sea borne containers. Apart from port authorities that manage the integration of rail and road into the port, or terminal operators that connect seaborne trade with rail or road, the structure and organisation of the rail network itself consist of several key entities.

In European rail freight, whereas ownership of rolling stock and operation of that stock can be done by the same or separate entities, the ownership and responsibility of the rail infrastructure is typically separated.

Entities that are responsible for managing and maintaining the rail infrastructure are called Infrastructure Managers (IM). They operate independently from transport companies and are typically, with some exceptions, state-owned. Germany, for example, as country with the largest rail infrastructure in the EU, has a total of 440 of these IMs [25]. The largest one is the DB InfraGO AG that operates a major part of the public rail network in Germany. Other European counterparts are e.g., ADIF (Spain), SNCF Réseau (France), or RFI (Italy).

The actual freight transportation services are done by so called Railway Undertakings (RU) that are basically freight operating companies. These operators can be either publicly owned, private, or a combination of both. These entities transport goods, including containers, across the rail network. A basic requirement of an RU is that the undertaking must ensure traction and also includes undertakings which provide traction only [26] (European Railway Agency, 2015). An RU can either own its own rolling stock or can lease the stock from a leasing company. Important for the differentiation to be an RU is not the ownership of the stock, not even the physical operation of the locomotive is necessary, but solely the provision and arrangement of traction, even if that traction is subcontracted to another RU. In Germany, for example, there are close to 700 licensed RU [25].

Other key players involved in rail freight, e.g. logistic service providers or intermodal transport operators, are regarded as *companies involved in a rail-transport chain* [26]and often act as intermediates between shipper and RU, similar to road or inland shipping.

4.4.2. Logistics Concepts in Rail

Various production concepts have become established in combined transport involving rail, which differ in terms of their composition and their bundling principles. The individual train relations for containerised hinterland transport are mainly based on the following bundling principles and its subtypes [13]:

- Direct train
- Hub-and-spoke-systems

A **direct train** is a train that runs from a starting point to a destination without intermediate stops or reloading. It is suitable for transport operations where a fast and uninterrupted connection between two points is required. Direct trains offer high efficiency and reduced transit times, as they carry out the transport without the usual delays caused by changing or reloading [27]. In combined transport, especially in hinterland transport from large container terminals, there are different subtypes of direct trains that fulfil specific requirements divided into **shuttle trains** and **block trains**.

With the **shuttle train**, fixed carrier wagon sets, typically around 70-90 TEU [28], shuttle between two combined transport terminals without intermediate shunting and without intermediate stops. It is therefore the most productive form of rail production but can only be used on routes with a correspondingly high volume, preferably in pairs [13]. **Block trains**, on the other hand, are adjusted to the actual volume on a daily basis, resulting in shunting costs that are offset by better utilisation of the rolling stock used [13]. Figure 16 shows the difference between the two types of direct trains.

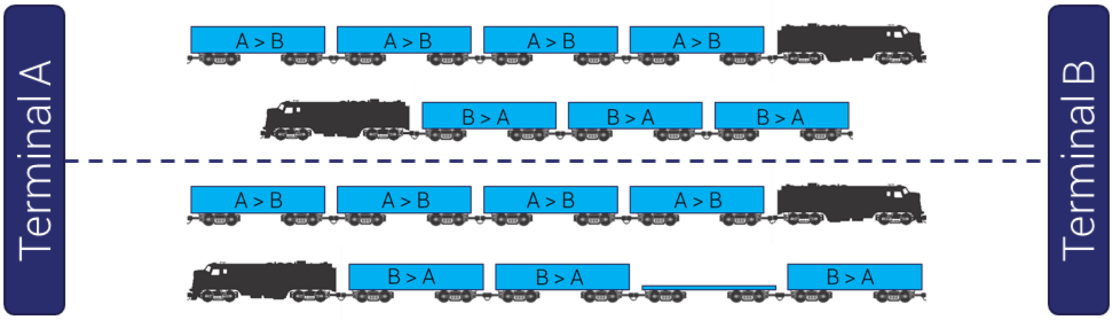

Figure 16. Block train (top) vs. shuttle train (bottom)
Source: ISL based on Ruesch et al., 2005

Hub-and-spoke-systems are characterised by the fact that containers with different destinations are transported in one train. The shipments come from different start terminals and are then bundled in a central hub and reorganised according to the respective destination terminals. Sorting by destination can be done either by vertically handling the containers using a gantry crane, container stacker or reach stacker, for example, or by manoeuvring the wagons [13]. It is possible for trains from one hub to be further consolidated in another hub [27]. In a hub-and-spoke system in seaport-hinterland transport, shunting is always necessary. Figure 17 shows a simplified illustration of a hub & spoke system.

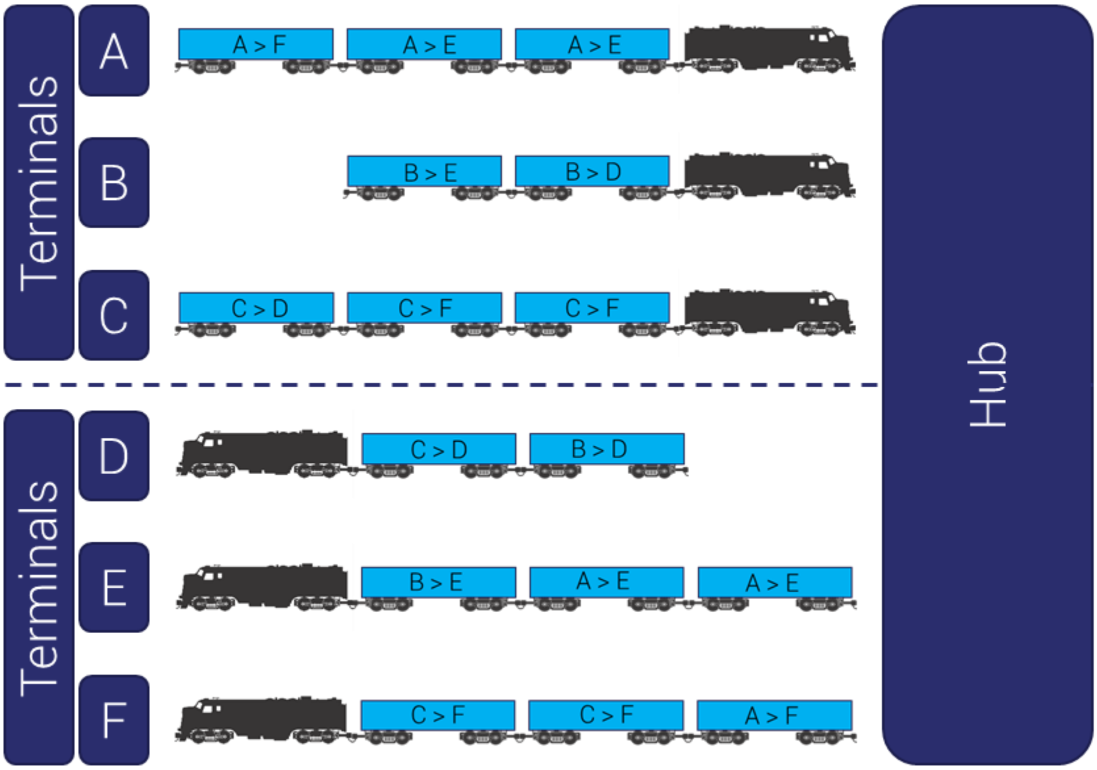

Figure 17. Hub & Spoke system
Source: ISL based on Ruesch et al., 2005

4.4.3. The rail terminal in the seaport

The typification of rail terminals in container ports is not standardised. In his analysis of trimodal transport chains, [13] proposed a typification of rail terminals that distinguishes between four terminal types with regard to how the terminals are connected to the hinterland transport by rail:

- Direct Handling Terminal
- Integrated Terminal
- Adjacent Terminal
- Port Terminal

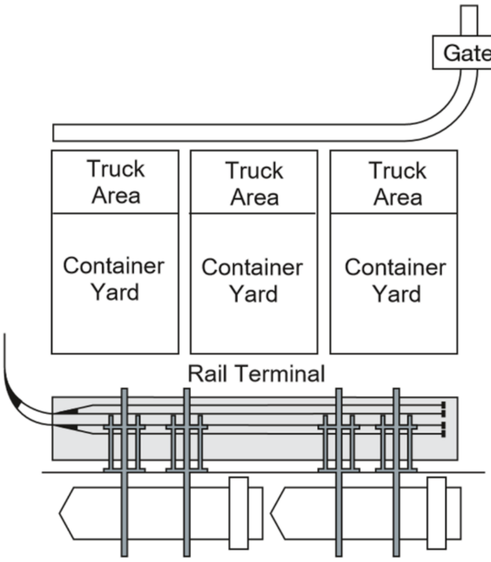

Figure 18. Direct handling Terminal [13]

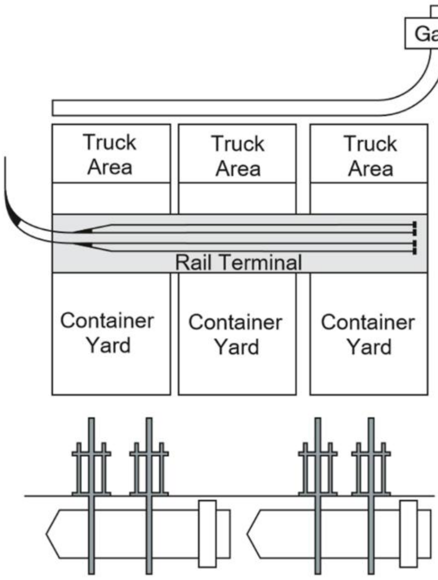

Figure 19. Integrated terminal [13]

At the **direct handling terminal** (see Figure 18), the tracks are located directly at the quayside, so that direct handling from the ocean-going vessel to the train is possible without prior storage of the containers. From the point of view of hinterland transport, this form represents the optimum connection. In maritime terminals, however, high transshipment productivity on the ocean-going vessel has the highest priority, which would be hindered by direct transshipment to rail. For this reason, direct handling is usually not found in modern container terminals [13].

The **integrated terminal** (see Figure 19) is characterised by the fact that the tracks are located within the storage area of the Maritime Terminal. The carrier wagons are loaded in the same way as trucks are loaded with van carriers. The disadvantage of this type of terminal is that a great deal of effort is required to divide the trains in order to create passages for the van carriers at reasonable intervals [13].

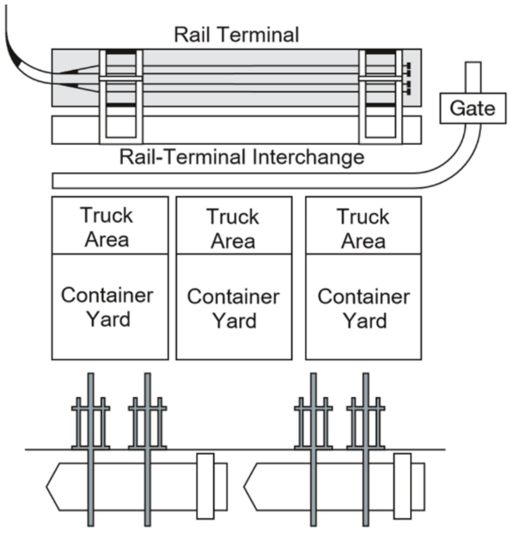

Figure 20. Adjacent terminal [13]

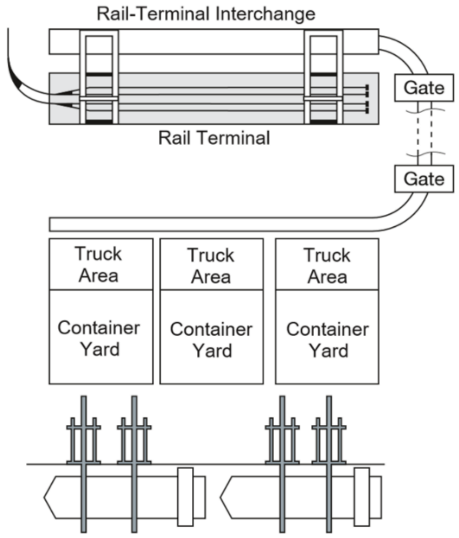

Figure 21. Port terminal [13]

In the **adjacent terminal** (see Figure 20), the loading tracks connect to the intermediate storage area of the maritime terminal. In this type of terminal, gantry cranes are normally used for loading and discharging. This requires additional handling of the containers, as the transport from the container store to the transhipment area is separate from the transhipment to the train or inland waterway vessel. As a differentiation from the port terminal described in Figure 21, it is defined that there are no restrictions from the road traffic regulations for the transport vehicles used for transport between the maritime terminal and the rail terminal. This enables, for example, the use of so-called multi-trailer systems, with which up to 10 TEU can be transported by one driver [13].

A **port terminal** (see Figure 21) is located anywhere in the port area. Containers are transported between the maritime terminal and the hinterland terminal by truck or, more rarely, by rail. In addition to sea containers, loading units of continental trailers (swap bodies, semi-trailers) are usually also handled in a port terminal [13].

4.4.4. The information flow in rail hinterland link

While the information flow regarding the loading and discharging operations are typically supported by the TOS, the administration of the movement of trains in the port area typically is not. Most ports have implemented software for the planning and operation of rail services in the port, which supports a number of tasks:

- Slot management
- Train composition announcement
- Loading - and discharging - orders including handling instructions
- Inspection of incoming and outgoing trains
- Dispatch (plan container on railcar)

The concrete workflow differs from port to port. Typically, information is exchanged between the following involved stakeholders:

- Freight forwarder
- Railway undertaking
- Shunting service provider
- Terminal
- Port railway

In the following, exemplary information flows are shown. Depending on the port terminal, process design and organisational structure, various different entities may be involved. These entities can be publicly or privately owned. For example, could the entire railway network in the port area could be managed and operated by the port railway, which could be a subsidiary unit of the port authority and thus being in public ownership. The shunting operations could then be carried out by various private shunting service providers. In such an example, the railway undertaking for the long haul would not normally enter the port area itself. However, any other combination of organisational structure and process design is also conceivable

Table 2. Inbound Train

Information	Sender	Receiver
Train announcement	Railway undertaking / Freight forwarder	Port railway
Arrival Information	Shunting service provider	Terminal
Train composition / inspection results	Terminal	Port railway
Container unload info	Terminal	Port railway / Freight forwarder

Table 3. Outbound Train

Information	Sender	Receiver
Loading order	Railway undertaking / Freight forwarder	Port railway
Container Dispatch	Port railway	Terminal
Container load info	Terminal	Port railway / Freight forwarder
Inspection results	Terminal	Port railway
Train ready	Terminal	Shunting service provider
Departure Information	Shunting Service Provider	Terminal

Currently there is no national, European or international standard for data communications regarding rail operations in the port. Hence, most ports have implemented proprietary systems and local or regional standards for data exchange formats. Some examples of systems in European container ports are:

- Port of Hamburg: TPR (formerly known as HABIS); Format: TD04
- Port of Bremen & Bremerhaven: CODIS / PRINOS; Format ANHA & TPA
- Port of Rotterdam: HCN Rail; Format: Web Interface (see Figure 22 for information flow)
- Port of Valencia: European standard TAF-TSI

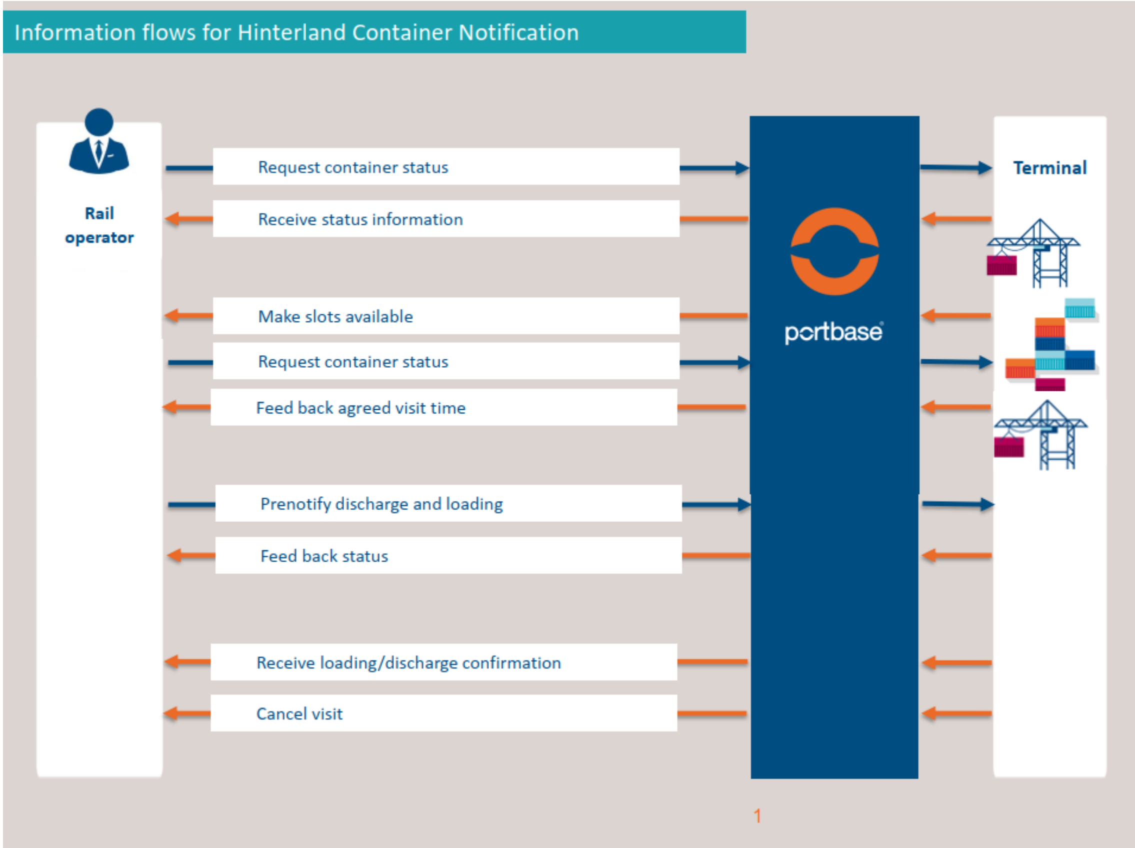

Figure 22. information flow in the port of Rotterdam [29]

5. Evaluation and recommendations

The SEAMLESS project outlines a comprehensive approach to enhancing port cargo handling through automation and digital integration, targeting operational efficiency and environmental sustainability across short-sea and inland waterways. This deliverable has examined the key elements of port operations, including equipment, digital systems, and communication interfaces that are essential for efficient terminal operations.

The project's scope extends from maritime and inland waterways cargo handling to hinterland connections, emphasizing the need for advanced technologies like Vessel Stowage Systems and real-time data exchange frameworks to facilitate streamlined, efficient processes. By focusing on automation in port equipment and integrating real-time data exchange in cargo operations, SEAMLESS aims to reduce bottlenecks and improve synchronization among key stakeholders, including shipping lines, terminal operators, and hinterland transport providers.

Moreover, innovations in multimodal logistics support a strategic shift toward sustainable transport modes, such as rail and inland waterways, reducing the environmental footprint of port operations. The anticipated implementation of advanced scheduling and digital tools, combined with structured cargo flows, promises to meet both operational demands and environmental regulations.

5.1. Autonomous processes evaluation

SEAMLESS project has identified several autonomous solutions which can improve the efficiency. This section describes the required changes to the port processes that will enable the full integration of autonomous cargo handling and mooring technologies.

5.1.1. Autonomous Ship management

Autonomous vessels represent a transformative advancement in maritime operations, utilizing automation and remote-control technologies to enhance efficiency, safety, and sustainability. As the level of automation increases, so does the role of the Remote Operation Centre (ROC), which serves as the primary hub for monitoring, controlling, and managing these vessels. The ROC functions as a shore-based control centre where operators oversee vessel operations, provide remote navigation support, and intervene when necessary to ensure safe and efficient voyages.

Functions and Capabilities of the ROC

The ROC's responsibilities depend on the level of automation of the vessel. In its low-attention mode, operators monitor multiple vessels simultaneously by tracking their navigational status, system health, and potential risks. If an issue arises, the system can alert operators, prompting a shift to high-attention mode. In this state, the ROC acts similarly to a remote-control centre, allowing operators to take direct control of a vessel's navigation, manoeuvring, and emergency response.

Within the SEAMLESS research project, an advanced ROC is being developed, integrating workstations for vessel operators, computing infrastructure for data processing, and network and power management systems. A key focus is on defining high-attention modes, establishing protocols for transitioning control between operators or ROCs, and ensuring seamless vessel handover procedures.

Advantages and Future Potential

The integration of autonomous vessels with a ROC enhances maritime safety, as operators can monitor multiple ships with greater situational awareness and respond to emergencies remotely. Operational efficiency is improved by optimizing vessel routes and reducing human workload. Additionally, remote operation reduces the need for onboard crew, lowering labour costs and mitigating risks associated with long voyages.

Looking ahead, further advancements in artificial intelligence, sensor technologies, and real-time data processing will enable greater autonomy in vessel operations. The continued development of ROC systems will be crucial in ensuring safe, coordinated, and efficient maritime transport, ultimately shaping the future of the shipping industry.

5.1.2. Autonomous Vessel Stowage

The changes required in autonomous vessel stowage as a high-level operation can be divided into changes in planning phase, execution phase and for physical equipment.

1. Planning phase

The changes required for autonomous vessel stowage in the planning phase are related to the information exchange between operating systems. The required systems that need to share information are the booking system and the vessel scheduling system. The main outcome from the planning phase is to ensure that the vessel is worthy of sailing and that the discharging and loading sequences are created for the execution phase. The information within these lists is included with Quay Logical Position that indicates the first or last landing spot of the container on the quay while it is discharged or loaded respectively.

2. Execution phase

During the execution phase the above-mentioned sequence lists are shared with Terminal operating system (TOS). Terminal operating system is then using the QLP information to create work orders for the autonomous terminal equipment. As the vessel is moored the vessel operator can initiate discharging process by communicating with TOS.

3. Physical equipment

In addition to the operating systems, the physical equipment needs to have autonomous functions built in. For land-based equipment, these functions include the possibility to receive work orders from TOS and, whilst in operation, update time stamps for each operation. In case discharging and loading is commenced with on-board crane, the crane needs to be able to receive workorders in a similar manner than the land-based equipment but from the vessel operating system. Within SEAMLESS project the vessel system is VCOP, that is able to communicate the timestamps further with TOS.

4. Information exchange

The machine-to-machine connections are to be executed through API REST functions. It's notable that the typical EDIFACT files should not be used as the file structure have certain limitations which does not support automation.

5.1.3. Autonomous mooring

The SEAMLESS project focuses on the gradual and efficient introduction of automated mooring systems. Among the various solutions available, those that require modifications to the ships themselves rather than extensive changes to port infrastructure are considered more practical for incremental adoption.

1. Ship Layout Modifications

One of the primary changes will be on individual ships to accommodate automated mooring systems with the integration of specialized equipment for mooring. These robots are designed to handle mooring operations autonomously, eliminating the need for manual intervention in the process. Installing such equipment will necessitate adjustments to the ship's layout to provide dedicated space for these systems. These modifications may include reinforcing specific areas of the deck, rerouting certain utilities, and ensuring that the robotic systems have unobstructed access to the mooring lines and connection points. While these changes represent an upfront investment, they are localized to the ship, avoiding the broader logistical challenges associated with infrastructure upgrades at ports.

2. Reduction in Personnel Requirements

Automating mooring processes will reduce the need for crew involvement in these tasks. Traditionally, mooring operations require a team of skilled personnel to manually handle lines, often under physically demanding and hazardous conditions. By replacing manual processes with robotic solutions, the number of crew members required for mooring can be minimized, leading to cost savings and a reduction in occupational risks. However, it is essential to provide adequate training for the remaining crew to service and maintain the automated systems. This shift will necessitate a focus on upskilling and familiarizing personnel with the new technologies to ensure smooth operations.

3. Comparative Advantage of Ship-Based Solutions

Unlike other automated mooring technologies that demand extensive and costly changes to port infrastructure, ship-based solutions offer a more flexible and scalable pathway. These systems allow for the gradual adoption of automation across the shipping industry without requiring ports to overhaul their facilities entirely. By concentrating modifications on the ships themselves, the SEAMLESS approach ensures that port processes remain largely unaffected, facilitating a smoother transition for stakeholders.

4. Safety Improvements

A significant benefit of automated mooring systems is the enhancement of safety for personnel. Traditional mooring operations are among the most hazardous tasks performed by ship crews, exposing them to risks such as heavy loads, moving lines, and adverse weather conditions. Automation removes crew members from these high-risk scenarios, reducing the likelihood of injuries and accidents. However, the introduction of advanced technologies also presents new safety challenges. Crew members must be trained to monitor, troubleshoot, and maintain these systems to prevent operational failures. Ensuring a comprehensive understanding of the automated equipment is vital to maintaining safety standards during and after the transition.

5. Minimal Impact on Port Processes

Since the proposed changes are confined to the ships, port processes and operations will remain largely unaffected during the implementation phase. This approach eliminates the need for extensive coordination between ship operators and port authorities for infrastructure upgrades, ensuring continuity in port services. Ports can continue to accommodate a mix of traditional and automated ships without significant adjustments to their workflows, making this solution particularly attractive for widespread adoption.

5.1.4. Autonomous port cargo handling

To achieve autonomous port cargo handling for over the railing operation the changes required can be divided into planning and operational level.

1. Planning

To automate planning process the actual operation processes are to be streamlined so that the all the sequences are optimised. After the sequences are optimised, sequential executions processes and work orders can be derived. By doing this it's possible to receive automated status updates as the operations are executed.

2. Manual operation

Below are described the main processes that require manual operation for container and Roro vessels considering loading and discharging operations.

- Container handling
  - Lashing onboard (lashing bars, turn buckles)
  - Hatch cover operation (not required if cell-guides used)
  - (un)loading containers by crane
  - De-coning at quay side
  - Cargo operation monitoring / securing acceptance
- Trailer handling
  - Trailer securing (trestle, chains, belts, releasing breaks)

- Folding ramp operation
- Trailer loading (tow master, truck)
- Cargo operation monitoring / securing acceptance

3. Autonomous operation

Considering the lashing equipment operation on a container vessel, the most effective way to achieve high level of automation is to use cell-guide structures, from tank top up to the topmost container. Use of cell-guide structures also removes the problem of (de)coning operations as twistlocks are not needed. Whereas the folding ramp operation within the RoRo vessel can be automated by using sensor technology even for existing vessels.

The most problematic part of the actual process is connecting the lifting/moving equipment to the cargo unit. Considering RoRo vessels this would mean automating the coupling process between the trailer and the AGV. In other words, autonomous trestles should be described and implemented. Semi-automatic trestles do exist, but they lack the autonomous interface for coupling process.

Autonomous (un)loading of containers requires additional censoring so that the container spreader corners can be fitted to the corner castings of the container itself. This is relatively easy to achieve considering picking up the container. The problem is to detect the correct landing spot when the container is hanging from the spreader, and container should be placed on top of another container within millimetres' accuracy. The problem can be reduced by using cell-guides on board. However, the accuracy problem persists if the containers are to be stacked to the quay side without supportive structures. To overcome this problem SEAMLESS is studying alternative crane construction.

In any case, all operations, manual or autonomous, must be monitored, so that aborting dangerous operations can be made possible. Considering this, autonomous equipment needs to have properties that will ensure that nothing or no-one is the vicinity of the operational area. Adding security, physical or cybernetical, requires even more censoring. Having said that, the easiest way to make any operation autonomous is to reduce the amount of equipment used.

5.1.5. Autonomous terminal

In previous chapters, the main processes carried out within a terminal in its most traditional form have been described in detail, highlighting how these are executed through the interaction between various systems and equipment. In all cases, each of these processes is performed manually, even though different systems are in place to facilitate process management. Despite this, decision-making and execution remain tasks that require active human intervention.

When transitioning from a manual process to an automated one, the key transformation lies in eliminating the need for a person to carry out the various tasks demanded by the process. This shift requires equipping the governing systems with decision-making capabilities to autonomously manage the different components of the processes. This is the main change that must be addressed not only for the management of the terminal's own activities but also due to the need to interact interdependently with the rest of the autonomous cargo handling activities. This section will describe the most appropriate structure according to the variety of systems and the corresponding forms and functionalities with which the terminal will interact to ensure the proper handling of cargo autonomously within the terminal.

5.1.5.1. Functional Hierarchy

In chapter 2.4, the fundamental characteristics of port terminal operations, their elements, and the systems that support these operations were detailed. However, to understand to what extent the governance of operations must change within an autonomous operations framework, it is necessary to analyse it from a functional perspective. The following are the five main functions of a container terminal [30].

1. ***Planning level***

The first phase focuses on operations planning — a function that, although previously described, remains fundamentally unchanged within an autonomous terminal framework. However, the key transformation lies in equipping systems, such as the TOS, with the necessary algorithms to autonomously perform various planning tasks based on the core requirements of each planning area (Berth, Vessel, and Yard). The following table provides a detailed description of the planning process for each area, the data supporting these plans, and the systems potentially capable of executing these functions.

Table 4. Operation planning level

Planning Process	Supporting Data	System Solution
Berth planners assign space and time windows to vessels based on Carrier SLAs.	• Schedule Proforma • Vessel Geometry	• TOS • In-house Solutions
Vessel planners sequence containers and assign them to cranes and shifts for a vessel.	• Crane Split	• New Optimization solutions
Yard planners establish the rules for container grounding and for discharge and selection of loads.	• Work Queues • Yard Allocations • Gate throughput demand	• Sometimes Simulation tools

2. Scheduling level

Once the planning phase is established, the next function in the overall process is scheduling. Scheduling involves converting the planning into execution by determining the optimal allocation of Container Handling Equipment (CHE) to perform each move efficiently. In essence, scheduling focuses on selecting the best combination of equipment and resources, considering operational priorities, real-time conditions, and the need to maximize productivity and minimize delays.

Table 5. Scheduling level

Scheduling Process	Supporting Data	System Solution
From generated work queues and work instructions in the Planning process, the scheduling process is calculating the best assignment coupling CHE with Move - the scheduling models can run with long-term (hours) or short-term (minutes) assignments.	• Terminal geospatial model • From and To Position • EMTs windows • Work Queues (WQ) • Work Instructions (WI) • Transfer Areas • CHE fleet and pools • Routing Possibilities (physical) • Driving Distances (& times)	• TOS or ECS (Equipment Control System) • External solutions for Optimization

3. *Dispatching level*

Once the operations plan has been established and the optimal equipment combinations identified during scheduling, the next step is to dispatch the instructions to the most suitable CHE to ensure the efficient execution of each movement.

Table 6. Dispatching level

Dispatching Process	Supporting Data	System Solution
From generated CHE-Move assignment at Scheduling Process, the Dispatching process is realizing the move, ready for execution. It means it initiates the move of the CHE - and as part of this process different dispatch validations can be executed such as, move feasibility or cross-checking specific business rules (e.g. container #ID mismatch).	• CHE Status • Wok Instruction (WI) Status • Work Order (WO) • Routing Plan • Transfer Zone & Point Status • Area Restrictions • Assistance functions (remote) • Traffic Control • Any other business rule	• TOS • ECS

4. *Move Execution level*

The execution level of the movement is, ultimately, the physical realization of the previous steps. It involves transferring a load from one point to another within the terminal under the conditions defined during planning, using the assigned CHE in the optimal sequence and within the designated timeframe.

Table 7. Move Execution level

Move Execution Process	Supporting Data	System Solution
From generated Move generated in Dispatching Process, move execution makes the move happen in physical terms but also implies monitoring and control of the move. Also with regard to the movement itself (and its safety) and the parameters related to machinery stress, energy and other parameters.	Exceptions Handling: • Area Restrictions • (Remote) Assistance • Traffic Control • Any other business rule	• CCS (Cargo Community System) • ECS

5. Status reporting

Finally, for all these processes to be carried out effectively, real-time monitoring of the status of each CHE is essential. This information directly impacts how the CHEs are utilized, as well as when and for how long they will be deployed.

Table 8. Status reporting level

Status Reporting Process	Supporting Data	System Solution
The ECS, or any other CHE sub-system (e.g., CCS or PLC), reports status and conditions about the CHE, or eventually a decision process. This information is important at different stages for the automated functions properly generating their required output: as well as for automation being flexible to react to operational changing circumstances.	• CHE Status • Work Instruction (WI) or Work Order (WO) Status • Geometry Parameters • Transfer Zone & Point Status	• CCS • ECS • IoT

5.1.5.2. System Architecture

Once the different functions responsible for each stage of terminal operations have been defined, a governance structure for these operations must be established. This involves defining the system architecture and interactions with the environment that respond to operational needs, meeting the necessary safety, quality, and efficiency standards. Due to the lack of a standardized reference for building autonomous terminals, the market displays a wide variety of solutions. Therefore, in order to create the most generic framework that represents the needs of the SEAMLESS project, the system architecture will be developed following the ISA-95 standard due to its adaptive nature to a system with multiple connected actors communicating through different interfaces.

International Standard: ISA-95

ISA-95 is a globally recognized standard designed to optimize the integration of enterprise and operational systems. This framework provides a structured approach to connecting business processes with operational systems. While originally developed for the manufacturing industry, its flexibility makes it equally applicable to other sectors, such as port terminals, where seamless system integration is essential.

The primary goal of ISA-95 is to define clear relationships and activities across the various levels of an organization. It bridges the gap between enterprise systems, such as ERP, and operational systems, including TOS and Maintenance Management Systems (MMS), ensuring a smooth flow of information. Additionally, the standard delves into technical details, encompassing sensors and physical processes, offering a comprehensive approach to system integration.

ISA-95 models are invaluable for identifying key data exchanges between systems managing business functions—such as sales, finance, and logistics—and those overseeing operational aspects, such as production, maintenance, and quality control. By leveraging UML (Unified Modelling Language) models, the standard facilitates the development of standardized interfaces, enabling consistent and efficient communication between ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) systems. This adaptability makes ISA-95 a powerful tool for defining user requirements, selecting MES vendors, or designing MES databases and solutions.

A defining feature of ISA-95 is its hierarchical structure, which organizes technology and processes into levels, with each representing a distinct layer of functionality (International Society of Automation, 2024):

- Level 0: Physical production processes.
- Level 1: Sensing and manipulating the production process.
- Level 2: Monitoring and supervising control.
- Level 3: Operations management.
- Level 4: Business planning and logistics.

The versatility of ISA-95 not only enhances system integration in manufacturing enterprises but also supports other industries in aligning operational and business objectives. This makes it a practical and effective tool for sectors like port terminals, where efficient coordination between systems is critical for success.

Implementation of the ISA-95 standard in the context of a port terminal.

When framing the processes of port terminals within the ISA-95 standard, it is necessary to identify which level of the standard each function belongs to based on its nature. This classification will also allow defining the subsequent interconnections between different levels and how they will be implemented.

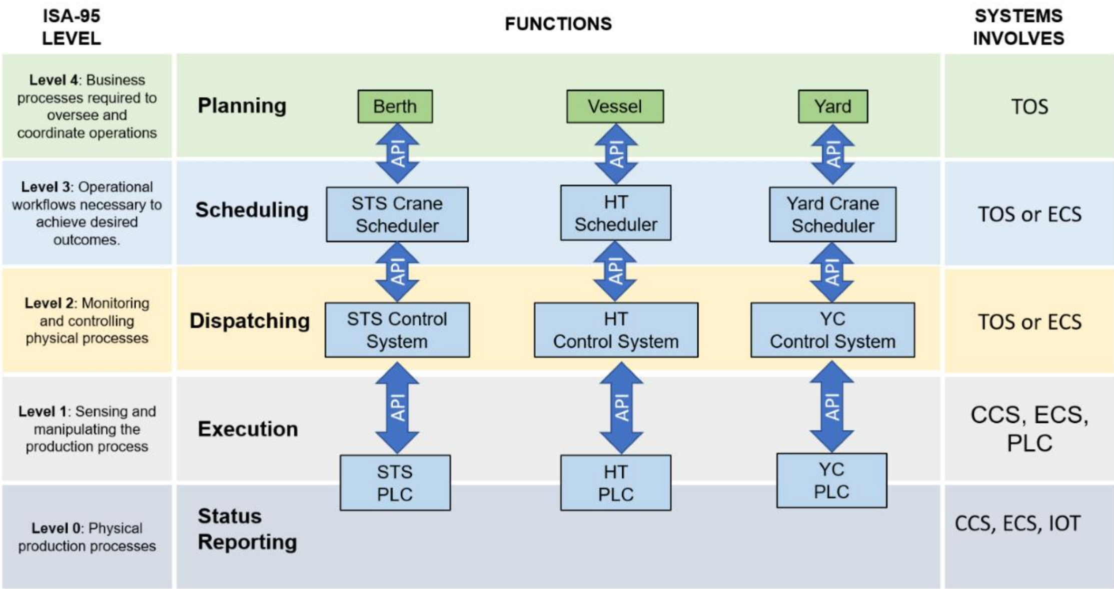

Figure 23. Implementation of the ISA-95 standard in a port terminal [30]

As shown in Figure 23, Level 4, which is described as the management and planning of resources to meet operational needs, corresponds in the context of port terminals with the planning function for the three main areas (berth, vessel, and yard). It is important to note that prior to this step, there are loading and discharging orders coming generally from ship agents, which according to D2.2 [2], in the case of SEAMLESS, the VCOP system plays the role of stowage planner responsible for transmitting this information.

As for the next level in the ISA-95 classification, which deals with scheduling and creating work orders with the necessary instructions for planning execution, it is directly associated with the Scheduling function in the context of terminal operations. This involves specifying the required types of equipment (such as STS, Horizontal Transport, or Yard Cranes) and establishing connections with the previous level in terms of Berth, Vessel, or Yard planning.

Regarding Level Two, which involves monitoring and controlling physical processes, the dispatching function is closely associated with this level as it represents the phase closest to the physical process. It facilitates the transition of work orders to the actual execution of operations, directly transmitting them as commands to the different CHEs that were established by the scheduler in the previous phase. At this level, real-time communication between the CHEs and the dispatching systems is crucial, as actions depend on the state of operations as they unfold. This implies a significant integration of IoT elements and sensors that provide the Dispatcher with the necessary information to optimally allocate resources according to the current needs.

Levels 1 and 0 correspond to the function closest to the execution of physical processes, in the case of terminals, this involves loading, discharging, and moving cargo, as well as monitoring the status of CHEs both before and after these activities. As seen in Figure 23, both execution and reporting of status are included at this level. The systems involved in this phase are primarily the CHE's PLCs in communication with the process management systems, whether ECS or TOS, depending on which system is assigned the function.

In this framework, the most significant changes to be implemented lie in the interaction between the various levels of automation. The evident high degree of interdependence necessitates a structured, precise, and secure management of the information flow. Human intervention in these processes should be minimized, focusing solely on incident management and process optimization rather than direct management of the operations themselves.

To address this need, the structure designed in accordance with the ISA-95 standard incorporates the development of APIs that act as bridges between the different systems. APIs, by their very nature, offer flexibility, enabling their implementation regardless of which systems perform specific functions. This adaptability ensures seamless integration across diverse platforms, fostering interoperability and scalability within the automated framework.

In conclusion, given the widespread existence of management systems capable of operating autonomously, the most significant step forward for modern terminal operations lies in enhancing the communication and integration between the various systems governing different functions. Achieving seamless, collective operation in a secure environment with higher levels of quality and efficiency than traditional processes require a robust approach to interoperability.

The development of specific APIs tailored to the unique requirements of each function presents a sufficiently flexible and universal solution. These APIs can be applied across diverse contexts and architectures while addressing the specific demands of terminal operations. This approach not only facilitates efficient coordination but also ensures scalability and adaptability to meet evolving operational needs.

5.2. Standard communications

Communications in such a fragmented environment are often characterized by high levels of complexity, posing challenges to maintaining operational security, ensuring effective message transmission, and achieving accurate semantic interpretation. This is particularly true in port terminal operations, where information flows between people, equipment, and systems. As a result, communications must possess the necessary attributes to reach their intended recipients as efficiently as possible.

To achieve this, it is essential to consider the systems involved, information protocols, data formats, and semantics. In addition to understanding these elements, striving for the greatest possible standardization is crucial to reduce the effort required for data adaptation and interpretation during the various operational processes. This becomes even more critical when external stakeholders are involved entities that both provide and rely on the data exchanged with the terminals.

As described in the systems overview of terminal operations, which have traditionally been manual, current communications are largely non-automated. They primarily rely on VHF radio communication between individuals to coordinate activities and VMTs to transmit work orders from the TOS to CHE operators for execution. Regarding communication with other stakeholders, methods such as emails and phone calls are predominantly used. In terms of information semantics, only standards like EDIFACT for Ship-to-Port communication are widely adopted in practice. Most other operational communications lack a standardized framework to harmonize exchanges effectively.

This disorganized approach to communication is not suitable for autonomous operational environments, where all parties must have prior knowledge of the message types, formats, and systems to be used for various tasks. In such settings, there is no room for reinterpretation, as communications are expected to be unambiguous.

This section will explore the potential benefits of applying standards such as those developed by TIC4.0 in the design of processes for autonomous terminals. The D2.2 document [2] provides a detailed description of the TIC4.0 Association, its structure, and its working methodology, as well as the characteristics of the standard related to port interfaces and intermodal cargo.

In this instance, the focus will be on identifying communication protocols, standardized systems, and semantics to support the operations of an automated terminal while ensuring seamless integration with the other systems within the ecosystem of these operations.

5.2.1. Semantic: TIC4.0

In terms of semantics, the most notable alternatives within the context of port terminals, specifically those related to operational activities, include TIC4.0, which has the closest connection to terminal operations and thus facilitates information exchange between the various stakeholders involved. Additionally, to extend the scope of application, DCSA[1] and EDIFACT standards also offer semantic solutions developed by the industry, which are actively being used to enhance the interoperability of maritime and port operations. DCSA's primary contribution lies in its focus on processes related to the arrival and departure procedures, while EDIFACT represents a series of messages for Electronic Data Interchange for Administration, Commerce, and Transport. It is a globally defined set of rules by the UN for electronic data exchange between businesses and their trading partners via EDI.

To briefly explain the TIC4.0 standard based on the description in D2.2 [2], it is important to note that TIC4.0 introduces a significant advancement in port operations by establishing a standardized language and set of semantics aimed at accurately representing the physical flow and realities of these operations. This is achieved through consistent definitions and an ontology that integrates five essential elements: the "Subject," "Concept," "Observed Property," "Measurement Point," and "Value."

A typical TIC4.0 message is structured as follows (Figure 24):

- Header: Contains critical information such as the origin or destination of the message, the reference time, and a unique identifier.
- Subject: Represents the entity responsible for performing an action (according to TIC4.0 semantics) or for embodying a specific concept.
- Concept: Always linked to a particular subject (or subsystem), indicating either the subject's state (status) or the action/event in which it is involved.
- Observed Property: Quantifies the concept by describing aspects such as status, physical attributes (e.g., pieces, length, weight), energy, speed, etc.
- Measurement Point: Specifies the time and location where the observed property is measured, whether in the past, present, or future.

[1] The Digital Container Shipping Association (DCSA) is a non-profit organization that promotes standardization and innovation in the container shipping sector. The association was founded by the world's most important shipping companies (MSC, Maersk, CMA-CGM, Hapag-Lloyd, ONE, Evergreen, Yang Ming, HMM and ZIM) with the goal of establishing IT standards for the interoperability of technology solutions across the industry.

- Value: The actual measurement derived from the combination of TIC4.0 semantic elements: time, subject, concept, observed property, and measurement point. Values can be expressed in various units.

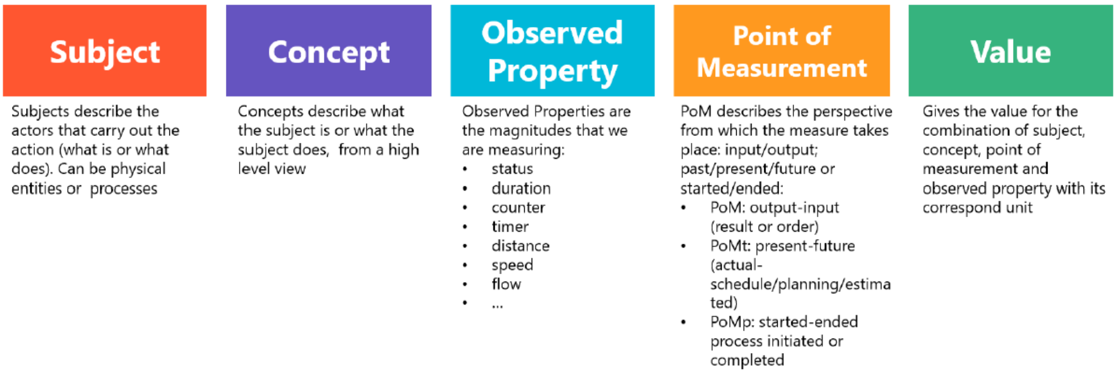

Figure 24. TIC4.0 Semantics [30]

One of the key features of the TIC4.0 standard is its interoperability with other standards, particularly those developed by DCSA and EDIFACT. TIC4.0 has incorporated a series of translations to represent the definitions of DCSA and EDIFACT, enabling them to be integrated into data models developed using TIC4.0 semantics, thus achieving semantic unification. This allows TIC4.0 to digitally represent the most relevant processes and events in maritime and port operations.

5.2.2. Communication protocols

When determining the implementation of various operational standards, it is essential to consider which communication protocols are best suited to support the technical requirements these standards demand. Technological infrastructures and system architectures define the requirements a standard must meet to be effectively implemented. Therefore, one key characteristic a standard should have is adaptability to the diverse structures existing within the sector.

In the context of automated port terminals, the primary communication protocols are those designed to interact with autonomous vehicles or robotic equipment.

It is in this context that the TIC4.0 standards stand out due to its flexibility. The semantics of TIC4.0 can be expressed in data formats such as JSON and XML, with JSON being the preferred format recommended by TIC4.0. JSON's hierarchical structure allows for the representation of a wide variety of relationships among different entities, making it possible to create entities and sub-entities as needed to reflect reality.

One of the main advantages of these data formats is their compatibility with a wide range of communication protocols. In Table 9 there is a list of the protocols compatible with the TIC4.0 standard.

Table 9. List of communication protocols compatible with the TIC4.0 standard

Name	Description
MQTT	Standards-based messaging protocol, or set of rules, used for machine-to-machine communication. Smart sensors, wearables, and other Internet of Things (IoT) devices typically have to transmit and receive data over a resource-constrained network with limited bandwidth.
OPC-UA	OPC UA stands for OPC Unified Architecture. It is an extensible, platform-independent standard that enables the secure exchange of information in industrial systems.
CANBUS	CAN bus (Controller Area Network) is a communication system used in vehicles/machines to enable ECUs (Electronic Control Units) to communicate with each other - without a host computer.
ModBus	Modbus is a serial communication protocol for use with programmable logic controllers (PLCs). In simple terms, it is a method used for transmitting information over serial lines between electronic devices.
PROFINET	PROFINET is an open Industrial Ethernet solution based on international standards. It is a communication protocol designed to exchange data between controllers and devices in an automation setting.

As shown in Table 9, the listed protocols cover a wide range of equipment and systems, including sensors, IoT devices, vehicles, and equipment control systems, among others. This adaptability provides the standard with the necessary flexibility to accurately represent the full spectrum of events and states involving processes, equipment, and people.

5.2.3. TIC4.0 in the context of SEAMLESS

The application in the context of the SEAMLESS project is broad due to the wide range covered by the TIC4.0 standard. In D2.2 [2], emphasis was placed on the potential of the standard to provide homogenization in order to improve interoperability in ship-port interface processes. At this stage, the focus will be on identifying the solutions it offers to the communication needs in the operational processes of terminals and in communication with stakeholders regarding the information that terminals require to plan and execute their processes.

In an automated terminal, interactions primarily occur between systems and machines, machines and machines, and systems and systems. Therefore, it is essential to define the data exchanged between these different entities. The TIC4.0 standard addresses these requirements through the development of two Data Models, which meet the communication needs of the proposed scenario. First, the CHE Data Model represents the digital reality of the equipment, providing information related to location, operational status, and the health status of the CHE. Second, the TOS Data Model consolidates information describing terminal processes, including both the planning and the management/control of operations. The following sections provide a detailed overview of the elements developed within these two data models.

CHE Data model

To interact with a CHE, at a minimum, it must have the ability to transmit its current status—what it is and what it is doing. Additionally, it is essential to be able to provide instructions to the CHE based on its status information. These two capabilities are fundamental, as they represent the minimum requirements for integrating the CHE into operational processes and enabling the effective planning of operations.

Table 10 presents the key concepts and entities defined in TIC4.0 that allow for the representation of the primary functions of a CHE. First, two essential concepts are related to the location of the CHE, enabling the determination of both its current and future positions and referencing them relative to other elements. Second, there are concepts that describe operationally relevant status data of the CHE, such as whether it is "On" and ready to work, in "Standby," or actively "Working." This information is crucial not only for analysing the CHE's performance but also for determining its eligibility to receive a work order. Finally, each CHE consists of several subsystems, each performing specific functions. Due to their critical role in operations, these subsystems have been represented in detail. For example, systems such as the Hoist, Drive, and Trolley are included in the data model, with their various states described to provide a comprehensive understanding of the CHE’s activities at any given moment during operations.

Table 10. List of the most relevant subjects and concepts in the TIC4.0 CHE data model

Data element	Description	Type
referencepoint	Location reference	**Concepts**
location		
powered	These concepts describe the operational states or behaviours of machines	
on		
off		
standby		
notstandby		
working		
idle		
onlydriving		
notonlydriving		
working_and_notdriving		
stability		
slowdown		
energytank	These represent the minimum set of subsystems or components of the main subject, the CHE	**Subjects**
control		
health		
powersource		
drive		
spreader		
hoist		
trolley		
boom		
firefighting		
cabin		
cycle		
trip		
inverter		
lights		
hydraulic		
lubrication		
auxiliary		

With the different combinations of these three main data groups, nearly any operational scenario involving a CHE can be accurately represented. The next step in this representation involves linking these data points to processes. The following section will explain how the TOS Data Model describes processes and connects them to different CHEs, enabling the interactions necessary to carry out automated operations.

TOS Data Model

In the previous section, a series of data elements were listed that enable a CHE to communicate its status and its ability to receive instructions—two fundamental functions for executing the operations assigned to each CHE. In this section (Table 11), we will explore which subjects in the TOS data model can be linked to the CHEs to associate them with the operational processes managed by the TOS, from planning to execution.

Table 11. List of the most relevant subjects and concepts in the TIC4.0 TOS data model

Data element	Description	Type
Cycle	A Cycle characterises a discrete process that involves a subject when moving a unitary cargo from one location to another.	**Subjects**
jobinstruction	Data elements that describe the work order process	
jobinstructionlist		
jobinstructionlogicallist		
jobinstructionsequencelist		
ordersequencelist		
che	Data elements that describe the link between the CHE and the process	
chelist		
chelogicallist		
chesequencelist		

The planning process of a terminal, whether for vessel operations or yard operations, is executed through the creation and assignment of work orders to carry out specific tasks. In this context, the tasks a CHE can perform are always related to Cargo Moves. These can involve either a horizontal move—transporting cargo from one point to another, such as between the quay and the yard—or a vertical move, such as lifting cargo from a vessel to the quay.

In TIC4.0, these actions are defined under Job Instructions, which are described as "a collection of orders that a source communicates to subjects to perform on an object in a coordinated manner" [30]. At a more granular level, an Order specifies a single action to be performed as part of the Job Instruction. Each order includes only one subject performing one action on one object.

The missing element at this stage is the link between the CHE and the Job Instructions. TIC4.0 addresses this by including, within the data of each Order, the specific CHE designated to perform the operation and the timing for its execution (see Figure 25).

```
"jobinstruction": [
  {
    "order": [
        "che": [
          {
            "pom": "input",
            "pomt": "planned",
            "computingtimestamp": "",
            "forecasttime": "",
            "timestamp": "2024-11-20T22:34:17.993Z",
            "id": "",
            "name": "",
            "number": 0,
            "type": "",
            "family": "",
            "brand": "",
            "model": ""
          },
```

Figure 25. Relationship between the CHE and the Order in the TOS data model

For the TOS to efficiently assign this action to a CHE, it must be aware of the operational status of all CHEs deployed or to be deployed in the operations. These necessary data points are obtained through the CHE subject. In Figure 26, the various concepts that must be transmitted to the TOS are illustrated.

```
"tos": [
  {
    "che": [
      {
        "id": "",
        "name": "",
        "number": 0,
        "type": "",
        "family": "",
        "brand": "",
        "model": "",
        "available": {…
        },
        "notavailable": {…
        },
        "notavailable_and_isscheduled": {…
        },
        "notavailable_and_isplanned": {…
        },
        "maintenance": {…
        },
        "assigned": {…
        },
        "dispatched": {…
        },
        "notdispatched": {…
        }
      }
```

Figure 26. List of the concepts of the CHE in the TOS data model

This combination of TOS assignments and CHEs sets the foundations for the operation of the terminal.

Benefits from using the TIC4.0 format in the SEAMLESS project

In the context of the SEAMLESS project, the TIC4.0 language could be used at several stages of the planning and execution of operations. Firstly, during the planning phase, stowage and cargo voyage planning information could be expressed and stored in the TIC4.0 format. The project could benefit from the various provisions the model has for container planning (stowage location, yard location, etc.). Furthermore, voyage information such as the departure, transshipment and arrival ports could be added as well. Of interest could be also the fact that the model can be adapted to portray past, present and future situations; the “point of measurement” field is used to express the moment in time an action could take place.

During the voyage phase, the automated vessel could be adapted to send the voyage information (Estimated Times of Arrival, etc.) in the TIC4.0 format. The TIC4.0 format, as mentioned before, has been adapted to DCSA’s requirements, which makes it compliant with the industry’s most accepted standards and timestamps. Besides this, pilots and other agents (mooring, etc.) would receive and send the information in the TIC4.0 language. Automated tugs and other autonomous vessels would also exchange data in the same format.

As for the vessel-shore operations, the current version of the TIC4.0 Data Model can fully portray the so-called “Carrier Visit” process. Especially, the auto-mooring system could communicate with the vessel or shore systems via a TIC4.0-interface. By doing this, both terminal manager and vessel operators would ensure compatibility and benefit from the unified format. However, both systems should be adapted beforehand to use TIC4.0. The vessel’s automated crane present at the vessel, a key part of the operation, could send and receive instructions in this format as well. In this sense, crane movements are an area where TIC4.0 has made significant advances; the data model is able to digitally portray movements and processes. If both TOS and crane are TIC4.0-compliant, the standard would act as a bridge for the job instruction transmission.

The autonomous cargo-handling terminal described in section 5.1.4 is a further area with potential TIC4.0 language applications. Nowadays, several crane manufacturers are able to provide TIC4.0-compliant equipment. Adding this would be a major advantage to coordinate information exchange between the vessel and the shore equipment. Seamless data information exchange on both cargo and operations would enhance transparency and operations planning. Using a common interface would help with compatibility and data transfer and minimize programming and compatibility efforts.

Lastly, Task 3.6 is foreseeing “the development of a software prototype intended for the integration with existing and future smart port systems to enable SSS and IWW autonomous vessels to make safe port calls, including just-in-time arrivals, berth allocation, mooring, and others. One integral part of this task is the “definition of requirements for new digital interfaces for automated ship-port interactions”. In this task, TIC4.0 will contribute with its expertise and common semantics, paving the way for their integration in them.

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