ING

Headwinds and tailwinds

in the decarbonisation and digitalisation of the Belgian port, transport and logistics industry.

VIL Empowering Logistics

University of Antwerp

Headwinds and tailwinds in the decarbonisation and digitalisation

of the Belgian port, transport and logistics industry

FINAL REPORT – 22 AUGUST 2025

PUBLICATION PREPARED FOR

ING Belgium

PUBLICATION PREPARED BY

Theo Notteboom, Faculty of Business and Economics, University of Antwerp

Kris Neyens, VIL, Flanders' Innovation Cluster for Logistics

DISCLAIMER

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the members of the Editorial Board of this publication for providing valuable input and comments on earlier drafts of this report. The Editorial Board consisted of (in alphabetical order based on last name): Chris Coeck (Port of Antwerp-Bruges), Elke Daniels (ING), Filip De Dycker (ADPO Group), Yves De Larivière (Antwerp Euroterminal), Johan De Raeve (Stukwerkers Havenbedrijf), Filip Declercq (Gilbert Declercq Group), Stephanie Feys (Zuidnatie), Martine Hiel (Hutchison Ports), Bart Laureys (SEA-invest), Dirk Leemans (Colruyt Group), Nadia Lonneux (ING), Karen Polfliet (North Sea Port), Bastiaan Snaterse (DHL Supply Chain), Stephan Vanfraechem (Alfaport-VOKA), Lawrence Vanhove (ING), and Dirk Vanhoutteghem (Gosselin Group).

Publication commissioned by
ING Belgium
Marnixlaan 24
1000 Brussels (Belgium)
www.ing.be

Title: Headwinds and tailwinds in the decarbonisation and digitalisation of the Belgian port, transport and logistics industry
Authors: Theo Notteboom and Kris Neyens
Publication date: 22 August 2025

Foreword

The transport and logistics sector is navigating through challenging times. While **regulatory and societal demands** are putting pressure on companies to decarbonise and digitalise, this transition also paves the way for **growth**, **innovation and stronger competitiveness**. At the same time, these developments are unfolding against a backdrop of growing global instability and geopolitical unrest.

At ING, we have a longstanding commitment to the Transport and Logistics sector which we regard as the lifeblood of the economy. One of our ambitions is to help clients respond to this evolving environment by **enabling dialogue and contributing to informed decision-making**. To conduct in-depth thematic research, we have partnered with the University of Antwerp and VIL, Flanders' single point of contact for logistics innovation.

In our previous studies we anticipated the growing strategic relevance of **digitalisation and sustainability**. Today's observations show that these trends have become operational realities.

This year's edition builds on earlier reports such as The Future of Port Logistics (2017). It aims to shed light on both the **challenges** - ***headwinds*** – **and opportunities** - ***tailwinds*** - that companies face as they adapt to the combined demands of sustainability and digitalisation. Its insights extend beyond **seaports and their direct stakeholders**, reaching **inland terminals**, **logistics and transport operators**, **technology companies**, as well as **broader industrial and economic players**.

Unlike previous editions, the current survey reveals a more **advanced and differentiated landscape**. Many businesses are actively implementing sustainable and digital strategies. Digital twins, AI and IoT are not just buzzwords - they are already reshaping how ports and logistics operate today, from predictive maintenance to real-time optimisation. Other businesses are still in the early phases of exploration or experimentation. These contrasts underscore the **complexity of the transition** and the **need for tailored roadmaps** both at the company level and across the wider ecosystem.

We would like to extend our sincere gratitude to Professor Theo Notteboom, Kris Neyens, members of the editorial board and all survey participants and contributors for their valuable work. We look forward to continuing to support our clients and partners in shaping a sustainable future for the port, transport and logistics industry.

Nadia Lonneux
Head of Transport, Logistics & Automotive
ING Wholesale Banking Belgium

Lawrence Vanhove
Head of Transport & Logistics
ING Business Banking Belgium

Table of Contents

1. Introduction

1.1. The ninth ING study on ports, transport and logistics

The logistics complex in Belgium is one of the largest in the world, partly thanks to its location, including the appropriate space for industry and hinterland access, and the cluster effects in the form of the presence of port and logistics areas, knowledge networks and hinterland markets. Belgium is home to an array of seaports, each displaying specific characteristics in terms of history, dimension and specialisation. The ports are strongly linked with their logistics hinterland in a functional sense. The economic significance of the Belgian port, transport and logistics industry for citizens and businesses in the national economy is substantial. For example, it plays an essential role in the Belgian open economy, and in shaping the energy transition, the circular economy and the pursuit of more sustainable and resilient logistics chains.

Figure 1.1. Overview of the previous eight ING studies on ports and logistics, period 2011-2022

Since 2011, the University of Antwerp and partners have prepared eight port studies commissioned by ING Bank, each addressing a series of themes concerning the ports in the Rhine-Scheldt Delta or the Belgian ports within the Delta (Figure 1.1). VIL and University of Antwerp teamed up in two of these 8 studies, namely in the 2017 and 2019 studies:

1. NOTTEBOOM, 2022, A kaleidoscopic view of the future of the Rhine-Scheldt delta port system, final report prepared for ING Belgium, UAntwerpen, 22 October 2022, 140 p.
2. NOTTEBOOM, T., VAN DER LUGT, L., VAN SAASE, N., SEL, S., NEYENS, K., 2019, Green supply chains: implications and challenges for Rhine-Scheldt Delta seaports, final report prepared for ING Belgium, UAntwerpen/VIL/Erasmus Universiteit Rotterdam, 17 July 2019, 121 p.

3. NOTTEBOOM, T., NEYENS, K., 2017, The future of port logistics: meeting the challenges of supply chain integration, final report prepared for ING Bank, UAntwerpen and VIL, 87 p.
4. VONCK, I., NOTTEBOOM, T., 2015, Strategic evaluation of the Belgian port sector and accompanying services, final report prepared for ING Belgium, ITMMA-UAntwerpen, Bietlot:Gilly, ISBN 978-94-9135-90-40, 91 p.
5. VONCK, I., NOTTEBOOM, T., 2013, Economic analysis of volatility and uncertainty in seaports: tools and strategies towards greater flexibility, resilience and agility of port authorities and port companies, final report prepared for ING Belgium, ITMMA-UAntwerpen, Bietlot:Gilly, ISBN 978-94-9135-90-33, 89 p.
6. VONCK, I., NOTTEBOOM, T., 2012, Economic analysis of the warehousing and distribution market in Northwest Europe, final report prepared for ING Belgium, ITMMA-UAntwerpen, JCBGAM: Wavre, ISBN 978 94 9135 902 6, 88 p.
7. VONCK, I., NOTTEBOOM, T., 2012, Economic analysis of break bulk flows and activities in Belgian ports, final report prepared for ING Belgium, ITMMA-UAntwerpen, JCBGAM: Wavre, ISBN 978 94 9135 901 9, 97 p.
8. NOTTEBOOM, T., VONCK, I., 2011, An economic analysis of the Rhine-Scheldt Delta port region, final report prepared for ING Belgium, ITMMA-UAntwerpen, Bietlot: Gilly, ISBN 978-94-9135-900-2, 130 p.

The previous studies thus covered a broad spectrum of important port themes. The present study, titled 'Headwinds and tailwinds in the decarbonisation and digitalisation of the Belgian port, transport and logistics industry', presents the third joint study by University of Antwerp and VIL, and the ninth ING port study prepared by University of Antwerp.

1.2. Theme setting and objectives

The Belgian port, transport and logistics sector consists of a diverse range of players, as well as established flows of goods and information. Due to consolidation, vertical integration, and the resulting economies of scale, many local companies have been replaced by international logistics firms that are expanding and optimising their global networks. However, numerous Belgian companies remain active and are growing both domestically and internationally.

Sustainability and digitalisation are key components of the latest technological and societal innovation wave. Supply chains are increasingly demanding in terms of environmental impact and sustainability. At the same time, international, supranational, and regional regulations concerning emissions and environmental standards are putting additional pressure on these chains to contribute actively to the decarbonisation of global supply chains. The push for greener practices in ports, transport and logistics is no longer just about gaining social support for logistics activities and development; it has become essential for maintaining and enhancing Belgium's competitive position as a logistics hub.

An increasing number of cargo stakeholders - driven by their own sustainability objectives - are choosing to work exclusively with ports, shipping companies, inland transport operators, and logistics service providers that are committed to greening their operations, both for reputational reasons and for practical outcomes. To achieve these sustainability goals, it is becoming increasingly evident that logistics companies and other stakeholders, such as port authorities, must not only optimise and reinvent their own operations and networks towards greener solutions but also enhance coordination and awareness among all involved parties.

Digitalisation and technological solutions are essential for improving the efficiency and sustainability of supply chains. The range of technologies available is extensive. For instance, consider the automation of logistics processes and activities at distribution centres, the application of digital tools (including AI) for cargo bundling, route selection, and modal choices; the use of digital twins to enhance operational efficiency; the implementation of digital marketplace platforms; the management of information flows through blockchain technology; and the utilisation of the Internet of Things (IoT), among others.

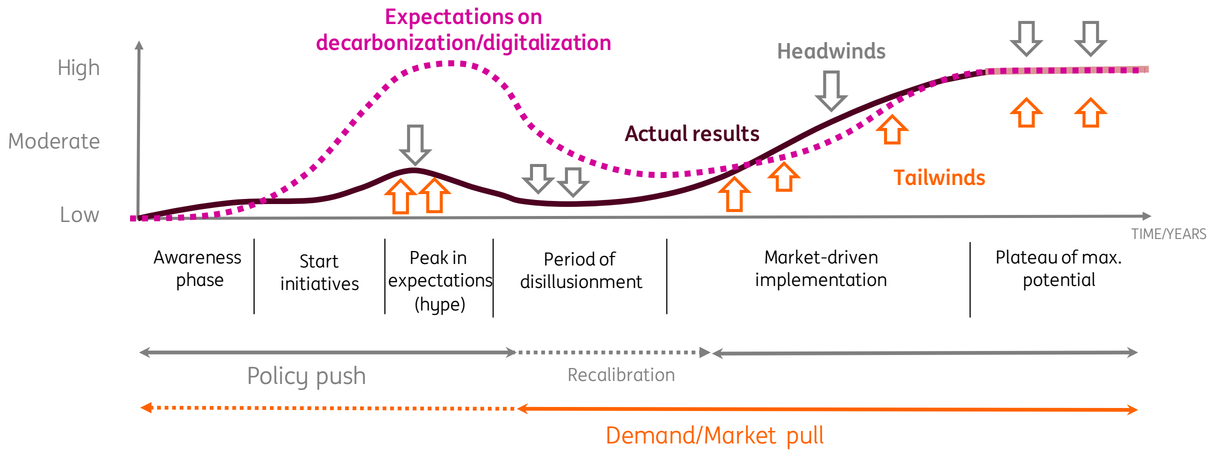
In recent years, various technological solutions have been proposed and partially implemented to enhance the decarbonisation and digitalisation of ports and supply chains. The policy framework is also undergoing significant changes. However, the processes of decarbonisation and digitalisation often face challenges. Over the past decade, many innovative initiatives have transitioned from the conceptual phase to actual implementation, but this shift can be quite difficult. As a result, many large and small projects have experienced delays, postponements, or even cancellations.

Several factors contribute to these challenges, including a substantial cost gap between traditional and new technologies (such as fossil fuels and green hydrogen); a lack of viable markets or customers; an unclear, complex, or unstable regulatory framework; lengthy and complicated permitting processes; difficulties in establishing effective project governance; ambiguous or inequitable distribution of project costs and benefits among partners; challenges in securing financing; social resistance to change; and limited accessibility or capacity of supporting infrastructure (such as electricity grids, pipelines, or port facilities).

The uncertainty arising from these issues can lead to disillusionment among project initiators, diminishing their willingness to pursue other innovative initiatives in the future. Figure 1.2 illustrates the interactions between 'headwinds' and 'tailwinds' during a transition process. The conception and emergence of a new innovative transition path are often welcomed with high expectations by the involved actors. This might lead to a period of heightened enthusiasm, where stakeholders make bold commitments regarding the transition targets and the projects or initiatives needed to achieve these ambitions.

However, during the actual implementation phase of these projects and initiatives, the actors may eventually encounter disillusionment. At this stage, the challenges (headwinds) can become overwhelming, overshadowing any supportive factors (tailwinds). For a transition process to continue positively, it is crucial to overcome these headwinds and bolster the tailwinds.

Figure 1.2. The interplay of headwinds and tailwinds during a transition process concerning decarbonisation and digitalisation



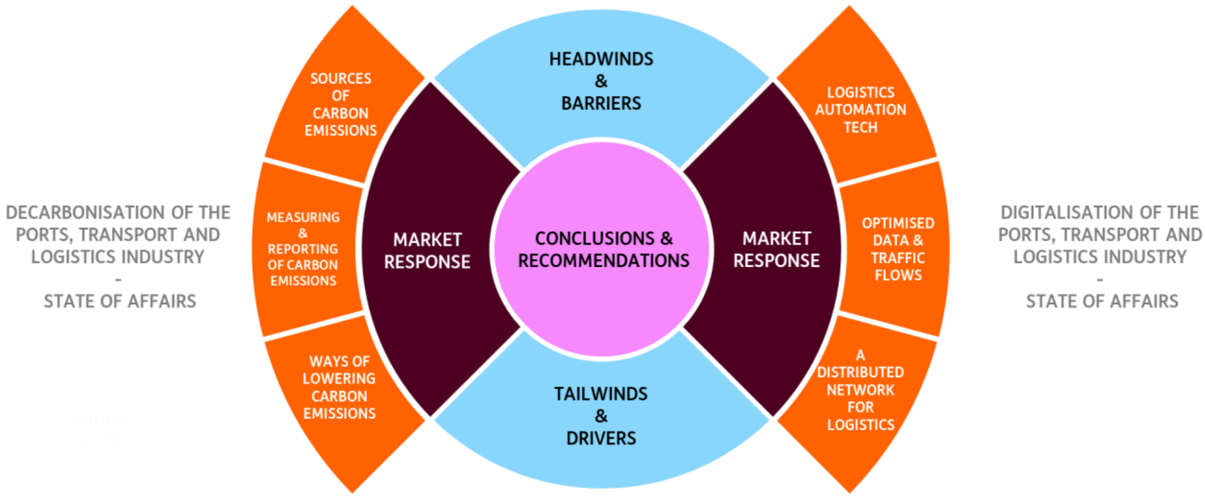
Source: own compilation

This study examines the viewpoints of various stakeholders involved in Belgian ports, transport and logistics regarding factors that may hinder the implementation of projects aimed at decarbonising and digitalising ports and supply chains, referred to as "headwinds." It also identifies factors that can support these efforts, known as "tailwinds." The primary focus of the study is on cargo flows and the related information flows. While industrial production processes, such as those in the chemical industry, and passenger mobility are important aspects of decarbonisation and digitalisation, they are not covered in this study.

1.3. Report structure

The report is structured as depicted in Figure 1.3. The first two sections provide an overview of the state of affairs in decarbonising and digitalising the ports, transport and logistics industry. This analysis is followed by a detailed discussion of the headwinds/barriers and tailwinds/drivers of decarbonisation and digitalisation in the port, transport and logistics industry, as perceived in the extant academic literature and business reports. The following part focuses on market responses. This empirical analysis is supported by an extensive survey among logistics players in Belgium. The survey questions provide insights into the achievements, initiatives, and expectations of these players in the field of decarbonisation and digitalisation of logistics and the associated business models and innovations. The survey also enables refining the mapping of factors and actors that jeopardise the decarbonisation or digitalisation process ('headwinds/ impediments/ obstacles') and the factors and actors that support this ('tailwinds/ drivers/ facilitating factors'). The last part of the study includes an integrated view of headwinds/tailwinds and recommendations. Key messages from the study are summarised and linked to specific challenges for the players in (port) logistics. In particular, we formulate strategic considerations and innovation trajectories for the further decarbonisation and digitalisation of the logistics sector, considering the observed tailwinds and headwinds.

Figure 1.3. Report structure



2. Decarbonisation of the port, transport and logistics industry

2.1. Sources of carbon emissions

The port, transport and logistics industry is a cornerstone of the global economy, facilitating the movement of goods across vast distances and ensuring the smooth functioning of supply chains. However, it is also a significant contributor to greenhouse gas (GHG) emissions, accounting for a substantial portion of the total carbon footprint. As mentioned above, the primary focus of this study is on cargo flows and the related information flows. Thus, industrial production processes in and outside ports, as well as passenger mobility, are not considered in this overview of sources of carbon emissions.

Figure 2.1. A classification of CO_2 emissions generated by the port, transport and logistics industry

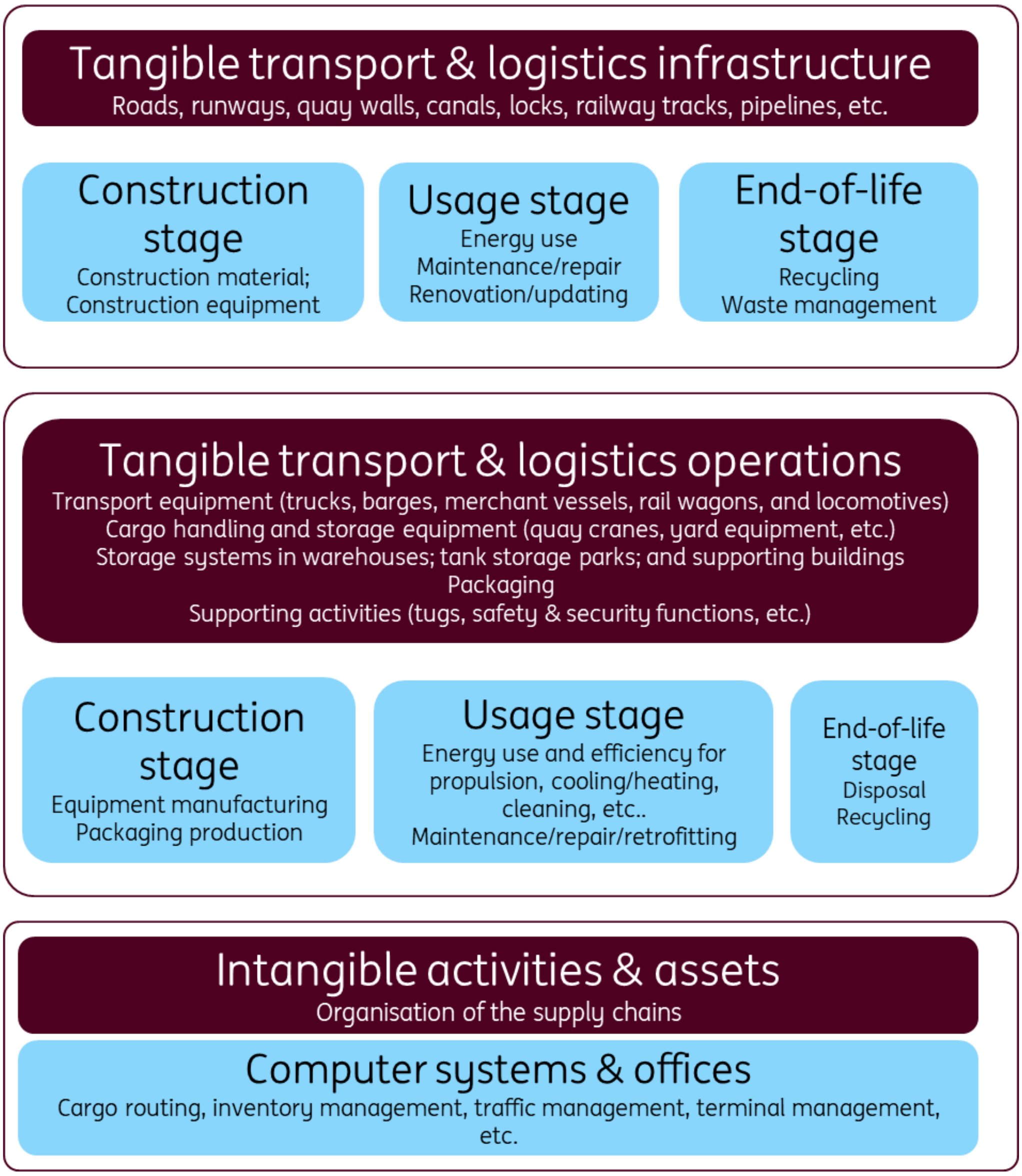


Figure 2.1 provides an overview of the primary sources of CO_2 emissions in the port, transport and logistics industry. The first source of carbon emissions relates to the **tangible transport and logistics infrastructure**. The investment in logistics and transport infrastructure is crucial for economic growth and underpins a large share of economic activity. However, the entire infrastructure process from the construction stage to the use stage and the end-of-life stage (i.e., recycling or waste management) generates emissions (Churchill et al., 2021). The construction of basic infrastructure such as roads, runways, quay walls, canals, locks, railway tracks, pipelines, and associated infrastructure requires materials like concrete and steel, which have high carbon footprints. Infrastructure projects are often characterised by the deployment of heavy-duty fuel-intensive equipment (construction cranes, bulldozers, excavators, backhoes, off-road trucks, dredging vessels, etc.), all of which contribute substantially to emissions. For instance, Krantz (2017) found that 30% of Sweden's annual emissions can be attributed to transport infrastructure development. The maintenance activities of these infrastructures, such as resurfacing roads, the refurbishment of rail tracks, and the maintenance dredging of port access channels, add to emissions.

The second source of CO_2 emissions in ports and logistics – and likely the most visible and discussed source - relates to **tangible transport and logistics operations.** It mainly concerns the CO_2 emissions associated with the construction, maintenance, use and disposal of transport equipment (such as trucks, barges, merchant vessels, rail wagons, and locomotives), cargo handling and storage equipment (such as quay cranes and yard equipment on cargo terminals; automated or semi-automated storage systems in warehouses; tank storage parks; air cargo handling equipment in airports; etc.) and supporting buildings (such as office buildings, maintenance halls, and distribution centres). Emissions associated with the production and disposal of packaging materials also belong to this category.

The total emissions of transport modes and cargo handling equipment are strongly correlated with the fuel type and related GHG emission reduction, the energy consumption levels, and the overall energy efficiency. In some cases, there could be more than one source of emissions. For example, merchant vessels typically use the main ship engines during sailing and deploy auxiliary engines for power generation while the ship is at port or during manoeuvres. Transport modes and cargo handling and logistics superstructure also bring about a series of additional CO_2 emissions associated with fuelling or bunkering infrastructure, maintenance (such as truck repair, or the cleaning of cargo holds in ships, etc.), security and safety features, lighting, the cooling or heating of warehouses/distribution centres and unit cargo loads (such as reefer containers) and supporting activities such as pilot boats and tugs used for guiding ships in and out of the port.

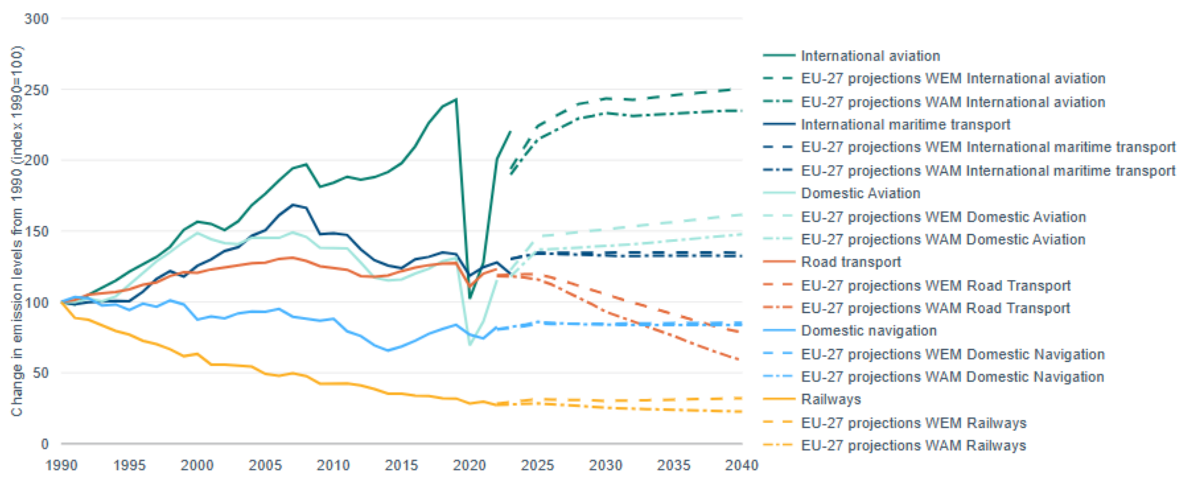
The third group of CO_2 emissions in ports and logistics is generated by **intangible activities and assets** associated with the organisation of the supply chains. It consists of activities not involving physical movable and non-movable transport and logistics assets. This category primarily includes emissions generated by computer systems used for optimal cargo routing, inventory management, traffic management, terminal management, etc.

2.2. Measuring and reporting carbon emissions

Despite methodological advances realised in the past two decades, the measurement of emissions associated with tangible transport and logistics infrastructure, tangible transport and logistics operations, and intangible activities in ports and logistics is not an easy task.

A lot of data has been generated on the CO_2 emissions of **various freight transport modes**. Passenger and cargo transport combined is responsible for 20% of total global carbon dioxide emissions into the atmosphere (a threefold increase since 1970) in the world. The transport sector is one of the largest sources of greenhouse gas emissions in the European Union. Except for rail and inland navigation, the freight transport modes have shown little progress in the reduction of emissions in recent decades. Member States project that domestic transport emissions will only fall below their 1990 levels in 2032 (Figure 2.2). International aviation and maritime emissions are projected to continue increasing during that time.

Figure 2.2. Greenhouse gas emissions from transport in Europe, by transport mode and scenario



Source: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport

When it comes to **seaports**, quite a few case studies calculate the shipping-related emissions in the port area. A variety of different methodologies and definitions have been applied (Mueller et al., 2011; Merk, 2014). Calculation-based methods look, for example, at the fuel accounts of ships to estimate emissions. Activity-based approaches consider the ship's activity (such as the hours spent cruising, manoeuvring and hoteling). Comparing emissions between ports is quite challenging as the estimations differ in terms of the geographical demarcations used (only port area, or also territorial waters), the ships included (only ocean-going vessels, or also port vessels (such as tugs) and inland river vessels), and the inclusion of other port activities, such as other transport modes within the port or cargo handling equipment. Still, some have attempted to produce rankings of ports in terms of total emissions. For example, Transport & Environment (2022) attempted to quantify CO_2 emissions related to ships at berth (i.e., loading, unloading, or refuelling in ports) and attributed maritime supply chain emissions – often referred to as scope 3 emissions for the land sector - to European ports.

Table 2.1. Examples of estimates of the average emissions or emission ranges in gram CO_2 per tonne-km per freight transport mode

	CEFIC (2021) - Chemical goods	ECTA / McKinnon (2011)	CE Delft (2021)
Air freight (long-haul)	N/A	602	544
Road transport - Van			1326
Road transport - Truck	71	62	88-256
Packed goods	63-154		
Bulk goods	55-101		
Barge transport		31	24-38
Tanker	21		
Container	20-26		
Dry bulk	19		
Rail transport	19	22	12
Container train	12-25		
Blocktrain	12-24		
Single wagon train	16-33		
Maritime Transport			
Short sea		16	22
Deepsea container		8	
Deepsea tanker		5	
Deepsea bulk carrier			7
Chemical tanker	10-105		
General cargo	12-35		
Gas tanker	12-75		
Pipelines	1-50	5	
Intermodal transport			
Intermodal road/barge	47	34	
Intermodal road/rail	27	26	
Intermodal road/short sea	17	21	

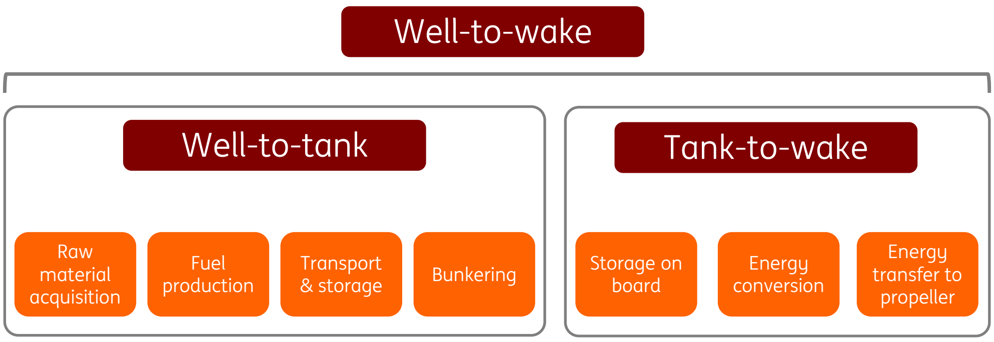
Note on CEFIC (2021): The range for trucks is determined by different assumptions on truck type (tank, hopper, tank container), temperature-controlled or not, empty running % and load in tonnes. The big differences in rail relate to diesel vs. electric. The differences in maritime transport relate to the cargo-carrying capacity of the vessel. The intermodal figures assume 85% of the distance by main carriage.

Source: own compilation based on sources mentioned

Turning back to **transport modes**, top-down and bottom-up methodologies are predominantly employed in the literature on CO_2 emission assessment in transportation (Alam et al., 2017). The **top-down method** is used to determine the overall CO_2 emissions by relying on tools such as energy balance sheets. Input-based measures are derived from estimates of the fuel/energy purchased by/supplied to companies in particular sectors. However, the practice of defining sectors with respect to dominant activities makes it difficult to obtain disaggregated CO_2 estimates for ancillary services such as logistics. The **bottom-up method** involves calculating the CO_2 emissions of specific ships or vehicles by analysing their fuel consumption during transportation. Output-based measures are derived from estimates of the actual amount of work done and the energy consumed per unit of output. The output of freight transport operations is generally measured by ton-km and energy consumption by litres of fuel or kilowatt-hours of electricity used per ton-km. The bottom-up method can only yield reliable analysis results when the data on each involved specific vehicle can be accessed. When based on extensive surveys of freight transport operators, these 'bottom-up' measures usually provide accurate estimates of CO_2 emissions. For most freight transport modes both types of CO_2 measure are available.

A wide range of estimates exists on the **average emissions of CO_2 per ton-km** for various freight transport modes. Table 2.1 offers a non-exhaustive overview of these estimates. However, it is important to interpret these general carbon data with caution (McKinnon, 2007). The CO_2 emissions per ton-km are highly sensitive to factors such as vehicle load or utilisation, vehicle size or capacity, and the type of propulsion (e.g., diesel vs. electric trains). Additionally, the emissions vary depending on whether the goods are temperature-controlled. Moreover, some transport modes move significant amounts of freight alongside passengers. For instance, about 70% of air freight is transported in the belly holds of passenger aircraft, complicating the task of isolating the CO_2 contribution of air freight. There are also considerable international differences in the nature and efficiency of freight transport operations, the primary sources of electricity used (for rail and pipeline), and the condition of transport infrastructure. Finally, using ton-km - calculated as weight transported multiplied by distance travelled - may not always be the most relevant measure of output for freight transport. For certain modes and types of commodities (e.g., packed goods versus bulk goods), it might be more appropriate to assess freight movement in terms of volume rather than weight. Unfortunately, the general lack of official transport statistics expressed in cubic volume makes this challenging.

Figure 2.3. Well-to-wake emissions in maritime shipping

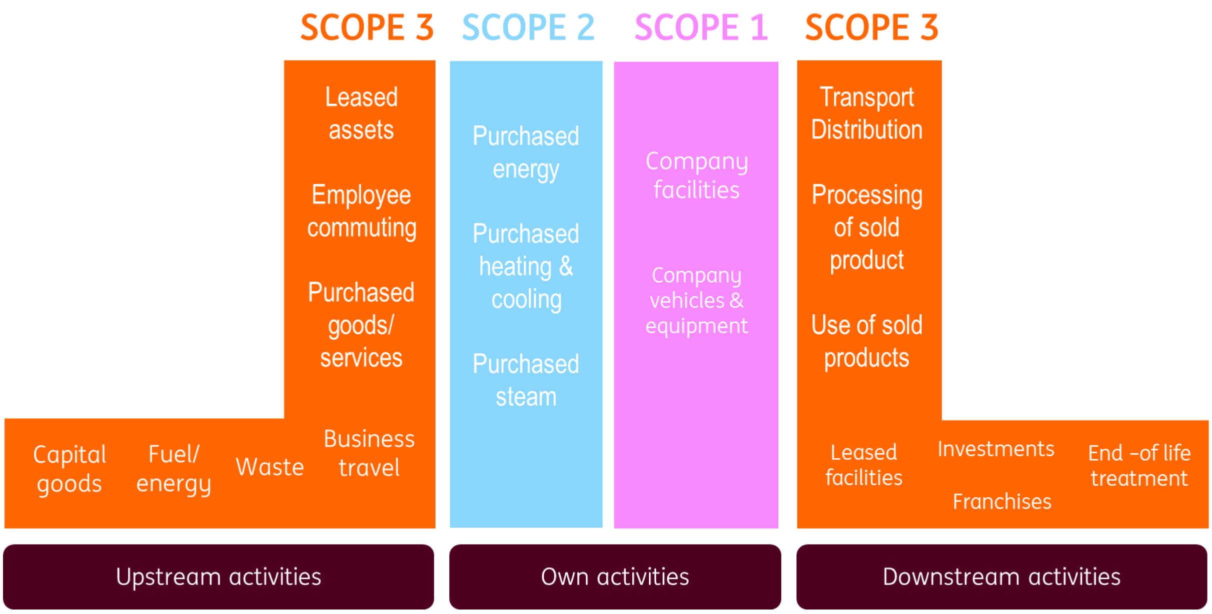


A major complexity in measuring CO_2 relates to the extent to which one considers a lifecycle assessment (LCA) perspective. Measuring **well-to-wake emissions** for maritime shipping (Figure 2.3) or **well-to-wheel emissions** for road vehicles includes emissions related to every stage in the life cycle of a fuel - from its production until it is used to fuel a vessel or truck. Thus, the LCA methodology refers to the assessment of emissions from the fuel production to the end-use by a ship or truck (well-to-wake/wheel) by combining a well-to-tank/wheel part (from primary production to carriage of the fuel in a vehicle's tank, also known as upstream emissions) and a tank-to-wake/wheel part (from the fuel tank to the exhaust, also known as downstream emissions). A fuel can be classified as carbon-neutral in this approach and still release tailpipe emissions if its overall carbon emissions are net-zero when considering the entire life cycle of the fuel. It is widely considered as the only way to accurately measure the climate and health impacts of a fuel.

However, many in the shipping industry and road industry prefer a **tank-to-wake** or **tank-to-wheel** approach to measure emissions. This approach only considers the emissions that result from burning or using a fuel once it is already in the tank. The emission figures per ton-km in Table 2.1 are based on such an approach. The emissions associated with the production and transportation of the fuel are not included in this approach. To qualify as a carbon-neutral fuel using this approach, the fuel must have zero tailpipe emissions. Battery-electric and hydrogen are two of the most common zero-tailpipe-emission fuels considered when taking a tank-to-wake approach. Thus, using a tank-to-wake approach, all hydrogen, whether produced using natural gas (grey and blue hydrogen) or renewable electricity (green hydrogen), would be viewed as a carbon-neutral fuel as no carbon emissions occur when powering a vessel or truck.

The differences between a tank-to-wake/wheel and well-to-wake/wheel approach have **policy implications**. A tank-to-wake/wheel policy framework primarily revolves around the shift to low-carbon fuels, and the identification, approval and support of carbon-neutral fuels for the future. In a well-to-wake-based policy context, transport operators can bring the whole fuel chain into the discussion to provide low-carbon and climate neutral fuels. For example, the scope of the 2024 IMO Guidelines on life cycle GHG intensity of marine fuels (2024 LCA Guidelines adopted during MEPC 81; Resolution MEPC.391(81)) covers well-to-tank, tank-to-wake and well-to-wake emissions of all possible marine fuels and energy carriers with a specific focus on CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions. On a regional level, the EU Commission's Fit for 55 package adopts a well-to-wake approach.

Figure 2.4. Emission classification according to Greenhouse Gas Protocol (GHG Protocol)



From a corporate perspective, measuring the carbon footprint of a port, transport or logistics company cannot be done without first determining the sources of CO_2 and other greenhouse gas emissions. The **Greenhouse Gas Protocol (GHG Protocol)** is an international standard that aims to provide enterprises, public authorities and other organisations with a consistent and reliable way to measure, manage and reduce their carbon footprint. The GHG Protocol is widely recognised as the basic standard for measuring and reporting greenhouse gas emissions. The second leading standard is ISO 14064-1: greenhouse gases. The GHG Protocol divides emissions into three scopes that are released across an organisation's entire value chain (Figure 2.4):

- **Scope 1** includes direct emissions from own sources, e.g., fuel combustion by ships, trucks and vans that are part of a transport company's fleet. Scope 1 emissions thus concern greenhouse gases that a port or logistics company emits from sources it owns or controls directly. These emissions are released when a port or logistics company delivers a service.
- **Scope 2** includes indirect emissions, i.e., those that come from purchased electricity or heat used to power the offices or warehouses of a logistics company. Scope 2 emissions are thus released by off-site and upstream energy providers when a company makes a purchase.
- **Scope 3** includes indirect emissions that need to be made to keep their business running. A company's scope 3 emissions, also known as its life cycle emissions, are those that arise across the value chain, both upstream and downstream. Even emissions not under a company's control – such as scope 3 emissions for a forwarder from a ship rerouted to avoid the Red Sea area – must be accounted for. Scope 3 emissions are the most complex, as they are released before and after a service is delivered. There are a total of 15 categories of indirect emissions included in this scope, covering both upstream and downstream activities: (1) Purchased Goods and Services; (2) Capital Goods; (3) Fuel- and Energy-Related Activities (not included in Scope 1 or Scope 2); (4) Upstream Transportation and Distribution; (5) Waste Generated in Operations; (6) Business Travel; (7) Employee Commuting; (8) Upstream Leased Assets; (9) Downstream Transportation and Distribution; (10) Processing of Sold Products; (11) Use of Sold Products; (12) End-of-Life Treatment of Sold Products; (13) Downstream Leased Assets; (14) Franchises, and (15) Investments.

Scope 3 greenhouse gas emissions reporting became mandatory in the European Union under the **Corporate Sustainability Reporting Directive (CSRD),** which entered into force on January 5, 2023. The directive introduces more detailed sustainability reporting requirements for EU companies, non-EU companies with a significant net turnover in the EU, and entities whose securities are listed on a regulated EU market. The implementation of the directive is phased over the period 2025-2029. In early 2025, the EC announced some major changes in the implementation trajectory and applicability of CSRD. The timeline adjustment includes moving the deadline for companies set to report in 2026 and 2027 to 2028. The scope of CSRD will be reduced by 80%: it will only cover companies with over 1000 employees (was 250) and a minimum turnover of 50 million euro (or 25 million euro balance sheet). For excluded companies, a simplified voluntary standard will be developed based on Voluntary Standards for SMEs (VSSME). Finally, data requests from CSRD-covered companies and banks to value chain partners with less than 1000 employees will be limited to the scope of the upcoming Voluntary Reporting Standard.

The **GHG Protocol** offers comprehensive guidance on how to measure greenhouse gas emissions across various economic activities, including logistics and transport. This guidance includes the determination of CO_2 emission indicators - metrics used to estimate the amount of carbon dioxide emitted per unit of activity. For transport activities, these emission factors differ based on several variables: the mode of transport, type of fuel, vehicle efficiency and utilisation, distance travelled, and the type of goods being transported. In the logistics industry, which involves goods transportation, CO_2 emission factors are typically calculated per ton-km. Once the gas emission rates are established, the port or logistics company can begin the data collection process. After collecting the necessary data, the next step is to convert this information into CO_2 emissions using appropriately selected and developed emission factors. The results should then be audited, preferably by external and independent experts, to ensure accurate emission calculations. Once the auditing is complete, an emissions report can be prepared. This report can serve as a foundation for developing a plan to reduce the organisation's carbon footprint. By understanding the level of emissions across the three scopes, specific actions can be designed to reduce them within a designated timeframe. Frequent measurement of the carbon footprint allows companies to monitor the effectiveness of their efforts to decrease CO2 emissions.

The GHG Protocol has a calculation tool for transportation that uses a combination of the fuel-based and distance-based methods (see http://www.ghgprotocol.org/calculation-tools/all-tools for details). The fuel-based method involves determining the amount of fuel consumed (i.e., scope 1 and scope 2 emissions of transport providers) and applying the appropriate emission factor for that fuel. A distance-based method is used to determine the mass, distance, and mode of each shipment, and then apply the appropriate mass-distance emission factor for the vehicle used. The calculation of CO_2 emissions is mostly based on a fuel-based method, while other emissions such as CH_4 and N_2O are better estimated using a distance-based method.

Calculating CO_2 emissions per activity can be a complex task. CDP, formerly known as the Carbon Disclosure Project, is the world's most widely used database of organisational environmental impact data, including global greenhouse gas emissions. The organisation is a non-profit global disclosure system operating in about 90 countries. CDP does not directly calculate CO_2 emissions for reporting organisations. Instead, companies and organisations self-report their emissions using CDP's standardised framework, which follows internationally recognized methodologies like the GHG Protocol, ISO 14064, and IPCC guidelines. Organisations gather activity data related to their operations. CDP then calculates emission factors, which indicate the amount of CO_2e (CO_2 equivalent) released per unit of activity, using various sources such as DEFRA (UK), EPA (US), IPCC, and IEA. Organisations typically update their emissions data annually. CDP also encourages recalculating past emissions if significant changes occur, such as acquisitions, divestitures, or methodological improvements. These updates can affect the reported carbon footprint, i.e., in some cases, a company's reduction in CO_2 emissions might result not from actual reductions but from updated emission factors. These methodological complexities can make it difficult for a company to measure genuine progress in reducing CO_2 emissions.

Gathering data on GHG emissions in scope 3 is often the most challenging part of carbon footprint management and reporting. It requires extensive data management at the corporate level, with accurate and comprehensive data collection to establish baselines for emissions, energy efficiency, and operational efficiency. The reporting process can reveal data gaps across departments that need to be addressed and may suggest methods to unify data collection, storage, and reporting. The port, transport and logistics industry can be a particularly complex environment for this due to fragmentation. Technology and good governance are essential to creating a unified approach that streamlines data collection and reporting.

2.3. Reducing carbon emissions of tangible transport and logistics infrastructure

As part of **circular economic principles**, one needs to consider circularity and thinking about design, development, and, crucially, what happens once an infrastructure reaches the end of its life cycle. Lifecycle management of infrastructure is an important aspect of circular principles and can help to significantly reduce CO_2 emissions. In this realm, the port, transport and logistics industry should rely as much as possible on infrastructures with an extended life cycle that can be repaired, refurbished, and reused. For example, embedding **circular principles within the design phase of port infrastructure** considers flexible port infrastructure design, which allows for upgrades, extensions, and alternative uses when needed. Integrating flexibility concerns in the design of quay walls and locks is not easy, given that the initial construction and any changes made afterward are typically very expensive. When port infrastructure has reached the end of its life cycle for economic or technical reasons, it should be stripped for parts and components, and anything left should be recycled and reused. New technologies, such as additive manufacturing, allow for new opportunities for the construction and maintenance of port terminal facilities, particularly if the materials are sourced from construction recycling materials.

Figure 2.5. Summary on ways of lowering carbon emissions of tangible transport and logistics infrastructure

Lifecycle management of transport and port infrastructure also involves **sustainable maintenance strategies**. A proactive and preventive maintenance approach considers the uncertainties and complexities of transport and port infrastructure.

Material usage during construction is another key area to lower carbon emissions related to the tangible transport and logistics infrastructure. Incorporating more recycled materials and renewable raw materials into transport and port infrastructure plays a significant role in reducing GHG emissions. For example, in rail, Deutsche Bahn plans to at least double its recycled content in rail steel, ballast and concrete sleepers by 2030 to reduce CO2 emissions by around 300,000 metric tons (Deutsche Bahn, 2025).

For decarbonisation infrastructure projects in ports that rely on retrofitting existing infrastructure or working within a constrained urban footprint, there may be nowhere to go but up. For example, renewable energy installations must be compact and efficient and consider innovations like floating solar platforms, vertical wind turbines, and multi-story energy storage facilities. Further, such projects often involve the design of modular solutions adapted to port-specific environmental and spatial constraints. Microgrids that integrate on-site solar, wind, and battery storage to support shore power and equipment electrification must stand alone, enhancing reliability without burdening the greater regional power grid.

2.4. Reducing carbon emissions of tangible transport and logistics operations

A wide array of measures and instruments are available to lower CO_2 emissions related to **tangible transport and logistics operations** (see Figure 2.6).

When it comes to **warehousing and distribution activities and facilities**, upgrading logistics hubs, warehouses, and cold storage facilities with energy-efficient designs and renewable energy systems can decrease operational emissions. Energy storage and in-company smart grid solutions further enhance energy efficiency. These efforts are supported by energy monitoring and energy management programs. Logistics companies can reduce their carbon emissions by increasing their use of renewable energy sources, such as solar or wind power, in their operations. They can install solar panels on warehouse roofs and distribution centres, use wind turbines to generate electricity and invest in renewable energy credits to offset their carbon emissions.

Logistics service providers can implement **circular economy principles** to minimise waste and emissions. This includes recycling packaging materials, optimising reverse logistics, and reducing empty hauls. Logistics companies can reduce their carbon footprint by paying more attention to **packaging practices**. Using sustainable packaging materials, such as biodegradable or recyclable materials and using reusable packaging can help reduce waste and lower costs in the long run. The use of lighter packaging material reduces the weight of shipments and improves fuel efficiency, which equals lower carbon emissions. There is also great room for improvement when it comes to empty space in packaging. Companies must make the best use of space in packaging individual packages, pallets, containers and other cargo units. The more empty space in a package, the more unnecessary space it takes up when being transported, and the more carbon emissions.

Figure 2.6. Summary on ways of lowering the carbon emissions of tangible transport and logistics operations

Tangible transport & logistics operations

Warehousing & distribution activities & facilities

- Energy-efficient designs & renewable energy systems
- Circular economy principles, e.g., recycling packaging materials, optimising reverse logistics, and reducing empty hauls.

Seaports (see also ING 2019 study)

- Facilitate green shipping: e.g., alternative fuel bunkering, OPS, etc.
- Facilitate green port operations: e.g., electrification of port operations, green energy production on terminals,
- Facilitate green inland transport
- Facilitate the adoption of circular economy principles in port
- Facilitate knowledge exchange and development

Transport vehicles

- Improve energy efficiency through maintenance, vehicle design, vehicle scale, vehicle speed, and responsive and ecofriendly driving/sailing.
- Use of low-emission vehicles and energy sources
- Modal shift, multimodal/synchromodal solutions
- Cargo bundling, inland terminals and port-hinterland concepts

Seaports are major hubs for CO_2 emissions from ships and heavy machinery. Transitioning to alternative fuels like methanol/methane, hydrogen, ammonia, and biofuels for vessels and equipment can significantly reduce carbon footprints. Electrification of port operations, including the adoption of electric cranes, forklifts, and trucks, also helps minimise emissions. Integrating renewable energy sources, such as wind, solar, and tidal power, into port infrastructure is vital. Shore power systems, which allow ships to plug into the electrical grid while docked instead of running diesel generators, are gaining traction as a decarbonisation strategy.

Transport vehicles such as ships, trucks and trains are a prime source of carbon emissions, requiring actions in several areas, as explained below.

2.4.1. Measures focused on improving the energy efficiency of the fleet or vehicles.

Regular and preventive vehicle maintenance and checks of the existing fleet play an essential role in maintaining favourable fuel efficiency. When maintenance is neglected, fuel consumption increases due to inefficiencies in mechanical systems, increased drag, and poor combustion:

- Key maintenance issues for **trucks** include engine issues (dirty air filters, worn-out fuel injectors, or poor engine tuning); tire pressure and state; damaged, missing or improperly fitted aerodynamic devices (such as fairings, side skirts, or wind deflectors); misaligned wheels and dragging brakes; and fuel system contamination.
- Key maintenance issues for **ships and inland vessels** include hull fouling; damaged, worn or unbalanced propellers; engine and fuel system issues; poorly managed ballast; and lubrication and friction issues.
- Key maintenance issues for **rail equipment and locomotives** include engine and fuel system issues; poorly maintained wheels or misaligned bogies; and cooling system failures.

For new vehicles, **technologies for vehicle design** can help to reduce CO_2 emissions. For example, a wide array of technologies are available to improve the **energy efficiency of merchant ships**, either at the design stage or via retrofitting (OECD, 2018; EFTE, 2018): (1) light construction materials; (2) slender vessel design; (3) propulsion improvement devices; (4) installation of a bulbous bow; (5) air lubrication systems to reduce the friction between the hull and the water; (6) the application of advanced hull coatings; (7) efficient ballast water system design; and (8) engine and auxiliary systems improvements. TNO (2016) and TNO (2017) estimate that **CO_2 emissions of long-haul trucks in Europe** can be reduced significantly by focusing on a more energy-efficient power train (potential of 17% carbon emissions reduction), air drag (7 to 9%), rolling resistance (7-9%) and the use of lightweight materials (2-3%).

An increase in the **scale of vehicles** often results not only in economies of scale (i.e., a lower cost per unit transported), but also ecologies of scale (i.e. a lower emission footprint per unit transported). This has been demonstrated in container shipping as reported in various studies such as Ge et al. (2021). In road transport, scale increases can be accomplished in multiple ways. The use of Eco-combis could reduce carbon emissions by up to 20% (TNO, 2017). Another solution is truck platooning. This is a way of truck transport where multiple trucks are electronically connected to each other like a train with wagons. The first truck in the row contains a truck driver, and the rest of the trucks are following without the involvement of a driver. Truck platooning offers multiple advantages over traditional truck transportation. First, by letting trucks drive closer towards each other, more space on the road is available, which leads to a better utilisation of the infrastructure. Second, this leads to CO_2 reduction because of a better aerodynamic flow. This could lead to a reduction in CO_2 emissions up to 10%. Third, it could lead to safer and cheaper transport, which is beneficial for the whole industry.

Reducing **vehicle speed** can, depending on the vehicle type, result in major savings in fuel consumption, thus also having a positive impact on carbon emissions. This is particularly the case in merchant shipping. For example, Cariou et al. (2019) demonstrated that the large-scale implementation of slow steaming and extra slow steaming practices in container shipping since 2007 (i.e. lowering the commercial vessel speed from 20-21 knots to 15 up to 18 knots) was one of the major contributing factors to the significant reduction in CO_2 per container carried in the period 2006-2016.

Responsive and eco-friendly driving or sailing behaviour of the drivers or crew is another field that can yield great energy efficiency savings. Logistics and transport companies can achieve this through a combination of training, technology, incentives, and operational strategies. Training and education initiatives typically include eco-driving programs, regular performance reviews and associated benchmarking, and the provision of immediate feedback on driving/sailing behaviour and fuel efficiency. Technology plays a role in controlling speed, planning the most fuel-efficient routes, or idle reduction technology.

2.4.2. The use of low-emission vehicles and energy sources

Logistics companies can use low-emission vehicles, such as electric or hybrid vehicles, to reduce carbon emissions. Logistics companies can also explore alternative fuels, such as biofuels, ammonia or hydrogen to reduce emissions further. Table 2.2 provides an overview of the wide range of alternative fuels currently being considered for the propulsion of vehicles, and the reduction of emissions.

Table 2.2. Overview of alternative fuels/inputs and their production pathways

	Production pathway	Input/feedstock
Hydrogen (electrolytic)	Electrolysis	Water and electricity
Methane (natural gas)	Natural gas extraction	Gas energy
Biogas	Biogas production	Farm waste
Methan (bio), CO2	Biogas upgrading	Biogas
Syngas	Steam methane reforming	Methane and water
Hydrogen (blue or bio) and CO2	Synagas pressure swing absorption	Syngas
Nitrogen and oxygen (and other traces)	Nitrogen separation (PSA and cryo)	Air
Ammonia	Haber Bosch process	Nitrogen, hydrogen and heat energy
CO2	Carbon capture (industrial)	Fuel gas
CO2	Carbon capture (air)	Air and electricity
Methane (synthetic) and oxygen	Sabatier process	CO2 and hydrogen
LCH4 (liquid methane)	Methane liquefaction	Methane (natural gas, bio) and electricity
LH2 (liquid hydrogen)	Hydrogen liquefaction	Hydrogen and electricity
LNH3 (ammonia)	Ammonia liquefaction	Ammonia and electricity
Hydrotreated vegetable oil, fatty acide methyl esters, etc.	Liquid bio-fuels	Wastes, oils and crops
Methanol (synthetic)	Methanol synthesis	CO2 and hydrogen
Blue crude, e-diesel	Fischer-Tropsch	Hydrogen and CO2
Water (+nitrogine oxides)	Hydrogen ICE (internal combustion engine)	Hydrogen
Water	Hydrogen fuell cell	Hydrogen
CO2 + NOx + CH4 (methane)	Methane ICE	Methane (+diesel)
CO2 + NOx	Methanol ICE	Methanol (+diesel)
CO2 + NOx + NH4 (ammonium) +N2O (nitrous oxide)	Ammonia ICE	Ammonia + diesel
CO2 + NOx	Diesel ICE	Diesel

Source: DNV (2022) and UNCTAD (2024)

The alternative fuels considered differ from transport mode to transport mode.

The **airline industry** currently focuses on Sustainable Aviation Fuel (SAF), which is an alternative fuel made from non-petroleum feedstocks, such as the food and yard waste portion of municipal solid waste, woody biomass and fats/greases/oils. SAF can be blended at different levels with traditional kerosene with limits between 10% and 50%, depending on the feedstock and how the fuel is produced. Next to bio-SAF, there is also clear interest in e-SAF (Electro-Sustainable Aviation Fuel), a type of synthetic fuel made from renewable energy sources like wind, solar, and hydro power. It is produced through a process called Power-to-Liquid (PtL), which converts green hydrogen and biogenic CO_2 into a liquid fuel that can be used in existing aircraft engines. Ports play a crucial role in these new energy supply chains. For example, OMV is developing a bio-refinery in the Antwerp port area for SAF and HVO production. Advario and Power2X are developing a production and storage hub for e-SAF and synthetic, ultra-low carbon fuels in the Port of Rotterdam.

The **shipping industry** mainly focuses on methanol, ammonia, biofuels and, for shorter distances, battery-powered vessels. In long-haul merchant shipping, LNG-powered ships are increasingly being deployed. While LNG does not lead to very significant CO_2 emissions reduction compared to heavy fuel oil, LNG brings much lower sulphur emissions. Bio-LNG is seen as the next step after LNG, offering a much easier path to decarbonisation and regulatory compliance, at least until 2030, probably even until 2034. Bio-methane should be '2050 proof' if methane slip issues can be solved. The storage infrastructure in ports for alternative bunkers like ammonia, hydrogen, methanol, and biofuels, would require specialised storage, safety protocols, and distribution systems, including scalable high-pressure storage tanks, cryogenic pipelines, and robust safety systems. For many products like LNG, the storage infrastructure in ports is already in place. Storage tanks also exist for methanol, and gasoline tanks can easily be converted. Not everything requires new infrastructure.

Onshore power supply (OPS) is a proven tool in the decarbonisation toolbox, enabling berthed vessels to shut down auxiliary engines, drastically cutting emissions. However, engineers must ensure systems can handle variable load demands, incorporate high-capacity transformers, and remain compatible with the diverse power requirements of modern and older vessels.

The **road transport industry** considers a wide array of alternative fuels and propulsion systems, including CNG, LNG, biofuels, synthetic fuels, hydrogen, electricity, and hybrid (ING, 2024). The EU primarily supports research for both BEV (Battery Electric Vehicles) and FCEV (Fuel Cell Electric Vehicles). BEVs are preferred for lighter and shorter transport, FCEVs for heavier and long transport. Table 2.3 demonstrates that even the most modern Euro 6 diesel vehicles have a significantly lower Ecoscore than all other alternatives. Battery-electric mobility clearly gives the highest score. There is no clear distinction between HVO (biodiesel) and CNG/LNG. The Ecoscore for hydrogen is low given the lower energy efficiency than battery-electric. In addition, the current hydrogen is still far from renewable. If we assume 100% renewable electricity, the Ecoscore of hydrogen will be comparable to that of electric vehicles. ING (2024) drafts the following implementation path for alternative fuels in the road transport industry:

- *Short term (till 2026)*: CNG/LNG or HVO (biodiesel) as immediately available solutions in function of Total Cost of Ownership (TCO) and business case. For shorter transport distances, battery electric solutions may be considered.
- *Medium term (2026-2032)*: battery-electric and hydrogen solutions next to HVO and CNG/LNG.

- *Longer term (2032-)*: Hydrogen and battery electric as full-fledged alternatives for every transport. BioCNG and BioLNG could also play a role.

Table 2.3. Ecoscores for different fuels

Emissions/km	Diesel	CNG	HVO	EV	Hydrogen
CO2	670.08	508.75	134.02	-	-
HC	0.0034	0.138	2	-	-
NOx	0.288	0.216	0.288	-	-
CO2	0.0096	0.288	0.0096	-	-
PM	0.0066	0.0066	0.0066	-	-
FC	25	18.5	25	120	4
dB(A)	78	78	78	78	78
Ecoscore	**20.43**	**34.3**	**34.49**	**37.73**	**34.03**

Note: The Ecoscore gives a final result between 0 and 100 based on various parameters, with a higher number meaning a better score. Vehicles with a higher Ecoscore therefore deliver better climate and environmental performance than vehicles with a lower score.

Source: ING (2021)

Electrification is the focus in the **rail industry**, with some attention also going to the use of bio-diesel. The European rail system has a relatively high electrification percentage but with drastic variations among countries. The Belgian rail network has the highest electrification rate in the EU (about 85%), while this figure amounts to 73% in the Netherlands, 60% in France and 55% in Germany (WSP, 2024). Electrification coverage is missing in crucial transport network corridors which are part of the Trans-European Transport Network (TEN-T). Further electrification efforts consider the current and planned share of energy from clean sources.

The **inland navigation** sector is experimenting with the use of batteries, hydrogen and other sustainable fuels with infrastructure primarily following a corridor approach. Innovative companies, such as Zero Emissions Services (ZES), are offering solutions for battery-powered inland barges that rely on exchangeable battery containers charged using renewable power. Skippers can exchange a depleted battery container for a full one at exchange and loading stations on land. While batteries can be used for short-haul journeys, this is not yet an option in long-haul inland waterway transport because of their range limitations. Fuel cells can cover larger distances but are not yet economically viable. An alternative is the development of internal combustion engines (ICEs) with the capability to transition from diesel to hydrogen. This requires changes in the fuel injection system, so the engine can handle hydrogen. Methanol can be an option to lower emissions as well, if inland navigation can learn from the experience being brought from seagoing vessels. However, ships will also need to be modified in other areas, including fuel storage and piping. Bureau Veritas, which classifies and certifies ships for insurance purposes, has published its first classification rules for hydrogen-fueled ships. These include safety requirements for managing hydrogen's flammability and special storage needs. LNG could in theory also be considered. Fan et al. (2023) found that the CO_2 emissions of LNG used for barges were 6.8% and 54% less than those of diesel and coal-based methanol, respectively, making it a suitable fuel alternative for ships.

The shift to alternative fuels needs reassurance from vendors (through long-term offtake contracts), standards bodies and regulators. As with much of the energy transition, the frameworks governing alternative fuels such as hydrogen are still nascent.

2.4.3. Modal shift, multimodal/synchromodal solutions and cargo bundling

Lowering CO_2 emissions requires a massive re-engineering of supply chains in favour of a shift to environmentally friendly transport mode combinations and synchromodality.

Multimodal and 'co-modality' policies (see Textbox 2.1 for terminology) have been implemented by supranational, national and regional governments aimed at stimulating the use of barges, rail and shortsea shipping. Measures to support the shift from trucks to lower-carbon modes, such as railways and inland waterways, are claimed to be among the most impactful. Pipeline networks should not be forgotten in the context, particularly when it concerns the transportation of liquids over both short and long distances. These networks can contribute to the CO_2 reduction goals in two ways. First, it reduces the amount of CO_2 that is emitted in the air because pipeline transportation is cleaner than other transport modes such as truck, rail and barge. Second, it is essential in the development of a circular economy and the application of carbon capture, storage and utilisation (CCUS) systems. Pipelines will be necessary for transporting CO_2 to places where it can be stored or where it will be used as a feedstock in other production processes.

Other new alternative modes can also be considered. An alternative or addition to the current freight transport mode landscape could be underground freight transport (UFT). This transport mode can have two variants. The first variant uses pipeline transport in the form of a capsule for goods with a diameter of less than one meter. The second variant needs individual trains or other vehicles to move forward. UFT could be applied in four ways of freight transport (Visser et al., 2018): (1) Urban area transportation; (2) Inside or between industrial/port complexes; (3) Long-distance transport; (4) Hinterland/cross-country transportation. One variant of a possible underground transportation system is the Hyperloop concept. A Hyperloop is a tube-based transportation system, above ground where possible, underground where needed, which includes freight capsules that move through a vacuum tube. The big advantage compared to conventional trains is that there is almost no friction in the tube due to the absence of air. The hyperloop could be applied for both passenger and freight transportation. Currently, hyperloop technology is not yet applied on a large scale within supply chains, but the potential exists. In general terms, there are no advanced underground systems for unitised freight planned or in operation in the Belgian port, transport and logistics industry.

Modal shift has several benefits. It can reduce congestion, air pollution, and other externalities associated with road traffic. Multimodal logistics solutions that combine transport modes should enable to enhance efficiency while lowering carbon intensity. However, not all commodities and routes work for rail and water transport, or multimodal solutions, particularly when considering the total transport cost. While sustainability is not yet considered by market players as a key factor in transport mode choice, it is critical for stakeholders across the logistics industry to value the use of low carbon fuels in the "hard to abate" transport sector.

Textbox 2.1. Multimodal transport, combined transport and co-modality

In general terms, **multimodal transport** deals with the movement of goods using various transport modes. The degree of multimodalism is a direct measure of the degree of integration in terms of interconnectivity and interoperability between the different transport modes in one transport system (Vandenberghe, 1997). Multimodal transport between land and sea, such as road-rail intermodal transportation, water-rail intermodal transport, and road-railway-water multimodal transport are the most frequently used combinations of modes.

Combined transport is often defined to be a specific type of intermodal transport, where environmentally friendly transport modes (rail, inland waterways, or short sea) are used for the major part of the journey (ECMT, 1998). The European intermodal freight transportation sector recently introduced a new definition of combined transport: "an intermodal transport operation where the non-road modes of transport carry out more than 50% of the actual distance that the intermodal loading unit is carried. The 50% should change to 60% in 2035, reflecting the anticipated enhancements in terminal density and rail infrastructure development" (UIRR, 2024).

While the use of the terms multimodal and intermodal transport took off in the 1980s, the notion of **co-modality** is of much more recent date and up to now have mainly been used in a European context (Yuan et al., 2024). Co-modality is a notion introduced by the European Commission (2006) and in principle refers to the use of different modes on their own and in combination to obtain an efficient and sustainable transport chain. The notion of co-modality underlines collaboration between transport modes and replaced the EU's earlier focus on achieving a **modal shift**. The latter notion is more about opposing transport modes one to another to realise a shift from road transport to rail, inland barges, and or shortsea/coastal shipping.

The terms modal shift and co-modality have been complemented in the past decade by the notion of **synchromodality**. The Platform Synchromodality defines this notion as "the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for his (inland) transport". The main difference between multimodal and synchromodal transportation is the role of the shipper in the process. In multimodal transportation the shipper determines which mode will be used for the transport. Whereas, with synchromodal transportation the mandate for this decision is given to the logistic service provider. The service provider will arrange the transportation with the mode that is most optimal at that moment, by taking into account the requirements of the customer with respect with delivery time (Topsector Logistiek, 2019). Also, a synchromodal approach assumes that the shipper books a-modally thereby leaving the decision on the mode(s) of transport to be used to logistics service providers. This renders the whole transport system more flexible in terms of mode choice. This integral system can add significant value to the supply chain because it results in higher loading rates and better utilisation of transport infrastructure such as roads, railways and waterways. Shipping lines, terminal operators, inland terminals, inland transport operators, 3PL companies, shippers and public authorities all have their role to play in the development of synchromodal solutions. Synchromodal transport especially has potential on corridors and in regions where sufficient volumes are present; this allows for highly frequent transport by rail and barge.

Pfoser et al. (2016) describe the most important requirements for synchromodal transportation to work. These are the following. First, close cooperation of all stakeholders within the transport chain is necessary to use the available resources in a flexible way. Second, technical ICT infrastructure is necessary to share chain information and optimise logistic flows. Third, a proper physical infrastructure consisting of hinterland connections and physical hubs is crucial in synchromodality. Also, it should be competitive with other transportation measures in terms of costs and service quality. Lastly, favourable legal conditions should be in place. Synchromodal transport is not easily realised because multiple modalities have fundamental juridical statuses, bookings procedures and transport performances. Parties that are suitable for offering these synchromodal services are not only freight forwarders. Every party that has an overview of the transport chain can develop these services. Think hereby of shipping lines, deepsea-terminals and consortia of shippers and forwarders.

Efficient cargo bundling plays a prominent role in lowering CO_2 emissions in multimodal supply chains. Bundling can be applied within a company but also between competitors. Bundling of load gives opportunities to individual parties that they generally do not have when they arrange transport on their own. By bundling cargo, the utilisation of the transport mode can be increased, as well as the scale of the transport mode. Besides, due to the availability of more load, the sailing frequency can be increased which improves the flexibility. An example of bundling can be found in barge container transportation. Small-scale inland terminals are bundling their load, both within and between terminals. This enables them to sail with bigger call sizes and bigger vessels towards the deepsea terminals. This leads to less vessels sailing towards the ports, which improves the efficiency in the deepsea terminals as well. The bundling of cargo towards the hinterland by joint services, intra-port cargo bundling or by using inland hubs as bundling points within rail and barge networks can help to reduce CO_2 emissions. As local or immediate hinterlands remain the backbone of ports' cargo bases, the bundling issue also plays at shorter distances. Coordination and collective actions between ports and market players is essential to meet the objective of increasing the share of co-modal solutions and to bundle cargo on short distances. A good example can be found in the Antwerp port area. To bundle rail volumes, Railport, along with and at the request of industry and shippers, has set up a system to facilitate collaboration. Railport identifies the cargo volumes for the first/last mile route, acting as a neutral facilitator, taking on the organisation through group purchasing. For the bundling itself, the port was divided into several zones, looking for one rail operator per zone. The neutral operation of the shunting facilities implies that all railway undertakings have access.

Inland terminals and port-hinterland concepts thus have a role to play in the path towards decarbonisation. In the past decades, the dynamics in logistics networks have created the right conditions for a large-scale development of inland ports and inland logistics platforms throughout Europe. The range of functions presented by inland logistics centres is wide-ranging, from simple cargo consolidation to advanced logistics services. Many inland locations with multimodal access have become broader logistics zones. Not only have they assumed a significant number of traditional cargo handling functions and services, but they also attracted many related services like distribution centres, shipping agents, trucking companies, forwarders, container-repair facilities and packing firms. The concept of logistics zones in the hinterland is now well-advanced in Europe: e.g. 'platformes logistiques' in France, the Güterverkehrszentren (GVZ) in Germany, Interporti in Italy, Freight Villages in the UK and the Zonas de Actividades Logisticas (ZAL) in Spain. Logistics zones are usually created within the framework of regional development policies as joint initiatives by firms, intermodal operators, national, regional and or local authorities, and or the Chambers of Commerce and Industry. The interaction between seaports and inland locations leads to the development of a large logistics pool consisting of several logistics zones. Many market players and port authorities have come to understand that landside operations are key to a successful integration along the supply chain and to move to a greener port-hinterland connectivity. A number of shipping lines extend their scope beyond terminal operations to include inland transport and logistics. Inland terminals and rail and barge services are combined to push import containers from the ocean terminal to an inland location, from where final delivery to the receiver will be initiated at a later stage. This "push" strategy is initiated by the shipping line, yet prioritised based on the required delivery date. Export containers are pushed from an inland location to the ocean terminal, initiated by the shipping line, yet prioritised based on available inland transport capacity and the estimated time of arrival (ETA) of the mother vessel. Some terminal operators in Europe are also increasing their influence throughout supply chains by engaging into inland transport. They seem to do so mainly by incorporating inland terminals as 'extended gates' to seaport terminals and by introducing an integrated terminal operator haulage concept for their customers. The advantages of the extended gate system are substantial: customers can have their containers available near their customer base, while the deepsea terminal operator faces less pressure on the deep-sea terminals due to shorter dwell times and can guarantee better planning and utilisation of the rail and barge shuttles. The success of both extended gates and terminal operator haulage largely depends on the transparency of the goods and information flows. Close coordination with shipping lines, forwarders and shippers is needed to maximise the possibilities for the development of integrated bundling concepts to the hinterland, which can also reduce the environmental footprint of port-hinterland connections.

2.5. Reducing carbon emissions of intangible activities and supply chain control

Inefficient logistics processes and supply chain gaps are responsible for wasted resources, detrimental to both organisational budgets and emissions. Logistics companies can cooperate with their suppliers and customers to reduce carbon emissions throughout the supply chain. This can include sharing best practices, reducing waste, and using more sustainable equipment and transport modes. Companies can also collaborate on transportation and logistics to reduce emissions.

Supply chain managers use **predictive analytics** – relying on historical data and external factors – to build solid forecasting models and leverage powerful data dashboards to determine the safety stock they need, to evaluate the capacity situation across ports and depots, to deploy their vehicles smartly and to support many other operational decisions. By analysing data on transportation routes, fuel consumption, and vehicle efficiency, logistics companies can identify areas for improvement and implement strategies to reduce emissions. These metrics are often digitally automated to consolidate all the data collected in dashboards and performance reports. Technologies such as GPS tracking, telematics, and fleet management systems provide valuable insights to logistics companies tracking every step in the supply chain.

Figure 2.7. Summary on ways of lowering carbon emissions of intangible activities and supply chain control

Intangible activities & assets

- Efficient logistics processes to avoid wasted resources
- Cooperate with suppliers and customers to reduce emissions
- Predictive analytics, forecasting models, data dashboards
- Routing and intermodal planning platforms
- Data platforms for utilisation degree and efficient use of vehicles and infrastructure
- Management & control of transport and logistics infrastructures (VTS, ERTMS, train path allocation systems, BICS, WMS, TOS, etc.)
- Location choice and distribution system

One of the most effective ways to lower carbon emissions in logistics is to **reduce the distance traveled** by goods. This can be achieved by optimising routes, using intermodal transport solutions, and consolidating shipments. By reducing transportation distance, logistics companies can lower fuel consumption, reduce emissions, and save costs. Next to other supply chain actors, port authorities can also play a role in this area. For example, the **Routescanner** of Port of Antwerp-Bruges aims to better inform the customers about the various transport options and the most optimal way in which they can take their goods to their destination, depending on their needs. This tool maps the maritime and intermodal connections between Antwerp and overseas and European destinations in a uniform way through search functions.

A second aspect related to supply chain organisation and control relates to the **utilisation degree and efficient use of vehicles and infrastructure**. Data solutions, predictive analytics and AI provide great visibility and transparency into **fleet performance**. For example, in road transport, tracking and real-time monitoring solutions enable operators to control idling, speeding, and other inefficient driving behaviour – preventing the production of excessive CO_2 emissions. Technology thus provides supply chain planners and experts with the tools to optimise asset positioning and utilisation. Ensuring that an organisation always has the correct number of assets (and utilising them optimally) at the desired location is vital for cutting carbon emissions and achieving logistics sustainability.

The **management and control of transport and logistics infrastructures** is a major area for reducing CO_2 related to **intangible activities and supply chain control**. A wide range of systems have been developed to optimise infrastructure capacity allocation and to enhance the smooth flow of goods and vehicles within the infrastructure networks. The efficiency with which these systems are deployed will partly determine the CO_2 emissions of the monitored goods and vehicles. These include the following.

Vessel traffic services (VTS) are shore-side systems which range from the provision of simple information messages to ships, such as the position of other traffic or meteorological hazard warnings, to extensive management of traffic within a port or waterway. The SOLAS regulation states that governments may establish VTS where, in their opinion, the volume of traffic or the degree of risk justifies such services (IMO, 2025). VTS are also referred to as Vessel Traffic Monitoring & Information Systems. The most important VTS instrument in Flanders is the Scheldt Radar Chain which is jointly managed with the Netherlands. The system covers an area on the North Sea from the French border to Domburg, and on the river Scheldt from Vlissingen to the Kallo lock. It consists of five manned traffic management centres, complemented by 22 unmanned radar towers (a further 8 will be added in the near future). The information systems of Flemish maritime ports provide data to SafeSeaNet, the European maritime information network. Lock planning systems are in place to ensure that shipping traffic can quickly and safely pass through the lock complexes in the Flemish seaports. In order to guarantee smooth vessel traffic and ensure proper coordination and collaboration between all partners in the nautical chain, a new Antwerp Coordination Centre is under construction in the northern part of the right bank of the Antwerp port area. North Sea Port uses ENIGMA+, an information and communication system between the various port users to report vessel arrivals, order pilots, boatmen, tugboats and other services. The focus of port authorities and government agencies is not only on nautical aspects. They also exercise their competencies on the landside to make the port area optimally accessible, for example by road and rail.

For rail in Europe, the **European Rail Traffic Management System (ERTMS)** aims to provide a single European signalling and speed control system that ensures interoperability of the national railway systems, reducing the purchasing and maintenance costs of the signalling systems as well as increasing the speed of trains, the capacity of infrastructure and the level of safety in rail transport. Next to rail traffic management, rail infrastructure managers also have a major role to play in the **efficient allocation of train paths**. A train path or train slot is the infrastructure capacity needed to run a train between two places over a given time period. Given the split between rail infrastructure management and rail operations in the EU, a train operator has to purchase a train path from a rail infrastructure manager (i.e., Infrabel for Belgium) to run a train on their tracks. RailNetEurope, an association of European rail infrastructure managers, helps to coordinate cross-border rail traffic in the areas of capacity management, traffic management, and corridor management. The Path Coordination System (PCS) of RailNetEurope is an international path request coordination system that aims to optimise international path coordination by ensuring that path requests and offers are harmonised by all involved parties.

Road traffic management: In Flanders, the 'Vlaams Verkeerscentrum', a division of 'Agentschap Wegen en Verkeer' acts as road traffic manager of the Flemish government. The traffic centre groups all tasks related to operational traffic management, technical surveillance and data exploitation on the Flemish roads. These traditional road traffic management systems, which are typically managed by government agencies, can be complemented with other initiatives. An example in a port context is the **spreading of truck traffic in time and space**. Ports, and especially terminal operators, face problems with truck congestion during peak hours. It would be in the interest of multiple stakeholders to spread this traffic more smoothly over the day. Terminal operators will experience a better utilisation of their terminal, trucking companies face less waiting hours and the public faces less congestion on the road which reduces CO_2 emissions and results in time savings. Terminal operators have three main tools to influence the arrival time of truck drivers (Zhang et al., 2019): (1) Truck appointment: reduce truck-waiting time by setting an arrival quota (upper bound) for each time window; (2) Time window control: In this method, two windows are assigned to each truck for container pickups and deliveries; (3) Truck congestion pricing: charging a traffic mitigation fee during peak hours. A variant of time window control is applying extended opening hours on terminals. This leaves more room for trucks to reschedule their trips to the ports from peak hours to off-peak periods. However, the shift to night driving is not easily implemented by trucking companies. They are dependent on the opening hours of the facilities of their clients, which have their own belongings and regulations. Clients will not shift their procedures without seeing clear benefits.

A wide array of systems ensures efficient **traffic management in the inland navigation sector:**

- **BICS (Barge Information and Communication System)** is a digital reporting system used in inland navigation to facilitate the exchange of voyage and cargo information between vessel operators and waterway authorities. It helps improve efficiency, safety, and compliance with regulations by streamlining administrative processes. BICS is compatible with River Information Services (RIS), allowing seamless data exchange with systems like RiverGuide for efficient inland waterway navigation.
- **RiverGuide** is an innovative platform developed collaboratively by waterway authorities to enhance the safety, efficiency, and sustainability of inland navigation. The platform is a result of collaboration among various organisations, including the Port of Rotterdam, Rijkswaterstaat, Port of Amsterdam, North Sea Port, and De Vlaamse Waterweg. It provides real-time information and route planning for inland waterway users, particularly focusing on commercial shipping. The platform offers detailed data on bridges, locks, clearance heights, operating times, communication channels, and contact information, all accessible through a user-friendly interface. In addition to route planning, RiverGuide has expanded its services to include functionalities such as the easy reporting of voyage and cargo details to relevant waterway authorities. This feature streamlines administrative processes for inland shipping operators, contributing to more efficient and timely voyages, with positive impacts on fuel consumption and associated CO_2 emissions.

By integrating and sharing data from these entities, RiverGuide aims to provide comprehensive and up-to-date information to its users, thereby promoting safer and smarter navigation on inland waterways.

- The **EuRIS platform** is the outcome of collaboration between 13 European countries. This system consolidates national information and services, making them accessible from a single location. The international cooperation was carried out under the RIS COMEX project, which took place from 2016 to 2022. This multi-beneficiary project was co-financed by the Connecting Europe Facility (CEF) and aimed to define, specify, implement, and ensure the sustainable operation of Corridor RIS Services. With the launch of EuRIS, the operational exchange of RIS data on a European scale is now a reality. This development enables traffic management by authorities and logistics management by the transportation sector. The range and quality of services and information are continually improving.
- **APICS Barge** has been developed as a digital solution for inland navigation in the **Antwerp port area**. APICS Barge can be used by barge operators to report when a barge sails in and out of the port, to find available moorings, and to book locks in Antwerp. The Port of Antwerp-Bruges implemented the **Barge Traffic System (BTS)**, a web application that makes the handling of inland navigation of containers at the port completely transparent. The platform allows inland shipping operators to submit slot requests to terminals. The inland shipping operator indicates which terminals it wants to call at and how many container movements are planned. The terminals can then offer an optimal schedule.
- In **North Sea Port**, barge traffic management is facilitated through mandatory electronic reporting systems. To further streamline operations, North Sea Port offers several tools such as the **Harmonie** system, a registration tool for inland shipping that reduces administrative tasks for skippers and provides the port with complete and timely information about a vessel's stay. An online resource providing real-time information on planned **lock operations**, berth occupancy, and waiting locations, particularly useful for navigating the lock complex in Terneuzen. These systems collectively contribute to effective barge traffic management in North Sea Port, promoting smoother and safer inland waterway navigation.

Warehouse Management Systems (WMS) help logistics companies manage and control daily warehouse operations, from the moment goods and materials enter a distribution or fulfilment centre until the moment they leave. WMS software systems are a key component of supply chain management and offer real-time visibility into a company's entire inventory, in warehouses and in transit. Efficient warehousing operations help to reduce CO_2 emissions. In addition to inventory management, a WMS offers tools for picking and packing processes, resource utilisation, analytics, and more.

Terminal operating systems (TOS) are digital platforms that help track and manage all the supply chain operations at terminals in ports and inland ports. TOSs help coordinate all the terminal logistics elements, including vessels, trucks, cranes, trains, and port staff, track cargo movement, optimise asset usage, and analyse data to support decision-making. A typical TOS includes different modules focusing on berth management (planning vessel visits and predicting ETAs), yard management (arranging cargo movement and allocating terminal resources); freight management (cargo tracking, storage, and other services); gate management (controlling access to the terminal facility); and financial and reporting modules. In many cases, TOSs provide data to other systems and supply chain actors such as shipping lines and forwarders using data transfer standards. They can also extract data from other platforms such as platforms that offer real-time ship positions (e.g., MarineTraffic or Vessel Finder). The power and efficiency of the algorithms used in TOS will determine the eventual energy consumption levels and CO_2 emissions of cranes, yard equipment and visiting ships and land transport modes.

Air Traffic Management (ATM) systems can help reduce emissions from airport activities by optimising airspace use, improving operational efficiency, and minimising unnecessary fuel burn. ATM systems help to optimise flight paths to reduce unnecessary detours and delays, minimising fuel consumption. For example, Continuous Descent Operations (CDO) and Continuous Climb Operations (CCO) reduce fuel use during ascent and descent. Advanced ATM technologies help reduce taxiing time by optimising runway and gate assignments. Collaborative Decision Making (CDM) among airlines, airports, and air traffic controllers enables better scheduling, reducing idle engine time. Furthermore, modern ATM systems use real-time data to manage air traffic flow, reducing the need for aircraft to circle in holding patterns, which wastes fuel. Programs like Single European Sky (SES) in Europe and NextGen in the US aim to modernise ATM systems to enhance efficiency, reduce congestion, and lower emissions.

Each segment of the port, transport and logistics industry comes with its specific challenges in the field of **intangible activities and supply chain control**. For example, TNO (2017b) identifies a range of challenges to reduce CO_2 emissions in **last-mile and city logistics**: (1) optimisation of the sequence of stops for vehicles and drivers in a delivery fleet; (2) increasing first attempt delivery rates by allowing consumers to indicate special delivery instructions and by investing in correct last-mile delivery information; (3) minimising and optimising returns; (4) develop new fulfilment options to help drive sustainability (e.g., in-store fulfilment, pop-up distribution centres, micro-fulfilment centres and utilizing dark stores as fulfilment centres); (5) accurate inventory forecasting and management.

Another example relates to **distribution networks**, in particular the location choice and operational modalities of distribution hubs and warehousing facilities. When it comes to overseas goods not all companies have the same distribution structure. Companies can opt for delivery without the use of a distribution centre, distributing through an EDC (European Distribution Centre), distribution through a group of NDCs (National Distribution Centres) or RDCs (Regional Distribution Centres) or a tiered structure with one EDC and several supporting NDCs/RDCs. The choice is mainly influenced by the type of product and the frequency of delivery, but also green considerations increasingly surface when making such decisions. For example, distribution network configurations might evolve in case environmental costs of transport and distribution would fully be internalised in the transport and distribution cost (for example, through environmental taxes such as a CO_2 tax). The future distribution system configuration obviously has an impact on the cargo routing patterns and vice versa.

2.6. Decarbonisation status and path in the Belgian port, transport and logistics industry

The long-term goal is to establish Belgian seaports and logistics networks as carbon-neutral, energy-efficient, and innovation-driven hubs. This vision aligns with the EU's Green Deal, Fit for 55 targets, the IMO's decarbonisation trajectory, and other policy and corporate targets at national and regional levels.

The Belgian port, transport and logistics industry is taking action in all fields of decarbonisation described in the previous sections. On the technology front, we see rapid light-duty electrification; early scale-up for e-trucks and depot charging; pilots in H_2 trucks; biofuels/methanol for shipping; and battery-electric urban fleets. The onshore power supply roll-out is picking up speed in Belgian seaports, while the ship fuel LNG is available as a transition fuel. Belgian seaports are taking action to develop into clean-energy gateways (green H_2, e-fuels, renewable import & storage) with near-zero emissions at berth operations.

Market players are investing in smart and integrated networks to allow for seamless intermodal handoffs, synchronized timetables, digital freight corridors, and open data to cut dwell times and empty runs. Various infrastructure managers, industry players and port authorities are partnering to develop resilient infrastructure, grid-ready logistics zones, H_2/CO_2 pipeline backbones, inland transport nodes, and urban microhubs.

The actors in supply chains increasingly collaborate to achieve a better operational efficiency, supported by dynamic routing and slot booking, load-factor commitments, and collaborative pooling to cut empty kilometres. Slowly but surely, public and large-shipper contracts emerge with CO_2e per-shipment thresholds.

However, there is still a long way to go in many aspects of the decarbonisation of the Belgian port, transport and logistics industry. Road transport continues to dominate long-haul transport and distribution. Belgium has strong assets – a dense rail network, Europe's best inland waterway network per km², and top-tier seaports (Antwerp-Bruges, North Sea Port, Ostend) - but rail/barge shares are below their potential. Systemic changes in the medium to long term (3+ to 10+ years, respectively) are needed to reach decarbonisation targets. Examples of fields of action needing further implementation steps include:

- Heavy-duty road electrification at scale with Megawatt Charging System (MCS) corridors on E-routes;
- Green corridors across modes;
- Electrified rail with high-reliability paths for freight;
- Zero-emission inland fleet renewal (battery-electric/hydrogen);
- The rollout of clean fuels for hard-to-abate segments;
- The import, storage, and bunkering of green H_2, e-methanol, e-ammonia for deep-sea;
- ReFuelEU Aviation compliance via SAF supply logistics at BRU/CRL/ANR;
- The provision of infrastructure backbones such as H_2 and CO_2 pipeline networks connecting ports, logistics zones, and industrial clusters;
- Trusted, auditable CO_2e accounting embedded in invoices and routing tools.

Belgium is well-positioned to remain a front-runner in green logistics and decarbonisation, thanks to its central location, industrial clusters, and strong maritime and logistics tradition. However, achieving long-term carbon neutrality requires coordinated investments, regulatory alignment, and stakeholder collaboration. Short-term measures such as efficiency improvements and modal shift provide immediate reductions, while large-scale transitions in fuel systems, infrastructure, and energy imports are expected to define the sector's resilience and competitiveness in the decades ahead.

3. Digitalisation of the port, transport and logistics industry

This chapter aspires to provide a comprehensive overview of how logistics automation technologies and optimised data flows interact, forming the foundational framework for a distributed logistics network. This ultimate network vision includes port, transport, and supply chain services that are geographically dispersed yet interconnected, operating as a unified system. The effectiveness of such interconnection relies on the implementation of data-sharing platforms and data spaces that ensure data sovereignty through a decentralised framework and policy-driven data sharing.

The study is structured sequentially, beginning with an analysis of various automation technologies in operations and infrastructure, which concurrently serve as sources for data collection[1]. Subsequently, the study will examine the multifaceted aspects of data flows, followed by a discussion of initial applications that illustrate the emerging trends shaping the future of logistics.

3.1. Logistics automation technologies

3.1.1. Vehicle automation and robotisation

3.1.1.1. Road

Self-driving or autonomous trucks integrate self-driving technology into freight transport vehicles, aiming to operate with little to no human input. They utilise sensors, radars, LiDAR, cameras, GNSS, and machine learning tools to adapt to changing road conditions[2]. These trucks are classified by levels of automation from Level 1 (basic driver assistance) to Level 5 (full automation). Currently, most operate at Levels 2 or 3, which require human oversight in complex situations. Efforts are underway to increase automation, especially in controlled environments like highways.

Autonomous trucks can enhance logistics operations[3]. They can cut fuel consumption by up to 10% through smoother driving patterns, reducing greenhouse gas emissions and aiding the industry's move toward sustainability. While autonomous trucks address driver shortages and improve efficiency, they raise socio-economic concerns, including potential job displacement. New policies will be needed to retrain workers for other roles in logistics. Companies like TuSimple, Embark, Kodiak Robotics and Waymo are testing autonomous trucks mainly on highways[4], enhancing delivery speeds and reducing driver fatigue. However, human operators are still required for loading, unloading, and navigating urban traffic.

[1] AUTOSUP, 2024. Classification of automation technologies, https://www.autosup-project.eu/wp-content/uploads/2024/12/AUTOSUP_D1.1_Classification-of-logistics-automation-technologies-V1.0-1.pdf

[2] https://www.sae.org/standards/content/j3016_202104/

[3] https://transportgeography.org/contents/chapter4/

[4] https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/autonomous-trucks-lead-the-way.html

Despite the promising advantages of autonomous trucks, several technological hurdles hinder their widespread adoption. One major challenge is ensuring that sensor technologies, such as LiDAR, radar, and cameras, can function effectively in adverse weather conditions like heavy rain, fog, or snow[5]. Additionally, the software systems that control these trucks must be capable of making real-time decisions in complex and unpredictable scenarios, such as responding to human-driven vehicles or navigating construction zones. Regulatory environments also present a significant barrier, with current frameworks unstable, particularly in the European Union.

It is hard to predict how fast this technology will reach full deployment. OEMS increase the levels of automation with each model line, and together with **Cooperative, connected, automated mobility or CCAM**, this will lead to much improved safety and operational efficiency. Effective communication among vehicles, infrastructure, and road users is crucial for the safety and integration of future automated vehicles into the transport system. Cooperation, connectivity, and automation are interconnected and will gradually merge. This concept is called Cooperative, connected, automated mobility, or CCAM. On November 30, 2016, the European Commission adopted a C-ITS strategy to promote cooperative, connected, and automated mobility across the EU. The plan aligns investments and regulatory frameworks, paving the way for deploying advanced C-ITS services. A large ongoing Horizon Europe project bringing this into practice is MODI , which will identify and largely resolve barriers in confined areas and on public roads for highly automated vehicles on the corridor from Rotterdam to Oslo. CCAM is a concept actively pursued and supported by various research centres and original equipment manufacturers (OEMs) conducting studies on the topic. Furthermore, the European Commission strongly supports innovation efforts in this area, allowing us to anticipate increased product development and real-world implementation of CCAM applications soon.

Truck platooning, or simply platooning, involves linking two or more vehicles (cars, vans, or trucks) in a convoy using connectivity technology (V2V and V2I) and automated driving support systems. These vehicles automatically maintain a set distance from each other during part of the journey. Platooning operates at various automation levels: Level 1 has all vehicles manned, Level 3 has a manned leader with driverless followers, and Level 5 involves both being driverless. This technology is expected to enhance road transport efficiency by lowering congestion costs, delivery delays, and freight transport expenses, mainly as driver costs decrease. It also reduces energy consumption and emissions, increases road safety, and maximises existing road capacity, promoting sustainability while minimising the need for costly infrastructure expansion. The overall costs of platooning depend on the number of vehicles involved, and regulatory requirements may increase expenses. While it has promising short-term potential for long-distance travel on non-congested roads, its effectiveness is limited in high-density areas[6]. Therefore, its effectiveness may be limited in regions like the Benelux, where high traffic density and frequent congestion reduce its benefits. In such areas, the constant need for acceleration and deceleration undermines the advantages of platooning, which performs best in more open and stable traffic conditions.

[5] https://spectrum.ieee.org/can-you-program-ethics-into-a-selfdriving-car

[6] Global Truck Platooning Systems Market : Size, Share and Forecast Report To 2023. http://prsync.com/bharatbook-market-research-reports/global-truck-platooning-systems-market--size-share-and-forecast-report-to--2576616/

Today's vehicles are increasingly connected devices, and soon, they will directly communicate with each other and road infrastructure through Cooperative Intelligent Transport Systems (C-ITS). This system allows road users and traffic managers to share information and coordinate actions, ultimately enhancing road safety, traffic efficiency, and driving comfort by aiding drivers in making informed decisions. Platooning is a technology still in various stages of development, depending on the level of automation deployed. It certainly has the potential for increased implementation in the short term, particularly on long-distance, non-congested routes. However, this also means that its potential in the delta region is limited.

Smart truck parking systems offer information and reservation services for safe parking of trucks and commercial vehicles. Through mobile apps or fleet management systems, drivers can locate parking areas in line with driving regulations, book spots, pre-pay, and leave ratings or comments. Real-time information on parking availability is communicated via variable message panels, apps, and onboard truck systems, supported by IoT-powered sensors for accurate updates. While improving social, environmental performance, and safety in multimodal transport, their economic efficiency contribution is limited, as parking does not significantly enhance asset productivity. The cost of implementing an e-booking truck parking system can vary widely based on facility scale, required features, and technology provider. Smart truck parking systems are now ready for deployment, given that the required technology is available. However, in a port environment, space and location are crucial factors.

3.1.1.2. Rail & tube systems

Self-operating trains, also known as driverless train systems, can operate without a driver or only require a driver to supervise operations. These systems utilise Driverless Train Operations (DTO) or **Automatic Train Operations (ATO),** which function across various levels of automation defined by the Grades of Automation (GoA). The range goes from manual operation to semi-automatic and finally to fully driverless and unattended systems. GoA4 represents the highest degree of automation, where trains are automatically controlled without any staff on board.

ATO systems manage train functions such as acceleration, cruising, coasting, braking, and stopping. They are connected to traffic management systems, allowing for continuous updates on schedules and route information. The automation enhances the safety of rail operations by automating train starts and stops at stations. Additionally, ATO systems can be integrated with Automatic Train Control (ATC), which oversees signalling operations, including routing and train regulation.

Implementing self-operating trains is expected to significantly improve the operational efficiency and productivity of expensive rail assets. Moreover, this automation contributes to railways' environmental performance as an eco-friendly transport mode. Rail is particularly well-suited for automation due to its fixed network structure. For example, many metro systems around the world have been operating fully autonomously for years.[7]

However, automating mainline railways presents unique challenges. It requires transitioning from a track-based approach to a communications-based control system for more accurate

[7] Fraunhofer 2024

positioning. Additionally, ensuring interoperability among different systems is crucial.[8] It is essential to note that the successful implementation of a fully autonomous heavy haul railway system by Rio Tinto in Australia in 2018 operates on a privately managed, dedicated line[9]. Automating rail operations over long distances, beyond terminals or private lines, is a disruptive concept that will be challenging to implement in the near future.

The **European Train Control System (ETCS)** is a foundational framework to facilitate ATO. ETCS provides common signalling and control standards at a transnational level. As a component of the European Rail Traffic Management System (ERTMS), which also includes safety equipment, automation strategies, management systems, and railway mobile communication systems (GSM-R), ETCS aims to replace the many incompatible systems currently used by European railways. This integration promotes interoperability across rail networks and equipment, significantly enhancing cross-border connections that typically require locomotive changes at borders. ETCS consists of two main parts: trackside equipment installed by network operators and onboard train equipment utilised by rail transport service providers. It is based on the ATO concept, allowing trackside information to be transmitted directly to the train's control cab, eliminating the need for trackside signals.

Hyperloop and spill-over applications: The Hyperloop is a proposed high-speed transportation system that moves passengers and cargo through low-pressure tubes at very high speeds. Its goal is to revolutionise transportation by significantly reducing travel times between cities and economic centres, including airports. The Hyperloop offers a high-capacity alternative to existing modes of transport. In this system, people and goods are transported in relatively small, individually travelling units known as pods. These pods range in size from 30 to a larger dimension determined by specific needs and can also consist of convoys of even smaller units. For cargo, pod designs are already in place to accommodate up to 5 pallets, with a capacity of 2.5 metric tons.

The pods' size and the system's high capacity enable fast and flexible direct connections, providing a high level of responsiveness to changing demand. Although still in the experimental and development stages, several companies and governments are exploring the feasibility of implementing Hyperloop systems in various regions worldwide. Currently, the leading developers are working towards standardisation and interoperability with other transport modes(Hyper4Rail project)[10].

Consistent progress is being made, and while most of the technology needed to make the concept a reality is well-developed, several critical systems, such as thermal energy management, still require further enhancement. The practical implementation of the hyperloop in its pure form, using low-pressure tubes, remains several decades away.

Cargo tubes utilise the hyperloop concept by operating in a low-pressure environment encapsulated within a tube. Unlike traditional hyperloop systems, cargo tubes depend on more conventional and readily available track technologies, such as those used in trains or streetcars, to guide and propel the vehicle inside the tube. They can adopt large-diameter steel tubes similar to those used in gas or water pipelines. By leveraging existing and well-

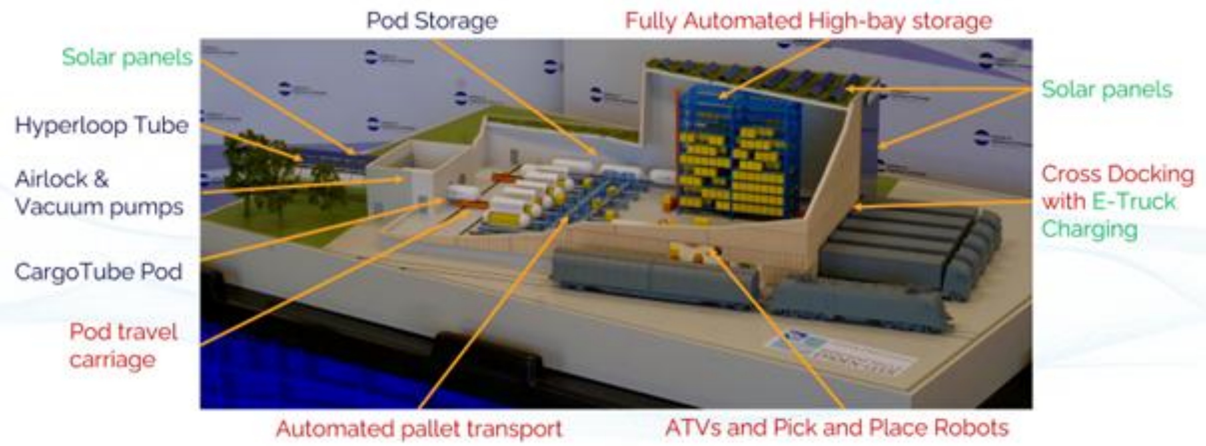
[8] New and Emerging Transport Technologies and Trends in European Research and Innovation Projects 2024, Rataj, M., Lodi, C., Zawieska, J. Stepniak, M. Cheimariotis, I., Grosso, M., Piazza, F. Marotta, A., European Commission, ISSN 1831-9424, 2025.
[9] https://www.riotinto.com/en/news/stories/how-did-worlds-biggest-robot
[10] https://www.hyper4rail.eu/

established technology along with "off-the-shelf" components, cargo tubes can significantly reduce development costs and enable the rapid scaling of transportation networks.

Cargo tubes also offer a high degree of automation through robotic cargo handling systems. An electric propulsion system powered by renewable energy sources lowers emissions and reduces the energy required per kilometre and ton of cargo. Two different acceleration systems are proposed: the first features a propulsion system and energy supply located within the vehicle, allowing for a cost-effective passive infrastructure. The second system suggests lower-cost lightweight vehicles combined with an active propulsion system integrated into the tube infrastructure. While this active system offers lower operational costs due to its lighter vehicles and a more efficient linear motor, it incurs higher tube infrastructure costs.

Hochschule Emden-Leer developed one such concept as part of the Horizon 2020 project ePIcentre[11]. It proposes a cargo tube linking a distribution centre outside Wolfsburg with the Volkswagen (VW) factory in the city's urban area.

Figure 3.1. Intermodal Cargo Tube Logistics Service Park



Source: Institute of Hyperloop Technology, Hochschule Emden Leer, Germany, 2023.

This design does not require a low-pressure environment compared to the pure hyperloop concept. Provided that all external conditions are met, cargo tubes present a realistic solution. Implementing this system is expected to be more cost-effective and will help alleviate congestion.

The application of Hyperloop and cargo tube systems is still a while away. However, the technology developed while pursuing the Hyperloop concept may have spillover applications that could be helpful for port operations and provide Hyperloop developers with opportunities to monetise their innovations. Examples include the **autonomous railway wagons** developed by the Polish start-up Nevomo, featuring the new "MagRail Booster" solution for freight transport, and Zeleros' container mover system with the SELF-Booster facility.

Hyperloop systems and technologies represent a disruptive shift in transportation. The trend, however, is toward simple and easy-to-operate autonomous systems, such as autonomous

[11] https://epicentreproject.eu/

rail wagons with linear motors, like the MagRail Booster developed by Nevomo. This innovation modernises rail transport by enabling these wagons to operate seamlessly on existing railway tracks, eliminating the need for extensive and costly infrastructure modifications.

Figure 3.2. Cargo MagRail Booster, retrofit

Source: Nevomo, Poland, 2024.

The MagRail Booster enhances track capacity and flexibility while supporting full electrification and automation of railway operations. This includes critical processes, such as shunting in terminals and industrial facilities, which have traditionally required significant manual intervention. By automating these functions, operators can achieve substantial cost reductions, increased safety, and improved efficiency in rail logistics.

The technology is versatile and adaptable, with a Level of Automation (LoA) that varies from supervised automation—where human operators monitor system functions—to highly automated operations that require minimal human intervention. This scalability makes this solution suitable for various use cases, from industrial logistics hubs to high-demand freight corridors, paving the way for a more sustainable and efficient future in rail transport.

Currently (2025), this technology is being further explored and developed in a joint venture between Nevomo and Hansebahn Bremen GmbH (HBB), a joint venture of rail logistics expert Captrain Deutschland and steel company ArcelorMittal Bremen, in a joint pilot project for automated freight transport at the Bremen factory. In this joint pilot project, HBB is responsible for organising and implementing rail transport on the 100-kilometre-long rail infrastructure.

An **Underground Container Mover (UCM)** is an autonomous transport system that uses electric vehicles and IoT sensors to move containers through underground tunnels efficiently. It benefits ports and logistics hubs by facilitating streamlined movements in crowded areas. The UCM Port-Loop[12] features a continuous looped tunnel connecting key points in the port, allowing for high-throughput, uninterrupted container movement. It integrates automated container stacking systems to optimise space and improve intermodal connectivity, making it ideal for busy environments. Key components include a minimalistic tunnel network, Autonomous Electric Vehicles (AEVs) for 24/7 operations, and automated stacking for higher-density storage. While still emerging, UCMs offer a promising but bold solution for enhancing logistics efficiency and reducing environmental impact in modern ports, requiring solid business cases and community support for expansion.

Other automation technologies include the **automated maintenance of rail wagons**. This refers to using advanced technologies and automated systems to inspect and assess the condition of in-service assets, enabling the estimation of when maintenance should be performed with minimal human intervention. Another key innovation is **Digital Automatic Coupling** (DAC), designed to couple and uncouple rolling stock in freight trains automatically. This system handles both the mechanical connection and the air line for braking, as well as electrical power and data connections. Currently, however, screw couplings remain the standard for freight trains in European countries. Digital automatic coupling has the potential to play a crucial role in modernising and digitising European railway freight transport.

3.1.1.3. Air

Unmanned Aircraft (UA), or **Remotely Piloted Aircraft (RPA),** are operated from a remote pilot station without a pilot onboard. Unmanned Aircraft System (UAS) refers to the entire system, including the unmanned aircraft and the equipment used to control it remotely. Similarly, the term Remotely Piloted Aircraft System (RPAS) encompasses the whole operating system, including the remotely piloted aircraft, associated remote pilot stations, and the necessary command and control links[13].

These aircraft can be controlled entirely from a different location, such as the ground, another aircraft, or even space, or they can be pre-programmed to execute flights autonomously without any intervention. Commonly referred to as **drones**, these aerial platforms can operate autonomously and come in various forms, including multi-rotor, single-rotor, and fixed-wing models (including those capable of vertical take-off and landing). Drones can carry payloads ranging from a few grams to several hundred kilograms, making them suitable for various applications, from parcel deliveries to medical and emergency supplies.

Drones vary in type based on their payload capacity, operational range, flight altitude, speed, and energy source (fuel or battery-electric). They can also be effectively utilised for inventory management operations.

Electric vertical take-off and landing drones, known as eVTOLs, are also being developed with larger capacities and ranges. These drones can carry cargo weighing up to 680 kg. Given the operations from Vertiports for these drones, it would be logical to consider situating such hubs near or within ports to optimise their use.

[12] https://www.denys.com/en/projecten/underground-container-mover

[13] Drone Innovators Network Summit 2019 | | Factly. https://factly.forumias.com/drone-innovators-network-summit-2019/

In recent years, drones have become a key component of the future green transport ecosystem, particularly in urban logistics applications. They are rapidly making headway in the commercial market, attracting the attention of major players in the logistics industry, such as Walmart in the US, Tesco in Ireland, and Meituan in China. However, most drone operations focus primarily on business-to-consumer (B2C) applications. Since 2018, the global number of drone deliveries has been growing at approximately 135% annually, surpassing one million deliveries in 2023 (McKinsey, 2023)[14].

The versatility of drones makes them suitable for various fields, some of which are being explored in large-scale European Union research projects. These fields include transport infrastructure maintenance and construction, agricultural monitoring, border surveillance, medical aid distribution, environmental monitoring, and landmine detection[15].

Since 2018, drones have been actively utilised for infrastructure inspection and inventory management at the port of Antwerp-Bruges. The technology has the potential to yield significant economic benefits by reducing operational costs, such as those associated with drivers. However, there are still constraints to consider, such as limited battery life, range, and payload capacity, as well as regulatory frameworks prioritising safety and security, thus limiting drone operations outside controlled areas or near critical infrastructure (e.g., airports, refineries, power plants).

Drones also have the potential to enhance the effectiveness of logistics systems in terms of speed and service. They can access hard-to-reach locations, and under suitable conditions, they can contribute to reducing environmental impacts. Consequently, as the number of drones in the sky grows, it is crucial to safely integrate them into existing airspace to ensure seamless operations alongside manned aerial vehicles. The absence of a drone traffic management ecosystem presents technological, legislative, and regulatory challenges for large-scale deployment. Recognising this issue, many aviation regulatory authorities have started to develop operational concepts for incorporating drones into existing air traffic management (ATM) systems and supporting research on the relevant technological challenges.

One such initiative in Europe is the development of the **U-space framework**, which was committed to in 2016. U-space is a set of services and specific procedures designed to facilitate safe, efficient, and secure airspace access for many drones. The necessary infrastructure and technologies, such as wireless communication, are essential components of this system, as U-space services depend on a high level of digitalisation and automation of functions, both on board the drones and in the ground-based environment[16].

3.1.1.4. Maritime

An unmanned ship, also known as an autonomous vessel or Uncrewed Surface Vessel (USV), operates without a crew and can be remotely controlled or fully autonomous. Autonomous cargo ships, or Maritime Autonomous Surface Ships (MASS), function with little to no human interaction and rely on advanced algorithms for navigation. These vessels are categorised by their Level of Autonomy (LoA) from 1 to 5, based on the degree of automation and the presence of operators on board, according to the International Maritime Organisation (IMO).

---

[14] Drone Innovators Network Summit 2019 | | Factly. https://factly.forumias.com/drone-innovators-network-summit-2019/

[15] TRIMIS, 2024

[16] https://www.sesarju.eu/U-space

Autonomous vessels may be integrated into the Antwerp L-Hub to align with shipping sector advancements. Economic benefits include reduced operational costs, such as crew and labour, alongside potential fuel savings, although psychological stress may increase for those on board. Environmentally, autonomous vessels are expected to operate more efficiently. Cost estimates vary significantly depending on size, type, automation level, and whether vessels are newly built or retrofitted.

Overall, autonomous vessels are an emerging technology with ongoing developments. There is no unified framework governing autonomous vessels, and it remains unclear how many port authorities want to interface with such unmanned ships. Economic factors further complicate this situation, including the need for technical redundancy systems and transitional safety measures that require crew on board. Progress continues in specific short-sea shipping lanes and applications such as tugboats and inland waterways. These regulatory sandboxes will promote the gradual integration of semi-autonomous solutions, ultimately paving the way for broader acceptance.

A **Remotely Operated Inland Vessel (ROIV)** is an innovative advancement in maritime transportation designed for inland waterways. These vessels use cutting-edge technologies for remote control and monitoring, eliminating the need for an onboard crew while ensuring safety, efficiency, and sustainability. ROIVs are equipped with sensors, cameras, and radar, providing real-time views of their surroundings. Data is transmitted to a remote operations centre, where skilled operators manage navigation and cargo handling. The navigation system utilises GPS, LIDAR, and advanced radar to detect obstacles and adjust routes, while AI algorithms optimise these processes based on environmental conditions. Communication networks, including satellite links, long-range Wi-Fi, or 5G, are essential for maintaining constant control. ROIVs often employ electric or hybrid propulsion systems that reduce environmental impact, featuring technologies like battery-powered motors or hydrogen fuel cells to enhance energy efficiency and reduce operational costs. The primary advantages of ROIVs include reduced human error, improved operational efficiency through continuous monitoring, and lower emissions, making them an eco-friendly option for inland logistics. They are well-suited for cargo transport, last-mile deliveries, waterway maintenance, and short-distance ferry services. Despite regulatory issues, communication reliability, and cybersecurity challenges, technological advancements pave the way for broader adoption. The rise of ROIVs represents a significant shift in logistics and transportation, promising a safer, more sustainable, and efficient future for inland maritime transport.

Remote operations utilise telecommunications technology to control and operate devices or machines from a location separate from where the operator is physically present. This process involves using remote control devices, sensors, and other technologies to transmit data between the operator and the machine. Remote operations hold significant potential in the field of autonomous vehicles. While AI models can be trained to handle standard control tasks, unpredictable or complex scenarios often require human intervention. In such cases, a remote human operator can take over, ensuring safety and precision.

An excellent example is Seafar, pioneering remote operations in the maritime industry by enabling captains on dry land to navigate vessels on inland waterways from afar. Unmanned vessels significantly reduce costs and provide solutions to rising mobility issues. Seafar has developed cutting-edge technology for the remote control of semi-automated inland navigation vessels. This technology is already being utilised on the estuary container ship 'Deseo', which sails semi-autonomously between Zeebrugge and Antwerp. Research conducted by the University of Antwerp and the Port of Antwerp-Bruges has indicated that 3D sonar sensors inspired by bats can enhance this technology. Seafar supports and operates these automated vessels from its Shore Control Centre (SCC) in Antwerp. The newly designed SCC features six control stations and two traffic control structures capable of managing up to 20 vessels, making it the world's first fully operational SCC for inland shipping. Additional offices have since opened in Charleroi, Belgium, and Duisburg, Germany.

By leveraging the latest AI and machine learning technologies, Seafar's Shore Control Centre assists captains in navigating and manoeuvring ships, improving efficiency and safety. The combination of vessel autonomy and remote pilotage is essential for effectively implementing smart shipping.

One significant benefit of remote support is the extended operational time for vessels. Remote access could theoretically allow for global control of operations, thus increasing operational efficiency and significantly reducing downtime—potentially by up to 500 working hours annually. Seafar's automation hardware and software are compatible with vessels up to 135 meters long and applicable for both inland and coastal navigation.

Remote operations also address Europe and Flanders' need to shift cargo transport from road to waterways. However, the industry faces challenges such as a shortage of captains and a lack of interest among young people in maritime careers. Utilising reduced crew sizes and semi-autonomous vessels supported by advanced technology and AI may provide a solution.

Figure 3.3. Seafar's shore control centre (Remote Operated inland vessels)

Seafar's innovations appeal to the next generation of captains. They allow them to operate from a Shore Control Centre with a 360° view of their vessels and access to extensive data. The system is intuitive, and captains only need to take control during critical manoeuvres, like passing through locks, which helps reduce costs for shipping companies.

Seafar employs Real-Time Kinematic (RTK) positioning to navigate ships remotely, providing 10-centimetre precision. Stable communication between the ship and shore is maintained through a combination of 4G, 5G, and satellite technologies developed in collaboration with the European Space Agency (ESA). Seafar offers a range of services to enhance vessel capabilities and efficiency:

- Crew Supported Navigation: Expanding vessel capabilities through integrating the Seafar control system and services.
- Crew-Reduced Navigation: Operating automated ships with a smaller crew, supported by the Shore Control Centre, maximises navigation time and vessel efficiency.
- Unmanned Navigation: For fixed routes, unmanned navigation enhances the competitiveness of smaller vessels by maximising operational efficiency without needing a crew on board.

Autonomous tugboats are a form of autonomous ship technology designed to assist with the complex task of ship berthing, which large merchant ships typically cannot perform without support. By automating this process, autonomous tugboats eliminate the need for human assistance. Autonomous tugboats have similar impacts as unmanned ships, notably reduced operational costs related to crew expenses and environmental effects, primarily concerning emissions in port areas. Costs for autonomous tugboats vary based on size, type, and level of automation. Leading companies in this sector include Rolls-Royce, Wärtsilä, and Kongsberg. Overall, autonomous tugboats represent an evolving technology that will likely see continued advancements soon.

Automated mooring technologies enable mooring and docking operations at ports without human intervention. All ship processes, including mooring, must be automated for fully autonomous ships. Mooring secures a ship to a permanent structure, preventing it from moving freely in the water. There are several automated mooring systems: vacuum-based systems like the MoorMaster, magnetic-based systems currently under development, and robotic arm solutions such as the one from MacGregor for the Yara Birkeland autonomous containership. Automated mooring is expected to lower operational costs and increase port efficiency by reducing docking times and enhancing safety. It will also benefit the environment when combined with electric or hybrid propulsion systems.

3.1.2. Cargo terminal and warehouse automation

There is an increasing trend toward the extensive automation of port infrastructure, with a particular focus on cargo terminals and warehouses. This shift goes hand-in-hand with the automation of various transport modes, including trucks, ships, and rail systems, as well as the operational equipment that supports them. Digitalisation stands at the forefront of this transformation, significantly enhancing the efficiency and productivity of port operations. Digitalisation streamlines cargo management by integrating advanced technologies, such as sensors, data analytics, and robotics. It optimises wider transport and supply chain processes, ultimately acting as a powerful catalyst for innovation and improvement in the logistics sector.

3.1.2.1. Cargo terminal automation

The potential for fully automated cargo terminals is significant, driven by various technological advancements that are fundamentally transforming the logistics and transportation sectors. As global trade expands, meeting the rising demand for efficiency, precision, and reliability in cargo handling has become essential. Automation presents transformative opportunities to enhance operational efficiency, reduce costs, and improve safety in cargo handling processes. Advanced technologies, such as robotics, artificial intelligence (AI), and the Internet of Things (IoT), play a critical role in this transformation. These innovations enable cargo terminals to evolve into intelligent and streamlined operations. Robotics can automate labour-intensive tasks like loading and unloading cargo, while AI can improve routing and scheduling efficiencies, ensuring the swift movement of goods throughout the terminal. Additionally, the integration of IoT allows for the connectivity of various equipment and systems, promoting real-time data exchange and monitoring, which can significantly improve decision-making and operational oversight.

A **fully automated cargo terminal** utilises advanced technologies such as robotics, artificial intelligence, and the Internet of Things (IoT) to streamline cargo handling operations. These terminals optimise processes like loading, unloading, and storage with minimal human intervention, thereby enhancing efficiency, reducing operational costs, and improving safety. Automation technologies—including automated guided vehicles (AGVs), automated cranes, and real-time data management systems—enable seamless integration with supply chain networks, making these terminals essential to modern logistics and port operations.

The Qingdao New Qianwan Container Terminal (QQCTN), Asia's first fully automated container terminal, is often cited as the world’s most advanced terminal. The terminal is controlled by laser scanners and positioning systems that can locate the four corners of each container with precision, allowing for accurate clamping and movement onto AGVs. Automated guided vehicles are programmed with routes and tasks, and also have the artificial intelligence to recognise when a recharge is needed. Equipment scheduling, vessel storage, container delivery and gate are all fully automated.[17]

Automatic Stacking Cranes (ASCs) are unmanned cranes that store and retrieve containers automatically. Each ASC module consists of two cranes: one located on the waterside to service vessels and another on the landside to handle trucks. The advantages of ASCs include time savings, as they operate 24/7; enhanced accuracy due to an integrated system of lasers and cameras that precisely determines the container's position and places it accurately on the truck's twist locks; and increased capacity, as ASC modules can stack containers up to six high.

Autonomous terminal trucks (ATT) are a technology that allows trucks to drive safely in mixed traffic within container terminals. This innovation enhances overall efficiency in port logistics, reduces errors, and improves safety in port environments. A key application of ATT is in port terminals, where autonomous trailer tractors are essential for handling shipping containers and trailers. These autonomous tractors have advanced navigation systems and communication tools that connect with Terminal Operating Systems (TOS). This setup helps minimise congestion and improve the flow of goods within the terminal.

Automated High Bay Storage Systems (AHBCS) store containers in individual racks, allowing each one to be accessed directly. These systems utilise tall racks that can increase the transhipment capacity of container terminals by 200% or more. The components of an AHBCS include:

- A high-bay steel structure with a roof and side cladding to house the containers.

[17] https://www.apmterminals.com/en/qingdao/about/qingdao-new-qianwan-container-terminal

- Fully automated electric overhead travelling cranes place containers in the high-bay racks.

- Overhead cranes with spreaders load and unload trucks in a designated container exchange zone.

- A Warehouse Management System (WMS) that optimises container movement and facilitates data integration within the distribution centre's material flow.

Autonomous terminal tractors are advanced vehicles designed to enhance operations in container terminals, logistics hubs, and industrial facilities. These tractors feature cutting-edge technologies that allow them to operate without human intervention, improving efficiency, safety, and sustainability in cargo handling and movement. Equipped with advanced sensors, such as LIDAR, cameras, and ultrasonic devices, autonomous terminal tractors possess real-time environmental awareness. These sensors enable the vehicles to detect obstacles, navigate complex terminal layouts, and perform precise manoeuvres like docking and trailer alignment. Powered by artificial intelligence (AI) algorithms and advanced navigation systems, these tractors process input from their sensors to find optimal routes, avoid collisions, and adapt to dynamic operational conditions. Communication technologies, including Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) systems, allow these tractors to coordinate with terminal management systems and other autonomous vehicles, ensuring seamless integration into the broader logistics network. Most autonomous terminal tractors are designed to be energy-efficient and environmentally friendly, utilising electric propulsion systems or hybrid engines. These power systems help reduce emissions and support the sustainability goals of modern logistics and port operations.

Automated Rail-Mounted Gantry (ARMG) and **Automated Rubber Tyred Gantry** (ARTG) systems operate without human intervention, utilising advanced software and sensors. These systems efficiently handle the stacking, retrieval, and transportation of containers, optimising yard operations and reducing the need for manual labour. Rail-mounted gantry (RMG) cranes, known for their stability and precision, are ideal for high-throughput environments. In contrast, Rubber Tyred Gantry (RTG) cranes offer flexibility and mobility, making them suitable for dynamic storage areas.

Autonomous container movers are an innovative logistics solution designed to transport cargo containers efficiently and sustainably within ports and logistics hubs. These systems use advanced technologies, including electric propulsion, sensor-based navigation, artificial intelligence, and safety mechanisms. The propulsion system is typically powered by electric motors that draw energy from onboard batteries or electrified tracks, providing an eco-friendly operation that eliminates emissions. Navigation relies on a combination of LIDAR, GPS with Real-Time Kinematic positioning, cameras, and ultrasonic sensors, creating a detailed map of the environment to help the vehicles detect and avoid obstacles. The control units utilise artificial intelligence and machine learning algorithms to process sensor data, allowing for autonomous navigation, route optimisation, and speed adjustments based on dynamic conditions. These systems function without human intervention while communicating with centralised management systems.
Infrastructure requirements are streamlined, with systems operating on embedded tracks or following predefined virtual paths. Battery-powered vehicles use charging stations, while electrified systems draw power from their tracks.

Safety is paramount; real-time monitoring systems provide feedback on position and speed, while fail-safe mechanisms ensure controlled stops in emergencies. These systems' adaptability allows them to handle various container sizes and weights.
Emerging technologies, like hyperloop-inspired systems (ZELEROS)[18] and digital twins, further enhance autonomous container movers, enabling high-speed transport and real-time operational optimisation.

Automated high-bay container storage systems offer an innovative solution for optimising space and efficiency in container terminals and logistics hubs. These systems automate the storage and retrieval of shipping containers, maximising vertical space and reducing the need for extensive storage areas. By utilising robotics and advanced control systems, these systems enhance speed, safety, and sustainability in container handling. Automated cranes and robotic shuttles efficiently move containers, quickly transitioning them between storage bays and transportation modes such as trucks, trains, or ships. A centralised control system optimises storage layouts and manages container movements. These systems significantly increase space utilisation by vertically stacking containers, which is especially beneficial in space-constrained environments. They also expedite container retrieval, reducing delays and improving the flow of goods, which is vital in high-demand situations. Human involvement in container handling is minimised, which enhances safety and lowers the risk of accidents and damage. Additionally, electric-powered robotic systems reduce reliance on diesel equipment, contributing to lower emissions and supporting greener logistics solutions.

A **Gate Automation System** (GAS) at terminals is designed to identify and record entities, such as drivers, trucks, and transport units, as they enter or exit the port. The integration of automation technology with a Terminal Operating System (TOS) has become indispensable for enhancing operational efficiency and bolstering security, particularly in large terminals. Typically, a GAS encompasses three fundamental subsystems: the Driver Identification System (DIS), Automatic Number Plate Recognition (ANPR), and Container Number Recognition System (CNRS). The DIS is responsible for verifying drivers' identities through applications, identification cards, and advanced biometric methods, including facial recognition and fingerprint scanning. This verification process may also involve assessing relevant certifications to ensure compliance with legal and safety standards. The CNRS utilises Optical Character Recognition (OCR) technology to automate the identification of container codes, employing sophisticated algorithms to guarantee accurate readings. The integration of OCR with ANPR facilitates the simultaneous recognition of container numbers and vehicle license plates, thereby streamlining the verification processes at ports and terminals.

A **Terminal Operating System** (TOS) is specifically designed to manage the movement and storage of various types of cargo within a port terminal. This system is capable of handling both containerised and non-containerised cargo. The TOS employs various technologies, including the Internet, Electronic Data Interchange (EDI), wireless communication, and Radio Frequency Identification (RFID), to monitor cargo. This data collection facilitates the generation of reports regarding the status and locations of goods and equipment within the terminal. The TOS encompasses many tools and functionalities, such as intelligent truck optimisation and yard optimisation, alongside stowage planning. Advanced Automatic Number Plate Recognition (ANPR), integrated with Optical Character Recognition (OCR) technology, is utilised at entry and exit gates, inspection lanes, and cranes. This technology

[18] https://zeleros.com/eurostars-electric-freight-forwarder/

automates the identification of container IDs, trailer numbers, and license plates. Furthermore, high-resolution images are utilised to assess the condition of containers and trailers. The processed information is automatically integrated with the TOS to enhance operational efficiency.

Today, mechanical seals are mainly used to secure containers and trailers. However, the process is prone to errors due to various individuals manually entering seal numbers at different times. These inaccuracies lead to additional costs, claims, and delays at terminals. The introduction of **e-seals (passive RFID)** can help address these issues. E-seals can be automatically read using handheld devices or gate readers, thus improving both efficiency and security. Technologies like GPS, 3G, 4G, 5G, LoRa, and Sigfox can also be integrated with passive e-seals to provide real-time status updates. Some e-seal models combine sealing functionality with tracking systems. Although these seals are significantly more expensive than traditional mechanical seals (costing up to 50 times more), this extra expense can be justified when considering the reduction in inaccuracies.

The **Container Weight System** (CWS) represents an automated solution specifically designed to accurately measure and declare the Verified Gross Mass (VGM) of shipping containers. This measurement is essential for ensuring the safe and efficient loading, transportation, and unloading of containers. As mandated by the International Maritime Organisation (IMO), effective July 1, 2016, all shipping containers must possess a verified gross mass (VGM) before being loaded onto a vessel, in compliance with the Safety of Life at Sea (SOLAS) convention. The VGM may be determined through two distinct methods: either by weighing the packed container using calibrated and certified equipment or by weighing all individual items, including packaging and dunnage, and subsequently adding the container's tare mass. Self-service weighbridges are automatically integrated with the terminal's Terminal Operating System (TOS), facilitating the recording of weight data and its transfer to pertinent stakeholders. This level of automation minimises human error and accelerates operational efficiency.

Slot Booking Systems (SBS) implemented at ports play a critical role in enhancing the efficiency and safety of road hauliers, particularly concerning the pick-up and drop-off processes for containers. These systems enable road hauliers to access multiple available time slots during which the required containers are prepared for collection. By facilitating the exchange of information in advance between road hauliers and terminals, both parties can effectively coordinate and schedule their respective pick-up and drop-off activities. Drivers can access the SBS using personal accounts, enabling them to view available time slots over a designated period and select an appropriate time based on the nature of their operations, such as imports. Furthermore, the SBS can be designed to accommodate a broader range of users, including truck drivers, terminal employees, and visitors. Systems also support pre-announcements for terminals, vessels, and other locations, providing users with pertinent information regarding the applicable rules and regulations at those sites. Due to its integration within digital platforms that connect various supply chain participants, SBS can also be considered a form of "Partial Automation".

The systems facilitate the optimal utilisation of existing port-related spaces, thereby systematically enhancing port spatial planning performance and security. Additionally, by streamlining port and logistics operations, SBS contribute to reducing congestion within terminal areas and decreasing pollutant emissions, ultimately resulting in improved energy efficiency across operations.

A Certified Pick-up system (CPU) platform receives and processes container information[19]. This information facilitates the generation of a digital release right and an authorized digital pick-up right, both of which permit the retrieval of the container. The shipping line issues the release right based on commercial release information, transferable among companies. The creation of the digital pick-up right occurs solely upon the identification of the final carrier of the container. A driver is permitted entry into the terminal only if a commercial release from the shipping line exists, a terminal release from the terminal operator, and a customs release. In the Port of Antwerp-Bruges, the utilisation of the CPU platform has been mandated for all supply chain partners engaged in the container release process. The CPU platform offers a user interface designed for companies managing a limited number of containers and an API interface for organisations handling larger volumes.

High-volume greenfield projects are generally more favourable for integrating a wide range of existing automation technologies. Their long-term return on investment (ROI) and compatibility with current systems tend to be more predictable than the complexities of retrofitting existing terminals. This includes the challenges of ensuring interoperability with private and port legacy systems.

3.1.2.2. Warehouse automation

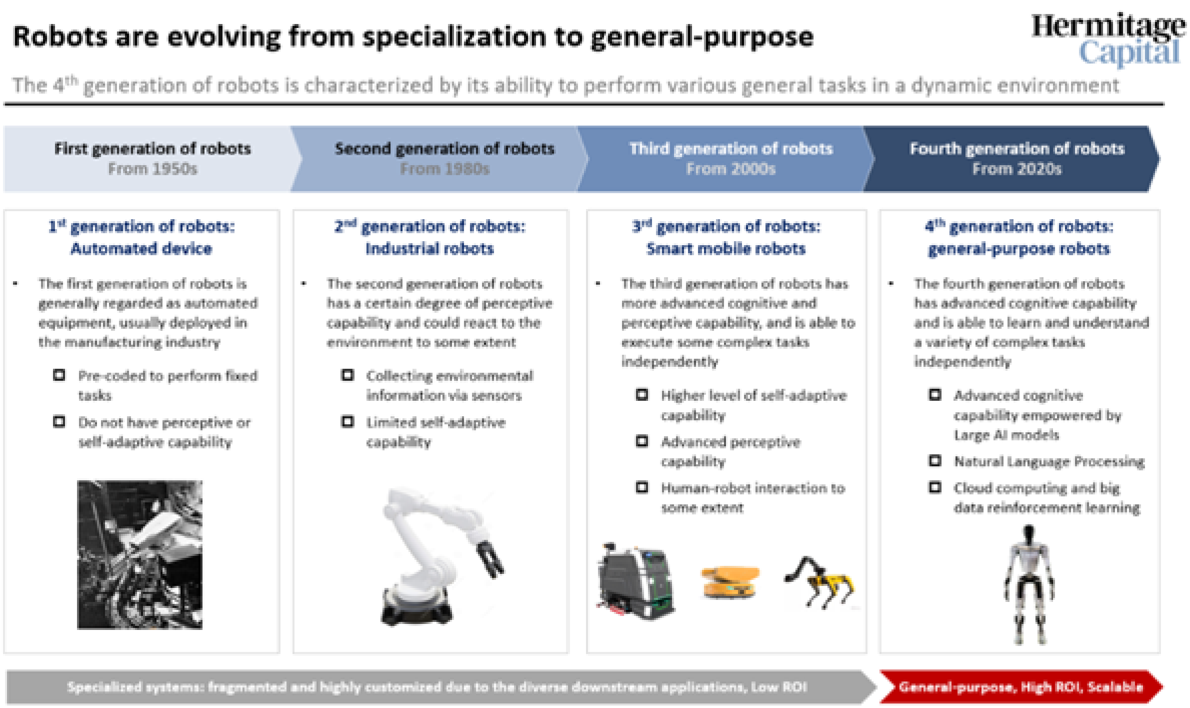
In warehouse operations, **robotics** is making significant strides by implementing advanced technologies that automate various tasks within the logistics chain, including handling, picking, sorting, shipping, storage, and retrieval.

These cutting-edge applications incorporate robotic arms, which are frequently integrated with Automated Storage and Retrieval Systems (AS/RS) and conveyor systems to establish streamlined workflows. Furthermore, autonomous mobile robots (AMRs) can navigate complex environments, transporting goods to designated locations while collaborating with human operators and other machines. Vision-guided robots, equipped with sophisticated sensors and machine learning algorithms, can efficiently identify, pick, and place items, adapting to diverse product shapes and sizes.

Automating repetitive tasks traditionally performed by human workers significantly enhances productivity, operational efficiency, and safety. Such automation reduces labour costs, minimises human errors, and provides real-time data that optimises inventory management and demand forecasting.

[19] MASP-C Part 2: Modernising Port Operations - The Certified Pick up Platform. https://www.portorium.solutions/blog/masp-c-part-2-certified-pick-up-platform

Figure 3.4. Robot generations



Source: Hermitage Capital, 2023.

Looking to the future, it is plausible to anticipate the emergence of multi-limbed, bipedal, and quadrupedal robots that approach the conceptualisation of humanoids and potentially synthetic humans. However, the current understanding underscores the necessity for further enhancement of the versatility and application domains of these robots to yield positive returns on investment (ROI)[20]. Ultimately, these advancements are poised to further bolster the responsiveness and resilience of supply chains.

A **Warehouse Management System** (WMS) is software designed to efficiently manage and track all operations within a warehouse. This includes handling inbound shipments, organising storage, and overseeing the picking, packing, and shipping processes. The system optimises these processes by minimising internal routing paths, implementing effective storage strategies such as ABC classification, and ensuring accurate and timely order fulfilment.

A Warehouse Management System (WMS) integrates Automatic Identification and Data Capture (AIDC) technologies, such as barcodes, mobile devices, and RFID, to streamline real-time data collection, inventory tracking, and process verification.[21]. A WMS enhances decision-making and resource allocation within the warehouse by providing insights into stock levels and movement patterns. A WMS typically facilitates the digitalisation and partial automation of manual processes. This increases operational efficiency while allowing for human intervention in the workflow.

[20] Humanoids 2025 (Jan), STIQ Ltd Research & Analysis, Andersson T., Al-Refaie Y., Dixon G., www.stiq.ltd
[21] Crisilinfotech. https://crisilinfotech.com/warehouse-management-software

Automated Guided Vehicles (AGVs), which are commonly referred to as **Autonomous Mobile Robots** (AMRs) when they operate independently of infrastructure-based navigation, are autonomous systems specifically designed for the transportation of materials such as pallets, rolls, racks, and totes in industrial and warehouse environments without the necessity for human operators. Equipped with advanced navigation systems, AGVs can move efficiently across designated areas, thereby facilitating the connection between Automated Storage and Retrieval Systems (AS/RS) and various operational zones, including picking areas, pre-loading stations, stowing locations, and truck-loading docks. AGVs employ various navigation technologies, encompassing wired tracks, magnetic strips, laser guidance, and vision-based systems, which enable precise navigation within their operational environments.

As a specialised category of AGVs, AMRs can dynamically map their surroundings through sensors and artificial intelligence, enabling them to navigate without predetermined pathways. This adaptability allows for real-time adjustments to changing warehouse layouts and the ability to circumvent obstacles, making them particularly well-suited for dynamic logistics scenarios.

Furthermore, AGVs are equipped with multiple battery-charging options, including opportunity charging, inductive (wireless) charging, and battery-swapping systems. These features enhance operational uptime and minimise downtime, a significant advantage in high-demand environments where maintaining an uninterrupted workflow is critical. Automated Guided Vehicles (AGVs) signify a sophisticated level of automation 4, which requires minimal to no human intervention for operations[22]. At this advanced level, AGVs substantially enhance productivity, safety, and cost-effectiveness by automating intricate material-handling tasks and decreasing dependency on manual labour. Consequently, they play a vital role in fully automated warehouse and industrial logistics solutions, facilitating seamless material flow and optimising supply chain operations.

Voice integration through voice-picking solutions is a transformative technology in warehouse automation that significantly enhances efficiency. These paperless, hands-free systems guide workers with voice prompts to specific locations in the warehouse, allowing them to pick up necessary items for customer orders using headsets equipped with microphones. Voice-picking systems increase productivity by enabling workers to concentrate on picking items without checking lists or devices. The voice-guided instructions help reduce errors and improve accuracy, leading to faster order processing and greater customer satisfaction. A significant advantage of voice-picking is its flexibility in adapting to real-time changes. Workers can quickly respond to updated picking priorities or navigate around obstacles, making it ideal for fast-paced logistics environments. Additionally, the system provides real-time feedback for immediate error correction, enhancing accuracy and lowering return rates. Thanks to the substantial efficiency gains, voice-picking technology also reduces onboarding time for new employees and improves worker safety by minimising manual data handling.

Augmented Reality (AR) and Virtual Reality (VR) technologies are emerging tools in logistics that allow companies to streamline operations, optimise resource use, and enhance customer

[22] AI and Chatbots for Lawyers - Duforest AI. https://duforest.ai/ai-and-chatbots-for-lawyers/

experiences. AR is vital in warehousing and inventory management, often applied through smart glasses or mobile devices[23].

"Vision picking" through smart glasses allows warehouse personnel to receive visual instructions, enhancing order handling and fulfilment accuracy. Augmented Reality (AR) facilitates warehouse planning by visualising layouts and identifying optimal pathways. Furthermore, AR-enabled devices improve cargo handling by expediting the scanning and identification of shipments. In transportation, AR delivers real-time information to drivers, including navigation guidance and cargo-specific instructions, particularly under challenging conditions. Virtual Reality (VR) allows logistics companies to utilise three-dimensional simulations for training purposes, effectively replicating complex operations in a secure environment. Both VR and AR are categorised as Level 1 automation technologies. They augment human capabilities without fully automating tasks, functioning as enhancement tools that improve accuracy and efficiency while allowing employees to retain manual control. This ultimately assists logistics and warehouse teams in operating more effectively.

Automated loading and unloading systems in cargo bays are designed to enhance the efficiency and safety of transferring goods to and from trucks, trailers, or containers. These systems are customizable to accommodate various cargo types, allowing them to adapt to differing operational requirements.

Technological components such as rollers, chains, and forks facilitate the rapid and precise movement of pallets, reducing handling time. Rolling tapes and conveyor belts effectively manage the transport of non-palletised goods, enabling smooth transfers without the need for manual intervention.

Automating these traditionally labour-intensive processes significantly enhances operational speed, safety, and accuracy. Furthermore, these systems contribute to a decrease in labour costs and mitigate the physical strain placed upon workers. They also minimise the risk of damage to goods due to improper handling or repetitive manual activities. Additionally, automation improves scheduling efficiency, rendering loading and unloading times more predictable and improving coordination with inbound and outbound transportation.

Automated loading and unloading systems operate with high autonomy, executing complex tasks previously performed by human workers. Such capabilities enable logistics operations to achieve high throughput while reducing reliance on manual labour. This level of automation is particularly advantageous in high-volume environments, where consistent performance, safety, and speed are essential to maintaining competitive logistics operations.

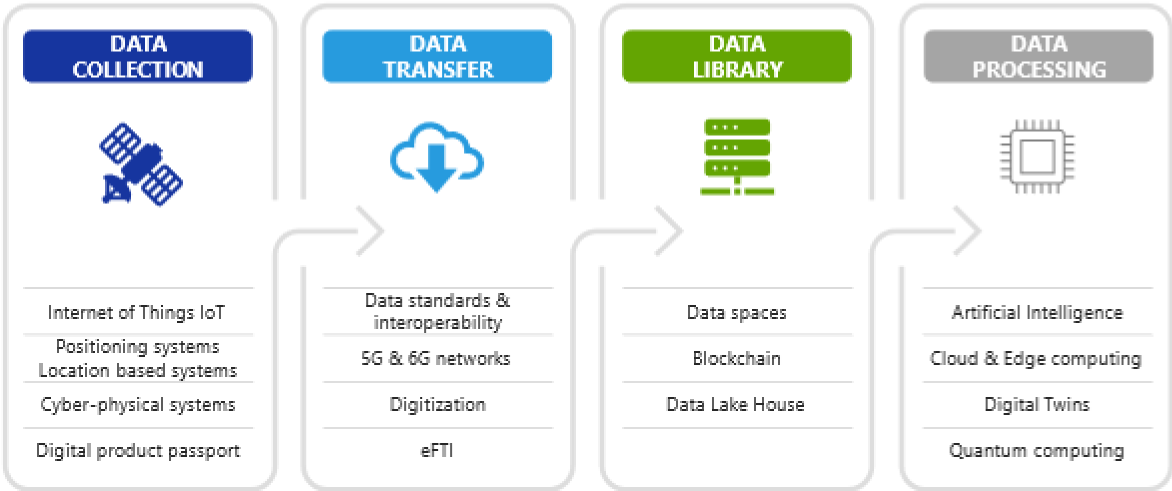
3.2. Towards fully optimised data & traffic flows

Operations, trade, and commercial activities generate substantial volumes of data. This chapter aims to organise and expound on the technologies involved based on the sequential data flow, enhancing operations and processes within port logistics and supply chains. Data is gathered from many sources, including devices, equipment, infrastructure, and external entities related to established trade or commercial agreements.

[23] Vinola, C., Deepu, S., Reddy, K. R., & Gowda, A. (2023). AR and VR on Real Estate Mapping. International Research Journal of Computer Science. https://doi.org/10.26562/irjcs.2023.v1005.25

This data must be securely transferred to a protected environment, referred to as a "data pool" or data library. From this repository, reliable and secure data can be extracted for processing, which can be applied to optimise operations in port logistics and supply chains. These technologies provide the foundational framework for a collaborative network approach to managing traffic flows and supply chains (see section 3.3). They are categorised into four distinct process areas: data collection, data transfer, data library, and data processing.

Figure 3.5. Data to Operational Excellence



Source: VIL, 2025

3.2.1. Data collection

The **Internet of Things** (IoT) connects physical devices within logistics and transport networks, enabling them to communicate and exchange data automatically without human intervention. It consists of three main components: (1) sensors for data collection, (2) connectivity for real-time data transfer, and (3) data analytics for generating actionable insights. IoT enhances supply chain visibility and transparency, optimising transportation and inventory management and improving customer experiences. IoT applications in logistics include real-time tracking, safety controls, automated inventory management, predictive maintenance, and driver monitoring. However, there are challenges to IoT adoption in this sector, such as the need for scalable infrastructure, vulnerabilities to cyberattacks, skill gaps, and concerns about data quality. IoT technology is a crucial component in the development and operation of autonomous vehicles, vessels, trains, and other forms of transportation. It enables these systems to collect and process vast amounts of data from various sensors and devices, allowing them to make informed decisions in real-time. IoT has been implemented at the Port of Antwerp-Bruges for remote data analysis, including energy management and monitoring of odour pollution through advanced sensors. This technology enhances safety, especially within the chemical cluster, by objectively detecting harmful chemicals in the air.

Additionally, the port utilises various sensors to monitor water quality and facilitate unmanned navigation[24].

Positioning systems are essential for maintaining the efficiency and accuracy of logistics movements[25]. Traditionally, the main emphasis has been on outdoor positioning systems. One of the emerging systems is EGNOS[26] (European Geostationary Navigation Overlay Service), an advanced outdoor positioning solution. EGNOS operates as a satellite-based augmentation system (SBAS) that enhances the accuracy of basic satellite navigation signals across Europe. This includes signals from the USA's Global Positioning System (GPS), particularly GPS III, and Galileo. EGNOS receives signals from GPS satellites, which are then processed at Mission Control Centres (MCCs). By integrating the capabilities and resources of both GPS and EGNOS, the system significantly improves positioning accuracy for safety-critical civil applications, reducing the precision radius from approximately 20 meters to just 2 meters. EGNOS's applications can be vital in logistics, particularly in areas where accuracy and integrity are critical, such as harbour entrances, approaches, coastal waters, and road and rail transport[27].

Location-based services[28] utilise data from various sources, including Global Positioning System (GPS) satellites, cellular tower signals, and short-range positioning beacons, to offer services based on a user's geographical location. Although location-based technologies have been commercially available for nearly two decades, the applications and services that use geodata have only recently gained widespread popularity, largely due to the increased use of Android and Apple smartphones and tablets. In addition to outdoor applications, indoor positioning systems provide enhanced real-time location tracking and monitoring capabilities within enclosed spaces. This feature is particularly valuable in large and busy environments such as warehouses, distribution centres, and manufacturing facilities. Indoor systems can assist with inventory management, optimise movement patterns, and facilitate efficient order fulfilment, helping to reduce search times and minimise the risk of mismatches.

Cyber-physical systems (CPS) represent a new generation of intelligent, interconnected systems that integrate computational intelligence with physical processes. CPS are built on the "3C" framework, which consists of computing power, communication, and control. CPS components include machines, robots, networks, computers, microchips, sensors, and actuators (devices causing a machine or other device to operate). These systems can process and convert information from the physical world into a digital format, making it accessible to

---

[24] Smart port | Port of Antwerp-Bruges. https://www.portofantwerpbruges.com/en/our-port/port-future/smart-port

[25] Abramowicz-Gerigk, T., Abramowicz-Gerigk, T., Burciu, Z., Gerigk, M., & Jachowski, J. (2024). Monitoring of Ship Operations in Seaport Areas in the Sustainable Development of Ocean–Land Connections. Sustainability, 16(2), 597.

[26] EGNOS | EU Agency for the Space Programme

[27] Durlik, I., Durlik, I., Miller, T., Kostecka, E., Łobodzińska, A., & Kostecki, T. (2024). Harnessing AI for Sustainable Shipping and Green Ports: Challenges and Opportunities. Applied Sciences, 14(14), 5994.

[28] What is a Location-Based Service and How Does It Work?. https://www.techtarget.com/searchnetworking/definition/location-based-service-LBS

other components through network-based services. Actuators, such as drive elements and programmable logic controllers, can use this information to influence processes in the physical world.

A prime example of CPS is the autonomous vehicle, which utilises a network of radars, lidars, cameras, and ultrasonic sensors to perceive its surroundings. A central controller processes this sensory data in real time, making precise decisions for vehicle control, while actuators execute acceleration, braking, and steering functions to enable autonomous operation.

Another well-known CPS application is in warehousing, where Autonomous Mobile Robots (AMRs) and robotic picking arms streamline logistics operations. AMRs, equipped with lidar sensors and AI-driven mapping, autonomously navigate warehouses to locate storage bins. Upon arrival, robotic picking arms, powered by vision recognition and AI, identify and retrieve the correct items, significantly enhancing speed, accuracy, and efficiency in order fulfilment.[29]

The Ecodesign for Sustainable Products Regulation (ESPR), which came into force in July 2024, introduces the **Digital Product Passport (DPP)** as a key mechanism to enhance transparency and sustainability throughout product value chains. The DPP serves as a digital record that consolidates comprehensive data about a product's composition, environmental impact, and lifecycle. By providing structured information, it enables stakeholders—including manufacturers, suppliers, logistics providers, retailers, and consumers—to access detailed insights regarding sourcing, production processes, and end-of-life management.

Manufacturers and producers are required to include essential product information in the DPP, such as core product data, CO_2 emissions, and the presence of substances of high concern. As the product progresses through the supply chain, additional stakeholders may contribute further data, including logistical updates, repair records, and recycling information. This dynamic and continuously updated dataset ensures that relevant sustainability and circular economy data remain accessible at every stage of the product's lifecycle.

The introduction of DPPs follows a phased approach, with the first product categories expected to require mandatory compliance between 2026 and 2027. By 2030, the European Commission anticipates that more than 14 billion products will feature a DPP. To ensure seamless implementation across different industries and supply chains, the regulation emphasises the importance of open standards such as GS1[30] and interoperability. This approach facilitates the exchange of product data across sectors, reinforcing efforts towards sustainability, regulatory compliance, and circular economy objectives.

[29] https://www.autosup-project.eu/
[30] https://www.gs1belu.org/en/digital-product-passport

3.2.2. Data transfer

Data standards (& interoperability) refer to universal methodologies for organising, documenting, and formatting data to facilitate aggregation, sharing, and reuse. They encompass technical specifications or recorded agreements detailing how data should be stored or exchanged across various systems. A data standard, or digital standard, is an organised set of components that uniformly describes data according to user expectations. This standardisation allows systems and teams to collaborate effectively by sharing a common language.

The fragmentation and variance in data standards create communication obstacles among stakeholders, which can impede effective collaboration and smooth information exchange, particularly in logistics, predominantly maritime and cross-border trade[31]. Diverse stakeholder standards, varying cross-border regulations, and dependence on legacy systems contribute to inadequate data standards in logistics.

Data standardisation is crucial for data-driven supply chains as it helps eliminate silos, enhances interoperability, and improves data exchange. It ensures data integrity, enabling accurate decision-making and unlocking the full potential of data while reducing the need for manual data cleaning.

Benefits of standardised data include: 1. improved operational efficiency; 2. effective route optimisation; 3. strategic capacity planning; 4. better customer service; 5. timely deliveries; 6. increased innovation; 7. reduced disruption risks; and 8. enhanced scalability of freight operations.

A very nice example of a data standards & interoperability initiative is the **Open Logistics Foundation[32].** The Open Logistics Foundation promotes the collaborative development and commercial use of open-source logistics software and hardware through a unique Innovation Community. The Foundation's primary goal is to facilitate the development of open-source solutions to address existing logistics and supply chain management challenges. It creates common standards, tools, and services that can be commercially utilised by any industry participant. Focusing on collaborative development and the use of open-source software and hardware ensures high process efficiency. The Foundation operates the Open Logistics Repository, a technical platform that supports collaborative development of open-source software (OSS) and hardware (OSH). This Repository provides access to open-source interfaces, reference implementations, and components available under a permissive license. Additionally, it monitors the quality and security of developed open-source tools and maintains neutrality in their development. This initiative is breaking down boundaries through real collaboration within an open standard setting and is expanding rapidly from a German initiative to an international community.

---

[31] What are Data Standards and Why Do You Need Them? - Satori. https://satoricyber.com/secure-data-management/what-are-data-standards-and-why-do-you-need-them/
[32] Open Logistics Foundation | Let's find better solutions. Together.. https://openlogisticsfoundation.org/

5G and 6G networks utilise wireless spectrum to provide significantly higher capacity and faster data transmission than 4G and other technologies[33]. A good example is the development and implementation of a private 5G network, known as 'Minerva', in Antwerp, which is carried out in collaboration with partners such as the Port of Antwerp-Bruges, police, and fire departments. This network offers enhanced speed, reliability, and security for the digital applications of these organisations, independent of public providers. It enables them to improve existing digital applications and explore new opportunities, such as real-time video streaming from vehicles and boats. This fosters more efficient emergency response and lays the groundwork for further developing advanced 5G applications in automation, logistics, and security. The network functions by installing 5G infrastructure, including transmission towers and antennas, within the partners' operational area, facilitating higher data rates, lower latency, and excellent reliability. As an independent network, it affords greater control over connections and protects partners from interference.

5G and 6G networks allow faster data speeds, more reliable connections, and enhanced security for digital applications, such as real-time information sharing and in-vehicle video streaming. The aim is to boost operational efficiency, manage emergencies more effectively, and continue to innovate in an increasingly digital world.

Digitisation in logistics refers to adopting and integrating digital technologies within logistics and supply chain processes. The primary goals of digitisation are to enhance efficiency, lower costs, and improve visibility. Basically, digitisation is the process of converting objects or data into a digital format, such as bits or bytes. However, it does not inherently mean changing the entire logistics process; that transformation is a separate concept known as digitalisation, which involves using digital tools to process data, thereby modifying existing business models.
Several challenges come with logistics digitisation, including high initial investment costs, concerns about data security and privacy, the complexities of managing change, and the difficulties of ensuring interoperability between systems.

A typical example of digitisation is e-billing, or electronic invoicing technology. This method allows for the structured issuance and transfer of digital invoices through specialised software platforms. E-billing offers timely and automated payment processes, providing significant advantages over traditional invoicing, including faster processing times, reduced errors and costs, and more efficient resource utilisation. Additionally, it helps mitigate the risk of scams and fraud, which is a significant benefit.

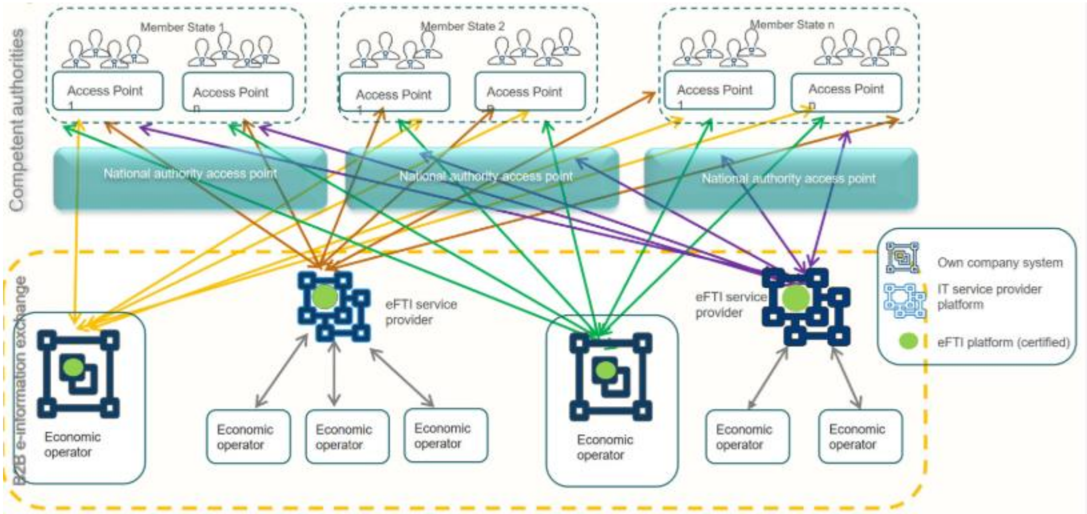
Moreover, e-CMR solutions are increasingly being adopted as a part of logistics digitisation efforts. These solutions use a digital consignment note (CMR) instead of paper-based CMRs, streamlining the documentation process for cross-border road transport. E-CMRs offer several benefits, including real-time data sharing, reduced paperwork, and enhanced data accuracy. They improve operational efficiency by allowing instant access to consignment information and facilitating better communication between transport operators, shippers, and authorities.

[33] *AUTOSUP – Port of Antwerp Contribution*

The **eFTI Regulation (Regulation (EU) 2020/1056)** is set to transform freight transport within the EU by boosting efforts to replace paper-based documentation with electronic data in all transport modes. This digital shift will apply to road, rail, inland waterway, and air transport. It will reduce administrative burdens for operators and authorities, enhance data security, and ensure compliance with EU and national freight regulations. Authorities in all EU Member States will be required to accept electronic data when shared by businesses via eFTI-compliant platforms.

The architecture of the eFTI System is designed to provide a centralised and standardised information exchange between various stakeholders. The key components of the eFTI System architecture are the standardised eFTI connector that connects with the eFTI gates of the national authorities. These components work together to provide a centralised and standardised platform for exchanging information related to freight transport within the EU.

Figure 3.6. eFTI implementation architecture



Source: Potec, 2022

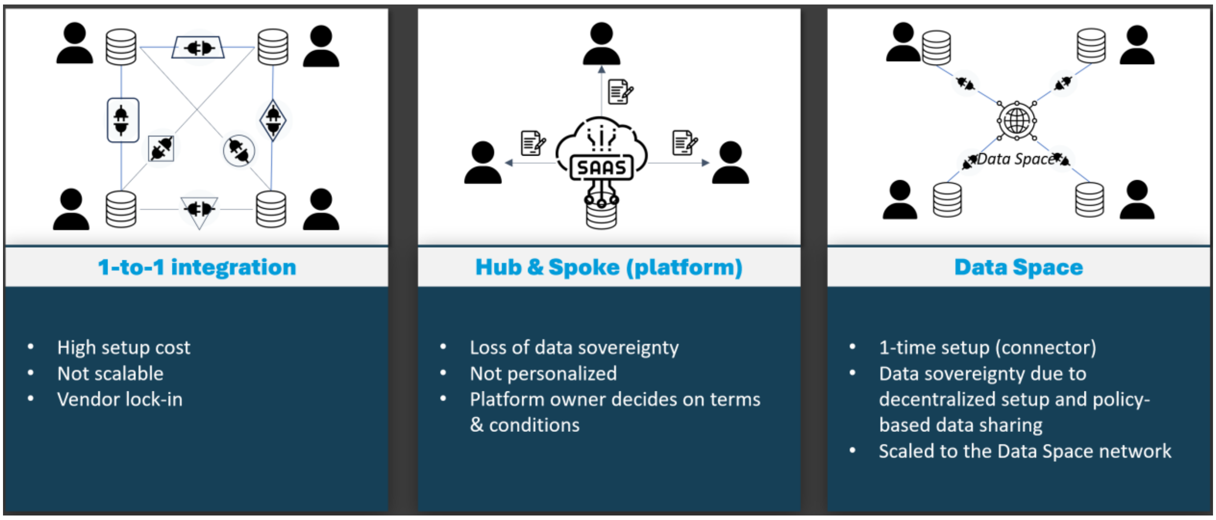
The interfacing protocol and components of eFTI are likely to create a new standard to share data on B2A and B2B level. Initiatives to enlarge the set of data to be shared in a B2A context, as well as initiatives to use eFTI in a B2B context are supported by EC funding possibilities such as the EFTI4EU and EFTI4ALL projects.

3.2.3. Data library (repository)

3.2.3.1. Data Spaces

Ad-hoc point-to-point connections dominate the logistics landscape, and there is a lack of trust to share data with partners in the supply chain. Historically, data interfaces between supply chain partners have been set up as point-to-point connections, either using the EDIFACT standard or specific protocols. Main disadvantages of the point-to-point connections are the number of connections to cover all processes, resulting in a high cost for implementation. Later on, public and commercial data sharing platforms were brought to the market in a SaaS model as alternative for the point-to-point interfaces. License cost, loss of control over the data and limited impact on the product roadmap of those platforms are indicated as the main barriers for these solutions. The concept of a dataspace combines the advantages of both point-to-point connections and platforms while minimising their disadvantages.

Figure 3.7. From centralised to decentralised networks



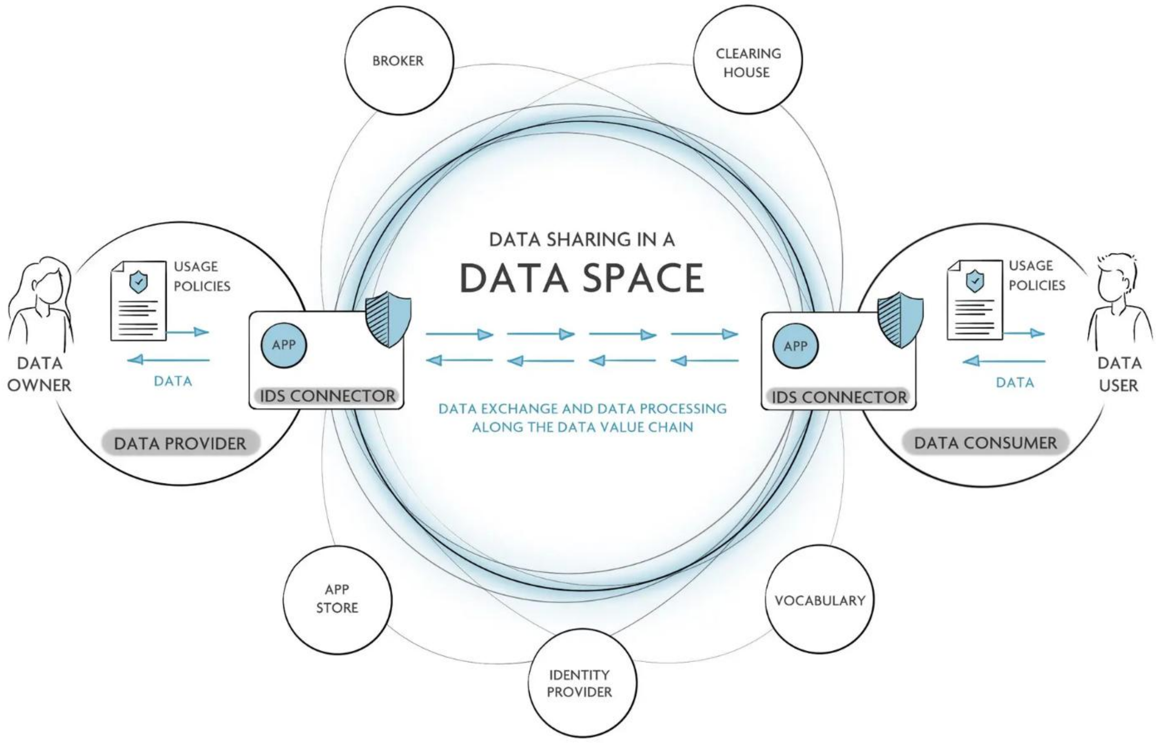
Source: imec, 2025

There is growing international momentum on the design and implementation of next-generation data sharing mechanisms between organisations, both business-to-business (B2B) and business-to-government (B2G). The European Commission has identified data sovereignty as a central focus in shaping the digital economy of the future. They have set ambitious targets to create data spaces that encourage and facilitate trustworthy data-sharing practices that align with common societal values and existing legal frameworks. Several overarching efforts are underway, led by consortia in organisations like the International Data Spaces Association (IDSA), GAIA-X, FIWARE or the Big Data Value Association (BDVA). These efforts have led to the positioning of the data space concept at the core of the EU's data space strategy, which aims to strengthen the innovation capacity of the European data economy.

A data space[34] is a framework that supports data sharing within a data ecosystem. It provides a clear structure for participants to share, trade, and collaborate on data assets in a way that is compliant with relevant laws and regulations and ensures fair treatment for all involved stakeholders. A data space is a federated data ecosystem where data can be shared and accessed across different organisations, platforms, and domains while maintaining control over data. This control, known as data sovereignty, is a key aspect of data space, emphasising the rights of data owners to determine how their data is used.

[34] Source: Data Spaces Support Centre (DSSC) https://dssc.eu

Figure 3.8. Data space components



Source: IDSA - imec

In the Flemish research and innovation project SYTADEL, a consortium comprising imec, VIL, the University of Antwerp, and the Vlerick Business School has brought the dataspace concepts into practice by applying state-of-the-art technologies on dataspaces to the context of logistics synchromodal planning.

A **blockchain** is a digital and distributed ledger of transactions recorded and replicated in real-time across a network of computers or nodes. Each transaction must be cryptographically validated[35]. In short, it is a digital database containing information (such as records of multiple transactions) that can be used and shared simultaneously within an extensive, decentralised, publicly accessible network. Key features of a blockchain include distributed ledger, cryptography, consensus, and smart contracts. Smart contracts are executed once specific terms and conditions are met (e.g., obtaining the consent of all stakeholders involved) without the need for brokerages, lawyers, or third parties to perform these tasks. Prospective use cases for blockchains in logistics and supply chain management relate to inventory tracking and provenance ('digital passport'), improved shipments, secure billing and payments, authenticity verification, and dispute resolution (e.g. missing or late cargo).

As such, blockchains enable secure and transparent record-keeping, ensuring accurate and tamper-proof tracking of goods from source to delivery and fostering trust among all

[35] (2021). Learning Mergers & Acquisitions: Blockchain. IJEBD (International Journal Of Entrepreneurship And Business Development). https://doi.org/10.29138/ijebd.v4i2.1121

stakeholders involved. Blockchain-based smart contracts automate and enforce the execution of agreements, avoiding administrative errors, fraud, theft, and faster payments. A nice example of the use of blockchain technology is T-Mining's Secure Container Release[36] solution at the Port of Antwerp. Secure Container Release is a system that uses blockchain to ensure that only authorised parties can access and release containers in ports. This solution enhances security by storing transaction data in a decentralised ledger, which is tamper-proof and transparent. Blockchain's cryptographic validation ensures that each transaction is secure and trustworthy, eliminating the risk of fraud and unauthorised access.

3.2.3.2. Data Lake Houses

A Lakehouse is a hybrid data architecture that combines the scalability and flexibility of a data lake with the structured management and reliability of a data warehouse. It enables organisations to store and process both structured and unstructured data in a unified platform, eliminating the traditional silos between analytical and operational workloads.

One of the key advantages of a Lakehouse is its ability to handle unstructured data, which is rapidly growing due to sources like IoT devices, social media, and multimedia content. Unlike conventional data warehouses that primarily manage structured data, a Lakehouse supports diverse data types, allowing organisations to perform advanced analytics, machine learning, and AI-driven insights.

3.2.4. Data Processing

Artificial intelligence (AI) and machine learning rapidly transform logistics by enhancing delivery planning, demand forecasting, and inventory management. These technologies utilise large datasets and computing power to automate complex decision-making along the supply chain, helping to identify patterns and improve forecast accuracy. AI addresses several logistics challenges, such as fragmented supply chains, market volatility, safety concerns, and environmental impacts. Its predictive capabilities are crucial for optimising supply chain operations and managing disruptions, delays, and bottlenecks, particularly in demand forecasting and transportation optimisation. Combining traditional AI with generative AI and operations research methods offers even more significant potential. Generative AI can outperform classical algorithms by effectively handling new datasets and generalising to unseen problems.

Cloud platforms are key enablers for AI adoption in business applications. They provide on-demand access to powerful computing resources, scalable infrastructure, and advanced AI tools without requiring heavy upfront investments. While AI can automate many tasks in logistics, human oversight remains essential to ensure alignment with real-world conditions. An example of an AI application at the Port of Antwerp-Bruges is voice-to-text technology[37],

[36] https://www.t-mining.be/news1/2022/6/8/cma-cgm-implements-t-minings-secure-container-release-blockchain-solution-in-the-port-of-antwerp

[37] Smart port | Port of Antwerp-Bruges. https://www.portofantwerpbruges.com/en/our-port/port-future/smart-port

which transcribes recorded VHF radio conversations for clarity in emergencies. Additionally, smart cameras equipped with AI monitor the port, recognising objects like ships and assisting with incident management and security alerts.

Cloud computing is a technology that allows businesses to store, manage, and process data over the internet instead of relying on physical servers or on-premise infrastructure. This means that computing resources—such as storage, processing power, and software applications—can be accessed on demand, from anywhere, at any time. Whether through public, private, or hybrid cloud models, businesses can optimise their IT infrastructure, reduce costs, and enhance operational efficiency. Cloud computing shifts the burden of IT maintenance and infrastructure management to cloud providers, reducing the need for in-house IT expertise. Businesses can focus on their core activities while benefiting from automatic updates, system optimisations, and 24/7 technical support. Leading cloud providers implement advanced security measures such as encryption, multi-factor authentication, and continuous monitoring to protect sensitive data. Additionally, cloud-based backup and disaster recovery solutions ensure that businesses can quickly restore operations in case of system failures, cyberattacks, or other disruptions. Cloud platforms are the core for innovations, new Software as a Service offerings for logistics software systems such as WMS and an enabler for new business models such as Pay for Use models.

Edge computing is a decentralised IT architecture that processes data closer to its source rather than relying on distant cloud servers or centralised data centres. By deploying computing and storage resources at the "edge" of a network—near sensors, IoT devices, or other data-generating sources—edge computing significantly reduces the need for constant long-distance communication between clients and servers.

This approach enhances processing speed, as data can be analysed and acted upon in real-time without delays caused by network latency. It also improves data security by keeping sensitive information closer to its source, reducing exposure to cyber threats. Additionally, edge computing enables faster response times to environmental changes, making it a crucial technology for applications that require instant decision-making, such as autonomous vehicles, smart factories, and real-time logistics monitoring.

By shifting computation away from centralised cloud infrastructure and distributing it closer to where data is generated, edge computing optimises efficiency, reduces bandwidth usage, and enhances the overall reliability of digital operations.

Digital twins are virtual models that replicate the conditions and behaviours of physical objects, assets, processes, facilities, or complete networks. By leveraging historical and real-time data alongside algorithms, they facilitate modelling, monitoring, simulation, and continuous optimisation of the physical world. Their development is enabled by technologies such as the Internet of Things (IoT) for data collection, cloud computing for processing and storage, and augmented/mixed/virtual reality for visualisations.

In logistics, digital twins enhance efficiency, resilience, visibility, and sustainability without altering the physical structure of supply chains. The maturity levels of digital twins range from visualisation and diagnostic analysis to predictive and prescriptive analytics, ultimately culminating in fully autonomous decision-making systems.

One key functionality of digital twins is their ability to make predictions based on historical and real-time data, exemplified by detecting potential bottlenecks in supply chain processes. Another essential feature involves "what-if" scenarios, such as simulating process or layout changes in warehouses, yards, and transport operations.

A notable example of the application of digital twins is the Horizon Europe project AUTOSUP, where digital twins are integrated into a decision-support system to simulate the impact of automation technologies on multimodal supply chain nodes.

Quantum computing is an emerging field of cutting-edge computer science, harnessing the unique properties of quantum mechanics to solve problems that exceed the capabilities of even the most powerful classical computers. The field of quantum computing includes a range of disciplines, including quantum hardware and quantum algorithms. While still in development, quantum technology will soon be able to solve complex problems that today's computers can't or can't solve fast enough. By leveraging quantum physics, fully realised quantum computers could process extremely complex problems at orders of magnitude faster than modern machines. For a quantum computer, challenges that might take a classical computer thousands of years to complete might be reduced to minutes.

A primary difference between classical and quantum computers is that quantum computers use qubits instead of bits to store exponentially more information. While classical computers rely on binary bits (zeros and ones) to store and process data, quantum computers can encode even more data at once using quantum bits, or qubits, in superposition. A qubit can behave like a bit and store either a zero or a one, but it can also be a weighted combination of zero and one simultaneously. When combined, qubits in superposition can scale exponentially.

Traditional computers are expected to remain the most suitable solution for most types of tasks and challenges. However, when scientists and engineers encounter specific, highly complex problems, quantum mechanics comes into play. For logistics, in particular, quantum computing could enable faster and more effective routing optimisation algorithms in multimodal networks.

3.3. Towards a distributed network for logistics

The future of logistics is evolving towards a distributed and interconnected network, where seamless collaboration among stakeholders is essential for enhancing efficiency, resilience, and sustainability. Central to this transformation is data sharing—the ability to exchange real-time, accurate, and secure information across supply chains.

Data-sharing platforms act as crucial enablers by integrating information from the business applications of various supply chain participants, including logistics operators, shippers, terminal managers, and authorities. By connecting these systems, data-sharing platforms eliminate operational silos and facilitate interoperable, data-driven automation throughout the supply chain. These platforms are vital in modernising logistics by gathering real-time information from diverse supply chain actors. They offer several key functionalities that enhance efficiency, transparency, and collaboration across multimodal transport networks. Some of the most tangible and impactful features include more reliable Estimated Time of Arrivals (ETAs), automated notifications and alerts, service level monitoring and performance tracking.

In the ultimate vision for the future, global and urban supply chains will be based on an open system of systems—referred to as the Physical Internet (PI)—that enables assets and resources within logistics networks to connect and operate at maximum capacity and productivity. This interconnection will increase supply chain agility and resilience while supporting a cost-effective transition toward zero-emission logistics.

3.3.1. Data provisioning

A **Transportation Management System** (TMS) is a software solution designed to help companies optimise their delivery planning. It processes sales orders to create the most efficient routes and schedules, often utilising multiple modes of transportation. Additionally, a TMS manages relationships with carriers, handling invoicing, delivery tracking, and notifications. Overall, a TMS streamlines delivery processes and reduces transportation costs by maximising vehicle capacity and closely monitoring deliveries. It can also partially automate transportation planning. By improving overall transport performance, a TMS significantly enhances the operational efficiency of transportation operations, providing decision-makers with optimal choices regarding costly assets. Furthermore, under certain market conditions, the use of multimodal transport is encouraged, improving transportation's environmental impact by enhancing energy efficiency and reducing pollutant emissions.

Slot management systems are software solutions that allow companies to plan and manage vehicle arrival and departure times (slots) at loading bays. The primary goal of these systems is to optimise asset capacity and streamline transport operations. This is achieved through intelligent digital planning and efficient management of resources and information, which helps maximise capacity while reducing loading and unloading times. These systems automate specific processes—typically between shippers and carriers—according to predefined conditions. Slot management systems help streamline and synchronise transport and logistics processes by minimising operational inefficiencies. This improvement optimises the use of expensive assets, such as trucks and warehouses, thereby enhancing the environmental performance of logistics operations. The costs associated with implementing slot management systems include installation, configuration, and integration with existing IT systems, such as Transportation Management Systems (TMS) and Warehouse Management Systems (WMS). Shipping companies increasingly adopt slot management systems, which should be considered ready-to-deploy technologies.

An **Order Management System** (OMS) is a digital tool focusing specifically on the order lifecycle, from order placement to fulfilment and delivery. It facilitates various activities related to order management, such as collecting sales orders, preparing orders, transmitting confirmed orders to sales managers and back-office staff, verifying order details, standardising order entries, billing, and reporting order statuses. The efficiency of an OMS can significantly affect the overall order cycle time and the company's logistics strategy. Increasingly, OMSs are being automated, enabling the system to automatically release orders based on predefined customer or supplier profiles, such as transport quotations. These systems use Natural Language Processing (NLP) algorithms and tools to enhance their functionality. When optimised, OMSs can streamline logistics operations and improve overall logistics performance, including from an environmental perspective. OMS systems should be viewed as ready-to-adopt solutions. However, automated features are still in the early stages of development and should be considered ongoing development options.

3.3.2. Platforms

A **Port Community System** (PCS) is an electronic platform that connects various systems operated by different organisations within a seaport, airport, or inland port community. It facilitates the safe exchange of data and information among port operators, thereby speeding up and simplifying port, maritime, and multimodal operations.

This integration supports the automation of relevant processes. Initially, PCS processes are standardised and automated at a single node level. As development progresses, ports work to standardise and automate their processes further while integrating their operations with other ports.

A PCS streamlines and synchronises operations by enhancing integration and interoperability among logistics operations for port actors and stakeholders. This fosters economic growth and local development within the port environment. Furthermore, PCS generates a positive environmental impact by minimising inefficiencies throughout the supply chain—such as reducing operational times, improving energy efficiency, and enhancing environmental performance.

One such example is APICS [38], the Advanced Port Information and Control System (APICS). APICS allows the port to plan, direct, and monitor shipping traffic to, from, and within the port. Several applications support and enhance APICS. These applications include a service that notifies the Antwerp-Bruges Port Authority about the arrival and departure of seagoing vessels. The timely submission of orders for sea, river, and port services is crucial for ensuring smooth and safe operations. This system acts as a Maritime Single Window (MSW), transmitting essential information such as vessel waste reports, ISPS reports, health declarations, crew and passenger lists, and customs declarations. Additionally, APICS offers services to bunkering companies and provides support to port terminals through its Terminal Planner tool. It also offers an app that helps inland navigation operators and skippers track

[38] APICS | Port of Antwerp-Bruges. https://www.portofantwerpbruges.com/en/shipping/applications/apics

their inland navigation trips, book locks, and request passage through construction zones. Furthermore, it supplies maps showing docking locations, enhancing navigation within the port.

A **Customs Clearance Platform** is a digital solution designed to streamline the process of managing customs declarations and procedures for importing and exporting goods. It centralises the legally required information, automates data entry, ensures compliance with regulations, and provides real-time updates on the status of shipments. This platform supports various cargo flows. By utilising a customs clearance platform, stakeholders, including importers, exporters, logistics providers, and customs authorities, benefit from improved efficiency, reduced paperwork, and enhanced transparency. The platform ensures that all necessary information is accurately recorded and shared, facilitating smoother and faster customs clearance and compliance with regulations. A global customs platform is a centralised system that enables businesses to manage international customs and trade operations efficiently. Unlike local customs software, these platforms offer end-to-end automation for filing declarations across multiple countries.

For example, the **Inbound Release Platform (IRP)** is a digital solution designed to streamline the communication and declaration process between supply chain actors and Belgian customs. The IRP supports various cargo flows, including RORO, ferry, container, breakbulk, and bulk, in a single, efficient process.

A **supply chain control tower** is a vital tool for reporting and monitoring, typically characterised by a dashboard that presents data, metrics, and events throughout the supply chain. This configuration significantly enhances end-to-end visibility and facilitates informed decision-making by incorporating predictive analytics. Furthermore, it fosters collaboration among various departments and divisions within an organisation. The integration and automation provided by dashboard and control tower technologies streamline many complex logistics and supply chain processes while minimising the need for human intervention. Concurrently, these technologies provide personnel at both managerial and operational levels with pertinent information and indicators necessary for monitoring and optimising overall supply chain performance.

Enhancing supply chain visibility and furnishing decision-makers with essential metrics, data, and dashboard and control tower technologies can markedly reduce operational and environmental inefficiencies and disruptions. This process optimisation promotes growth and economic development, alleviates bottlenecks and congestion, and improves environmental performance regarding emissions and energy efficiency.

It should be noted that dashboard and control tower tools are evolving technologies that more and more organisations within the supply chain are integrating into their operations.

Freight e-procurement refers to the digital purchasing of transportation services, offering a faster, more efficient, and cost-effective solution compared to traditional methods. This approach enables businesses to access various suppliers, compare prices, and seamlessly book shipments through cloud-based platforms that connect shippers with carriers and operators. There is a growing trend towards autonomous procurement, particularly for short-term capacity needs, where publishing requirements and receiving carrier proposals are automated. E-procurement improves operational, socio-economic, and environmental efficiencies by streamlining transportation processes.

3.3.3. Operating as a network

The digital transformation of the logistics and supply chain sector has led to a paradigm shift, moving from siloed operations to an interconnected network in which data-sharing platforms and data spaces play a central role. These platforms enable supply chain actors—including manufacturers, transport providers, terminal operators, retailers, and regulatory bodies—to exchange critical information in real-time, improving operational efficiency, decision-making, and service reliability. By leveraging shared data, supply chains become more transparent, resilient, and adaptable to disruptions, ultimately leading to greater cost efficiency, sustainability, and automation.

A key functionality enabled by data-sharing platforms is real-time visibility across the supply chain. Access to real-time data allows stakeholders to monitor goods in transit, track inventory levels, and optimise logistics operations. One of the most impactful applications is the provision of estimated time of arrival (ETA) predictions, which are continuously updated based on public data and operational data for the supply chain partners. Accurate ETAs help to streamline multimodal transport, improve coordination among different logistics actors, and enhance overall customer satisfaction.

Data-sharing also facilitates smart notifications and automated alerts, providing real-time updates on potential delays, disruptions, or deviations from planned schedules. These proactive notifications allow logistics managers to take immediate corrective actions, minimising inefficiencies and ensuring the timely delivery of goods. Additionally, service level agreement (SLA) monitoring becomes more efficient through automated tracking and reporting, ensuring compliance with contractual obligations and performance benchmarks.

The integration of data-driven insights also enhances decision-making processes. With access to historical and real-time data, companies can implement predictive analytics to anticipate demand fluctuations, optimise warehouse storage, and adjust transportation routes dynamically. This leads to optimised planning and capacity management, ensuring that transport resources—whether road, rail, air, or waterways—are utilised efficiently.

Furthermore, the automation of multimodal transport management is a significant advantage of a networked supply chain. By integrating data from different transport modes, companies can automate booking processes, dynamically reallocate shipments to alternative routes in case of disruptions and ensure seamless handovers between different transport providers. This automation reduces administrative burdens and eliminates manual inefficiencies, contributing to lower operational costs. A good example is the network state and route planner that has been developed in the PILL[39] project, allowing real-time rerouting

[39] https://www.imec-int.com/en/pill

in a synchromodal network, based on the logistics dataspace that has been developed in the SYTADEL[40] project.

Finally, cost reductions emerge as a key benefit of data-sharing networks. Real-time access to supply chain data reduces inefficiencies such as empty miles, excess inventory, and prolonged dwell times at terminals. Enhanced visibility and predictive analytics allow logistics managers to optimise fleet utilisation, reduce fuel consumption, and minimise waiting times, ultimately leading to lower overall logistics costs and a more sustainable transport ecosystem.

In summary, a networked supply chain, enabled by data-sharing platforms and data spaces, transforms traditional logistics operations into an agile, intelligent, and interconnected system. By leveraging functionalities such as real-time visibility, ETA predictions, smart notifications, SLA monitoring, multimodal automation, and predictive analytics, supply chain actors can significantly enhance efficiency, resilience, and sustainability.

3.4. Vision on and impact of the digitalisation of the Belgian port, transport and logistics industry

3.4.1. Short Term

The short-term vision for optimised data and traffic flows in the Belgian port, transport, and logistics industry hinges on the integration of advanced technologies that enable real-time visibility, predictive analytics, and operational automation.

The deployment of IoT sensors, positioning systems, and cyber-physical systems is already enhancing data collection across vehicles, infrastructure, and cargo units. These technologies feed into secure data repositories—such as data lakes and data spaces—where structured and unstructured data can be processed using AI and machine learning. In the immediate future, this will allow logistics actors to optimise routing, reduce idle times, and improve asset utilisation. The implementation of slot booking systems, certified pick-up platforms, and terminal operating systems is streamlining traffic flows at ports and terminals, reducing congestion and emissions. These developments are laying the groundwork for a more responsive and efficient logistics ecosystem, where data-driven decision-making becomes the norm.

3.4.2. Long Term

Looking toward the long term, the industry is transitioning from siloed operations to a distributed logistics network characterised by decentralised data governance, interoperable platforms, and collaborative automation. The emergence of logistics dataspaces and federated data-sharing frameworks—such as those promoted by GAIA-X and IDSA—will enable secure and sovereign data exchange across supply chain actors.

[40] https://www.imec-int.com/en/sytadel

This evolution supports the vision of the **Physical Internet**, where logistics assets and services are interconnected and dynamically allocated based on real-time demand and capacity. Distributed networks will allow for multimodal optimisation, synchromodal routing, and seamless handovers between transport modes.

The integration of digital twins, edge computing, and autonomous systems will further enhance the agility and resilience of logistics operations. In this future state, supply chains will operate as intelligent networks, capable of self-adjusting to disruptions, environmental constraints, and market fluctuations.

The impact of this transformation towards a Physical Internet is profound. In the short term, companies will benefit from improved operational efficiency, reduced emissions, and enhanced competitiveness. Digitalisation will enable better coordination between stakeholders, while automation will alleviate labour shortages and support 24/7 operations. In the long term, the shift to a distributed logistics network will redefine the industry's structure, enabling new business models based on shared infrastructure, collaborative procurement, and data-as-a-service. Ports will evolve into smart nodes within a broader network, offering integrated services and real-time connectivity. This transformation will not only support Belgium’s ambition to remain a leading logistics hub but also contribute to the EU’s climate goals and the global transition toward sustainable and resilient supply chains.

4. Tailwinds of Decarbonisation and Digitalisation in Ports, Transport and Logistics

4.1. Environmental and Climate Goals

As sustainability becomes a global imperative, decarbonisation has emerged as a critical priority for achieving environmental goals. At all governmental levels, we find policy goals related to sustainability: goals for sustainability in general and goals for sustainable supply chains specifically. Next to governments, also companies have set decarbonisation ambitions.

Alternatively, digitalisation and automation can support the transition towards a zero-emission logistics reality aligned with the ambitions of the **EU Green Deal**.

Increased digitalisation and the automation of logistics technologies will greatly enhance the efficiency of port and terminal operations. This improvement will lead to a more effective use of existing infrastructure, reducing the strain on current facilities and delaying the need for expansion to accommodate rising trade volumes.

At the supranational level, sustainability goals are developed within various global organisations/institutes, each consisting of a set of member countries. These member countries then commit themselves to the jointly agreed-upon policy goals, which could be binding or indicative. This means that they develop their plans and policies in line with those goals. The most relevant organisations/institutes are mentioned below. A key example is the **Paris Agreement**, an international agreement between 195 countries to reduce the GHG emission worldwide. On the 12th of December 2015 this agreement was presented at the climate conference in Paris and will hold for the period 2020-2050. The main point agreed upon relates to keeping the average temperature increase on Earth below 1.5 °C compared to the pre-industrial era. The Paris Agreement requires all Parties to put forward their best efforts through nationally determined contributions (NDCs) and to strengthen these efforts.

Another frame setting example is **the United Nations Sustainable Development Goals (SDGs).** The United Nations presented the agenda for sustainable development in 2015. The SDGs build on decades of work by countries and the UN, including the UN Department of Economic and Social Affairs. This agenda presents the goals that are crucial for reaching a sustainable development of our planet from an environmental perspective. In total, 17 main goals are set which should all be reached in 2030 (Figure 4.1). The United Nations defines sustainable development as: "the needs of the present without compromising the ability of future generations to meet their own needs". A main goal that matches the decarbonisation of the port and logistics industry relates to responsible consumption and production (SDG 12). This goal is mainly about promoting resource and energy efficiency and sustainable infrastructure. One of the relevant sub-goals aims to encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle. Also, the promotion of sustainable procurement practices to companies and organisations has high relevance for the port and logistics industry. Another main goal relevant to this report is the promotion of climate actions worldwide (SDG 13).

Figure 4.1. UN Sustainable Development Goals

Source: United Nations

Specific targets and associated policies have been put forward by international organisations that focus on specific transport modes. For example, the **International Maritime Organisation (IMO)** has set targets for the shipping industry. Initially, IMO argued that, to align with the ambitious goals of the Paris Agreement, the shipping industry must reduce CO_2 emissions by at least 50% by 2050 (IMO, 2015). During IMO's MEPC80 meeting in July 2023, member states agreed on a more ambitious path using so-called indicative checkpoints of reducing emissions by at least 20%, and striving for 30%, by 2030 compared to 2008 levels, and at least 70%, striving for 80%, by 2040, reaching net-zero "by or around, i.e., close to 2050" (IMO, 2023). These decarbonisation challenges remain very significant for all segments of the maritime industry.

In February 2024, the **Inland Transport Committee of the Economic Commission for Europe of the United Nations** adopted its ITC Strategy on Reducing Greenhouse Gas Emissions from Inland Transport. The Strategy provides integrated solutions for the reduction of GHG emissions from the inland transport sector with an aspirational goal of net-zero by 2050. The framework provides guidance for countries and the Inland Transport Committee and its subsidiary bodies to take concrete steps. The Strategy complements the IMO Strategy on Reduction of GHG Emissions from Ships and the long-term aspirational goal of the International Civil Aviation Organisation (ICAO) for net-zero carbon emissions from aviation by 2050. The ECE argues that, while many United Nations Member States are already taking action to decarbonise transport, current transport policies and measures are insufficient to put transport on a decarbonisation pathway in line with the 1.5°C target of the Paris

Agreement. Thus, further ambitious innovative action is needed. The decarbonisation strategy from the Inland Transport Committee includes an initial climate action plan, with 33 coordinated actions for the Committee and its 21 subsidiary bodies, and it also recommends further actions for the inland transport sector of individual countries. The strategy follows a broad decarbonisation framework based on three groups of measures: avoid (reduce unnecessary vehicle km), shift (transition to low- and zero-carbon sustainable transport modes and operations), and improve (enhance vehicles, infrastructure and operations to be more environmentally friendly).

The **European Union** and its national governments have set objectives in line with the Paris Agreement to guide European environment policy, with the support of dedicated research programmes, legislation and funding. Transport is a critical component of the European Union (EU) economy, facilitating essential connections between individuals and businesses across diverse regions and member states. The coronavirus pandemic has underscored the significant impact of mobility restrictions on the free movement of people, goods, and services while highlighting the vital role of the transport sector in maintaining crucial supply chains. Nevertheless, transport generates substantial societal costs, including greenhouse gas emissions, environmental pollution, accidents, congestion, and biodiversity loss.

The EU has progressively intensified its efforts to address these adverse effects. In December 2019, the European Commission unveiled the **European Green Deal**, which aspires to achieve carbon neutrality for the EU by 2050. This objective has received support from both the European Parliament and member states. To realise climate neutrality, the EU transport sector is required to reduce its CO2 emissions by 90%. This expectation represents a significant departure from historical trends, given that the transport sector is the only sector in which greenhouse gas emissions have consistently increased, despite the implementation of prior measures.

In response to these challenges, the Commission has proposed a comprehensive strategy to transform the EU transport sector, ensuring alignment with the European Green Deal by fostering a greener, more digital, and more resilient framework. The European Green Deal also addresses the pressing challenges of global warming and climate change. The EU has reported that one million out of eight million species worldwide are at risk of extinction in conjunction with the ongoing pollution and degradation of forests and oceans[41].

4.2. Regulatory Pressure

Government regulation increasingly forces companies to become more environmentally friendly (regulatory push). Governments and regulatory bodies are introducing stricter

[41] Sources: (i) Intergovernmental Panel on Climate Change (IPCC): Special Report on the impacts of global warming of 1.5°C; (ii) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services: 2019 Global assessment report on biodiversity and ecosystem services; (iii) The International Resource Panel: Global Resources Outlook 2019: Natural Resources for the Future We Want; (iv) European Environment Agency: the European environment — state and outlook 2020: knowledge for transition to a sustainable Europe

emissions standards. The logistics industry is under increasing pressure to align with international agreements like the Paris Agreement, which aims to limit global warming to 1.5°C above pre-industrial levels. Ports and logistics operations must adapt to meet these goals.

There is an important role for (inter)national governments and organisations in driving decarbonisation in the port, transport and logistics industry. Governments have the ability to set the pace for transformation by setting clear and ambitious policy goals, by establishing regulatory frameworks to implement their policies for reaching these goals, and by making available the resources needed for setting things in motion. Governments are not only responsible for the environment, but they are also responsible for economic prosperity, the general welfare of the population, and overall socio-economic development. Their policy goals reflect this broad perspective on their responsibilities, incorporating a balance between environmental protection and economic growth.

Figure 4.2. Possible public interventions to enhance green behaviour in the port, transport and logistics industry

INSTRUMENTS THAT DIRECTLY LIMIT ENVIRONMENTAL IMPACTS Setting of fixed impact reduction targets	
Single-source instruments ("command and control") Company needs to comply with an emission limitation or face penalties	
Harm-based standards	Description of required end results (e.g. cap on CO2 emission of a terminal or logistics facility)
Design standards	Description of required emission limits based on model technology
Technology specifications	Specification of the technology the company must use to control its pollution
Bans and limitations	Ban or restrict equipment or operations that present unreasonable risks
Multi-source instruments (limits on cumulative impacts from multiple sources) Company has some flexibility in how it complies with specific environmental targets => change own behavior or make other entities comply on the company's behalf	
Integrated permitting	Multiple requirements into a single permit
Tradeable emissions	Allow companies to trade emission control repsonsibilities among themselves given an aggregate regulatory cap on emissions
Challenge regulations	Companies are given responsibility for designing and implementing a program to achieve imposed target.

INSTRUMENTS THAT DO NOT DIRECTLY LIMIT ENVIRONMENTAL IMPACTS Encouragement of pollution control without setting specific emission targets	
Pollution charges	Company pays fixed amount for each unit of pollution (no ceiling)
Liability	Company pays compensation to those that are harmed by impacts
Information reporting	Company needs to report impacts publicly
Subsidies/discounts	Financial assistance or discounts to companies as an incentive/carrot to change their behavior, or to help defray costs of mandatory standards.
Technical assistance	Knowledge support to companie (good practice guide, training, information centre)

Source: adapted from Environmental Policy Tools: A User's Guide September 1995 OTA-ENV-634 GPO stock #052-003-01441-6

The environmental policies of governments and other public entities can have a significant impact on emissions in the port, transport and logistics industry. These policies typically define the emission and energy targets for economic activities and freight mobility. To reach these targets, a range of instruments and intervention mechanisms are available to public policy makers (Figure 4.2). For instance, governments can change the behaviour of individuals and market actors by imposing restrictions and bans to eliminate or restrict choice. Through (environmental) pricing instruments, public policies can incentivise and penalise market actors active in supply chains. Market-based mechanisms, such as carbon pricing, emission trading schemes, and green financing, can incentivise decarbonisation. Moreover, non-regulatory and non-financial measures can be used to (gently) push towards greener solutions and transport modes.

There are plenty of examples of how governments and government agencies deploy instruments to reduce CO_2 emissions in the port, transport and logistics industry and alter the behaviour of market actors. We respectively focus on (1) the policy initiatives of IMO to decarbonise shipping; (2) major policy lines of the EU to reduce CO2 emissions in transport and logistics; and (3) some main policy lines of Belgium/Flanders.

In maritime shipping, **IMO** focuses strongly on **operational and technical energy efficiency measures**, for example through the application of Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Index (EEOI), Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Index (CII) (IMO, 2020; Mallouppas and Yfantis, 2021). The EEXI is a technical measure in force since 1 November 2022 and concerns design parameters of the vessels and measures their structural efficiency in terms of energy efficiency level per capacity mile. The CII is an operational measure that also applies to existing ships. It links the CO_2 emissions to the cargo carrying capacity over distance travelled, and rates the vessel on a scale of A to E. The CII is calculated according to the Annual Efficiency Ratio (AER), which is the ratio of CO_2 produced in a year, divided by the product of deadweight tons multiplied by miles sailed in a year. CII ratings are recorded in a ship's SEEMP (Ship Energy Efficiency Management Plan). If the ship is rated as D or E for three consecutive years, its SEEMP will need to be reviewed and include corrective actions to improve the rating. IMO will review the effectiveness of the implementation of the CII and EEXI requirements by 1 January 2026 at the latest and develop and adopt further amendments as required. **Market-based measures (MBM)** are also considered a part of the solution (Psaraftis et al., 2021) with most advances in this area made by the European Union, particularly through the inclusion of shipping in the EU Emission Trading System (ETS) since January 2014 onward to cover CO_2 emissions from all large ships (5 000 GT and above) entering EU ports. At the 83rd session of IMO's Marine Environment Protection Committee (MEPC 83), held in April 2025, several pivotal decisions were made to advance maritime environmental protection and decarbonisation efforts in shipping. MEPC 83 approved draft amendments to MARPOL Annex VI, introducing the IMO Net-Zero Framework. This framework aims to reduce greenhouse gas (GHG) emissions from international shipping, targeting net-zero emissions by or around 2050. It encompasses a goal-based marine fuel standard to progressively lower the GHG intensity of marine fuels and a pricing mechanism for maritime GHG emissions. For the first time, a mandatory emissions pricing mechanism was approved for ocean-going ships over 5,000 gross tons. These measures are set for adoption at an extraordinary MEPC session in October 2025 and are expected to enter into force by March 2027.

The **EU** is using a wide array of policy instruments to decarbonise the port, transport and logistics industry. The EU Green Deal is a new growth strategy that aims to transform the European Union into a fair and prosperous society. It seeks to establish a modern, resource-efficient, and competitive economy characterised by no net emissions of greenhouse gases by 2050 while decoupling economic growth from resource use. In pursuit of this transition, the European Commission has adopted a series of proposals to align the EU's climate, energy, transport, and taxation policies to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. This comprehensive set of proposals is known as the Fit for 55 package.

The **Fit for 55 package**[42] is a set of laws designed to reduce greenhouse gas emissions in the EU by at least 55% by 2030, setting the EU on a path towards climate neutrality by 2050. This package ensures a fair transition while enhancing EU industries' innovation and competitiveness. It provides a level playing field for economic operators from non-EU countries. Additionally, the package reinforces the EU's leadership in the global fight against climate change. Following the ordinary legislative procedure, several legislative acts were finalised and adopted as part of this initiative.

The **EU Emissions Trading System** (EU ETS) is a **carbon market** based on a cap-and-trade system for emission allowances. It targets explicitly energy-intensive industries and the power generation sector and serves as the EU's primary tool to reduce emissions. Shipping is gradually being included in ETS since 2024.

The **Carbon Border Adjustment Mechanism** (CBAM) ensures that the European Union's efforts to reduce emissions are not undermined by production shifts to non-EU countries, where climate policies may be less stringent. It also aims to prevent the increased importation of carbon-intensive products that could offset the EU's emissions reduction goals, all while adhering to international trade rules.

The effort-sharing regulation establishes binding annual targets for greenhouse gas emissions for member states in sectors not included in the EU emissions trading system (EU ETS) or the rules regarding land use, land use change, and forestry (LULUCF). These sectors encompass road and domestic maritime transport, buildings, agriculture, waste management, and small industries. As part of the Fit for 55 package, the new rules will raise the EU-level target for greenhouse gas emissions reduction in these sectors from 29% to 40% by 2030, based on 2005 levels. National targets will also be updated accordingly.

The **land use, land-use change, and forestry** (LULUCF) regulation establishes a binding commitment for the EU to reduce emissions and enhance carbon removals in the land use and forestry sectors. The Fit for 55 package makes the objectives more ambitious.

Cars and vans contribute 15% of total carbon dioxide emissions in the European Union (EU). As part of the Fit for 55 package, the EU has implemented new regulations to reduce CO2 emissions from these vehicles. The regulations establish **progressive emissions reduction targets for cars and vans**, including a goal of achieving a 100% reduction for new cars and vans by 2035. Additionally, the new rules set an EU-level target of at least 310 million tonnes

[42] https://www.consilium.europa.eu/en/policies/fit-for-55/#0

of CO2 equivalent net removals of greenhouse gases for 2030. Binding national targets have also been established for each member state.

Sustainable aviation fuels, including advanced biofuels and electro fuels, have the potential to reduce aircraft emissions significantly. However, this potential is largely untapped, as these fuels currently represent only 0.05% of total fuel consumption in the aviation sector. The ReFuelEU Aviation regulation aims to reduce aviation's environmental impact and enable the industry to contribute to the EU's climate targets.

The maritime sector depends largely on fossil fuels, contributing to greenhouse gas emissions and other harmful pollutants. The FuelEU maritime initiative aims to decrease the greenhouse gas intensity of energy used on board ships by up to 80% by 2050. These new regulations encourage the adoption of **renewable and low-carbon fuels in shipping**[43].

The primary objective of the regulation on **Alternative Fuels Infrastructure** (AFIR) is to ensure that citizens and businesses have access to a comprehensive network for recharging or refuelling road vehicles and ships using alternative fuels[44]. These new regulations aim to reduce the transport sector's carbon footprint significantly. They establish several targets to be met by 2025 or 2030, including:

- recharging stations for cars and vans to be installed every 60 km
- hydrogen refuelling stations serving both cars and lorries to be deployed from 2030 onwards in all urban nodes
- users of electric or hydrogen-fuelled vehicles to be able to pay easily at recharging or refuelling points

The **EU renewable energy directive** was revised for the Fit for 55 package. This revision aims to increase the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030, with an additional indicative target of 2.5%, which could bring the overall share up to 45%. The directive includes specific sub-targets and measures across various sectors, particularly focusing on areas where progress in integrating renewable energy has been slower, especially in transport, buildings, and industry. The revised **EU Energy Efficiency Directive** aims to reduce final energy consumption across the EU by 11.7% by 2030, compared to projections made in 2020. This new legislation will enhance energy efficiency efforts among member states by increasing annual energy savings obligations and lowering energy consumption in public sector buildings.

Buildings account for 40% of energy consumption and 36% of energy-related direct and indirect greenhouse gas emissions in the EU. The **Energy Performance of Buildings Directive**, updated in 2024, intends to improve the energy efficiency of buildings in the EU by 2030 and beyond.

The main goals of the directive are:

[43] https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/

[44] https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/alternative-fuels-infrastructure-council-adopts-new-law-for-more-recharging-and-refuelling-stations-across-europe/

- all new buildings will be zero-emission buildings by 2030
- existing buildings will be transformed into zero-emission buildings by 2050

The **hydrogen and decarbonised gas market package** aims to reduce the gas market's carbon footprint. Its goal is to transition from natural gas to renewable and low-carbon gases, encouraging their adoption in the EU by 2030 and beyond.

Additionally, the proposal for revising the Council directive on the **taxation of energy products and electricity** seeks to:

- align the taxation of energy products and electricity with the EU's energy, environment and climate policies
- preserve and improve the EU internal market by updating the scope of energy products and the structure of rates and by rationalising the use of tax exemptions and reductions by member states
- preserve the capacity to generate revenues for the budgets of the member states

European Union rules mandate that large companies and publicly listed firms regularly publish reports on the social and environmental risks[45] they encounter. Additionally, these regulations require them to detail the impact of their activities on both people and the environment. To this end, the EU has established the **Corporate Sustainability Reporting Directive** (EU) 2022/2464[46]. According to EU law, companies that exceed a certain size must disclose information about the risks and opportunities they associate with social and environmental issues and the impact of their operations on society and the planet. This transparency enables investors, civil society organisations, consumers, and other stakeholders to assess companies' sustainability performance, aligning with the objectives of the European Green Deal. The first companies required to comply with the Corporate Sustainability Reporting Directive (CSRD) will implement these new rules for the 2024 financial year, with reports published in 2025. Companies under the CSRD must report under the European Sustainability Reporting Standards (ESRS), which are being developed in draft form by EFRAG (the European Financial Reporting Advisory Group). This independent body includes various stakeholders.

On February 26, 2025, the European Commission adopted an Omnibus simplification package of proposals to simplify EU regulations and enhance competitiveness. Among these proposals is the postponement of the start of reporting until 2028 and the suggestion to apply the CSRD solely to the largest companies—those with more than 1,000 employees—thus concentrating sustainability reporting obligations on firms more likely to significantly impact people and the environment. Additionally, the proposals aim to ensure that reporting requirements placed on large companies do not burden smaller companies within their supply chains.

[45] https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

[46] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

The European Regulation on the Governance of the Energy Union and Climate Action (EU 2018/1999) requires European Member States to draw up a **National Energy and Climate Plan (NECP)**. At the end of 2019, Belgium submitted a NECP for the period 2021-2030. The same regulation requires each Member State to submit a draft update of the last submitted NECP 2021-2030 by 30 June 2023. The federal Energy and Climate Plan (FEKP) is still subject to updating.

On 12 May 2023, the **Flemish Government** approved the draft update of the Flemish Energy and Climate Plan (VEKP) 2021-2030 – a revision of the original plan adopted in 2019. The EU is asking Belgium for a 47% CO_2 reduction by 2030 (compared to 2005). Currently, the reduction by 2030 would be 33.7% at the Flemish level. To close this gap, the Flemish Government approved a final Flemish Energy and Climate Plan (VEKP) on July 18, 2025 (Flemish Government, 2025). This is an update of the draft VEKP approved in 2023. The 2021-2030 VEKP implements the Flemish greenhouse gas reduction target of minus 40% by 2030 (compared to 2005) in the sectors covered by the European Effort Sharing Regulation (ESR sectors). To this end, the VEKP 2021-2030 contains a comprehensive package of measures that touches upon all policy areas of the Flemish government. The main envisaged measures relevant to freight transport and logistics are summarised in Textboxes 4.1a and 4.1b.

Textbox 4.1a. Key transport and logistics aspects in the Flemish Energy and Climate Plan (VEKP) 2021-2030 of the Flemish Government

Road transport

To reduce the sector's climate impact, two overarching objectives are being pursued: a reduction in the number of vehicle kilometres driven and a greening of the vehicle fleet. The first objective aims to reduce the total number of vehicle-km driven in Flanders. For passenger transport, the focus is on a reduction in road kilometres, while for freight transport, a further levelling off of growth is envisioned. For light transport, the aim is a minimum reduction of 4% in road kilometres driven by 2030 compared to 2015. For heavy transport, the target is set at a maximum increase of +13% in the number of kilometres travelled by road by 2030 compared to 2015. An integrated multimodal and synchromodal mobility system should support these targets. To avoid kilometres travelled by road, a well-considered spatial policy in Flanders that supports sustainable mobility and logistics is also essential to implement.

To green the vehicle fleet, the following objectives are being pursued. For newly purchased light trucks (vans), the share of zero-emission vehicles will be 36% by 2030. In line with European policy, 100% of newly sold vans will be completely emission-free from 2035 onwards. For newly purchased heavy trucks, the share of zero-emission vehicles will be at least 28% by 2030. The Flemish government is aware that a transition to zero emissions is not so evident for trucks. In the coming years, the government looks forward to more new trucks based on advanced renewable fuels (bio and synthetic), with fuel cells, supported by innovations in the area of batteries and charging infrastructure. The expansion of a well-equipped network of charging points for vans and trucks is essential. It is expected that trucks will primarily charge at private locations (e.g., in the depot). To ensure the operational reliability of logistics operations, a network of public charging points is also needed. Based on recently developed charging forecast maps, a network of public and semi-public charging points for vans and trucks is being developed.

To ensure that road freight transport using zero-emission trucks is not disadvantaged compared to diesel-powered trucks, definitive regulations are being developed and approved to increase the maximum permitted weight and length of electric trucks and to allow longer and heavier trucks (LHVs) / eco-combis.

Inland waterway transport

Investments are being planned and made in the development of well-connected modal networks and innovative transhipment points at attractive rates. Flanders has invested heavily in inland waterway infrastructure in recent decades. However, these investments have not yet sufficiently achieved a modal shift from road freight transport to inland waterway transport. The underlying causes will be investigated together with the sector and how they can be addressed.

Innovation in ship concepts and propulsion systems can also improve the competitiveness of inland shipping. To map out a clear future path for the greening of inland shipping and involve all relevant stakeholders in the inland shipping sector, a Flemish Green Deal for Inland Shipping has been launched. This Green Deal aims to achieve optimal greening of inland shipping through emission reduction targets by 2030, looking ahead to 2050 with shared objectives and realistic actions that remove barriers and bring about change in the field by 2026. Furthermore, efforts are being made to facilitate autonomous sailing to increase the efficiency of inland shipping by providing the necessary regulations and enabling pilot projects, for example, using remotely controlled barges (including a pilot project on the Yser River). The shore-side power network for inland shipping will also be further expanded, and its use will be encouraged, in close cooperation with the port authorities. The Flemish government is exploring the possibility of incorporating the provision and use of shore-side power installations into VLAREM (Flemish Environmental Management Act) when building new quays and supplementing existing quays.

Source: Flemish Government Climate Plan (VR 2022 1507 DOC.0869), July 2022

Textbox 4.1b. Key transport and logistics aspects in the Flemish Energy and Climate Plan (VEKP) 2021-2030 of the Flemish Government (continued)

Rail - The Belgian federal government is being urged to increase investments in infrastructure and rail transport services to promote the modal shift towards rail. This includes improving infrastructure, improved regulations, support mechanisms, operational improvements, and enhanced intermodality. The Flemish Rail Strategy (2013) contains the intended developments. In 2018, a cooperation agreement was concluded between the federal government and the regions regarding the financing of strategic railway infrastructure. This agreement ensures the realisation of various studies and infrastructure works. Some of these projects are co-financed by the Flemish Region.

Pipeline Transport - To be able to implement pipelines as a fully-fledged transport mode, it is important that the Department of Environment (re)initiates the necessary planning processes. This specifically concerns the GRUP Leidingstraat Antwerpen – Ruhr, provided that the necessary preconditions for a smooth process flow are met.

Air transport - Flanders, together with the three airport operators, will take the lead in the sustainable transition to greener aviation. This will focus on diversifying airport charges and technological developments in the aviation industry. The main focus will be on blending SAF (Sustainable Aviation Fuel) where economically feasible, promoting electric flight for flight training and recreational flying, and the extensive electrification of ground traffic and the provision of space for generating sustainable energy at airports.

Multimodal nodes - To achieve a multimodally integrated transport system, the Flemish government uses a corridor approach and develops a hierarchical network of nodes. This also requires effective data exchange. The Flanders Spatial Policy Plan (2018) aims to make freight transport more sustainable by concentrating logistics activities at well-connected locations with multimodal accessibility. Water-bound business parks remain reserved for companies that effectively utilise the waterway. New logistics developments must align with the principle of careful spatial use, prioritising reuse and densification over expansion.

Modal shift in ports - The port authorities themselves have set ambitious targets for modal split by 2030. Together with the port authorities and other partners, the Flemish government wants to examine which concrete measures can be taken in the short and medium term to achieve these ambitious targets. This could include (but is not limited to) reserved berths for inland vessels in the port; stricter (tax) regulations for polluting modes; support measures for inland waterway transport in the port hinterland; and, mitigating measures to shift additional freight traffic off the road. Key focus areas within this hinterland strategy for seaports include data sharing and convincing the various logistics players to make greater use of rail and inland waterway transport. Since 2018, the Flemish government, together with the port authorities, has launched initiatives to improve the ports' hinterland connectivity. The modal shift is a key focus of the Flemish Port Strategy (2022). Specifically for inland waterway transport, the support program 'Versnelling modal shift' (modal shift acceleration), with financial support measures for the sector, will run until the end of 2025.

Zero-emission logistics

Several cities and municipalities have the ambition to establish zero-emission zones for urban logistics (ZES) in the coming years and to focus on, among other things, deliveries by water, with zero-emission vehicles, or via bicycle logistics. In the implementation of the Zero-Emission Urban Logistics Framework Agreement (2024), the Flemish government is providing cities and municipalities with the necessary tools for this, for example, through charging infrastructure for logistics vehicles or legal thresholds for zero-emission vans.

Source: Flemish Government Climate Plan (VR 2022 1507 DOC.0869), July 2022

4.3. Market Pressure and Corporate Reputation

Consumers and businesses are increasingly demanding sustainable supply chains, compelling the industry to innovate and pursue low-carbon or zero-carbon solutions.

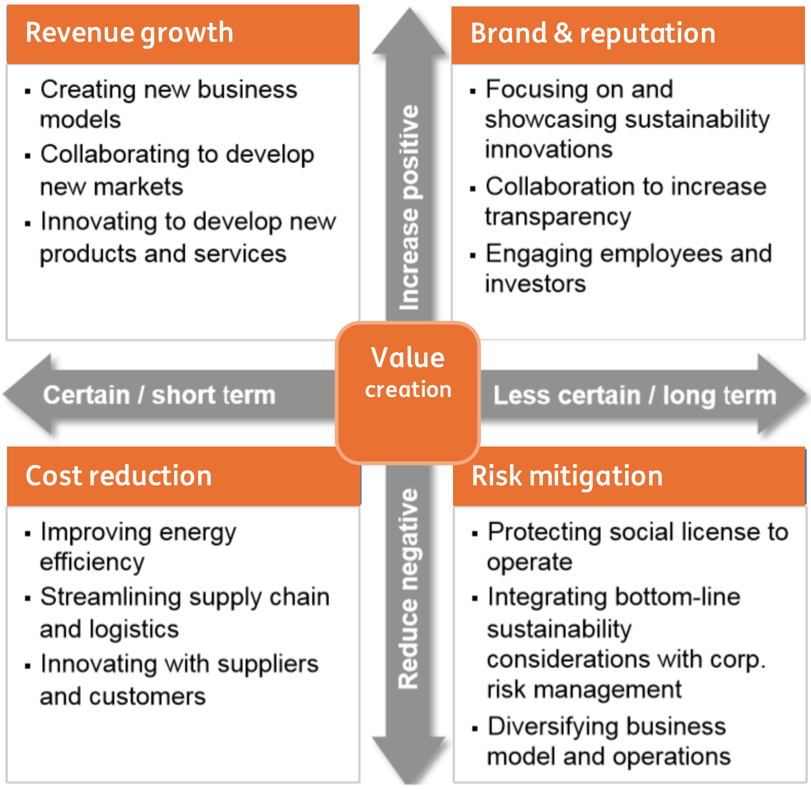
In the 1980s, the pursuit of environmental excellence in product development, process design, operations, logistics, regulatory compliance and waste management was still spread over a large number of organisational units in companies. This started to change with the SCM revolution of the 1990s, when environmental management started to become more integrated in overall operations. For the first time, studies started to emerge that analysed environmental practices as a means to gain competitive advantage and economic benefits (see e.g. Frosch and Gallopoulos, 1989). The idea of using environmental strategies to gain a competitive advantage was further developed by Porter and van der Linde (1995). Investments in greening can be resource-saving, waste-eliminating, and productivity-improving. Thus, the greening of supply chains does not have to be a burden but could constitute a potential source of competitive advantage (van Hoek, 1999). These ideas further ripened in the early 2000s with a slow mental shift from just being environmentally friendly to an integration of green initiatives as a way to achieve good business sense and higher profits. In other words, the industry started to show a growing awareness that GSCM could constitute a business value driver, not just a cost centre (Wilkerson, 2005).

In the past decade, the corporate pressure for decarbonisation of supply chain management practices has grown significantly. Customers want companies to consider the environment when pursuing a more profitable supply chain (demand pull). Thus, companies might initiate decarbonisation practices due to motivational drivers such as sales to customers, and legislative and stakeholder institutional pressures. Decarbonisation efforts also enhance corporate reputation and help attract environmentally conscious clients and investors. Financial institutions are increasingly linking funding to ESG ratings, creating incentives for investments to decarbonise activities.

When focusing on the corporate context, there are clear signs that not opting for a decarbonisation of supply chains can negatively affect companies' cost base and profitability, and that a focus on GSCM is needed to secure revenue growth, achieve cost reductions, develop brand value and mitigate risks (Figure 4.3). Furthermore, a focus on the environment has a positive impact on brand value.

Even in less-regulated markets, some companies have engaged in decarbonisation practices to reduce production costs, enhance brand image, meet changing customer expectations, protect aftermarkets, and pre-empt pending legislation or regulations. There is a growing awareness that the greening and decarbonisation of supply chains can be an important business value driver and source for competitive advantage for companies.

Figure 4.3. A holistic view on value creation through green supply chain management



Source: adapted from WEF (2015) and Accenture

Along these lines, it is increasingly important for a company to have visibility of its CO_2 emissions, as such visibility goes beyond compliance but is about being able to set and reach achievable goals and share these with upstream and downstream partners in the supply chain. A wide array of standards is available to calculate emissions. For example, CO_2 emissions at the shipment level can be assessed using the EcoTransIT World Methodology, ISO Standard 14083:2023, the Global Logistics Emissions Council (GLEC) Framework for Logistics Emissions and the Greenhouse Gas (GHG) Protocol (see earlier in this study).

The increasing demand for sustainable transportation and supply chains is driving the need for improved overall efficiency. Digitalisation and automation technologies are vital in facilitating efficient and integrated services. Consequently, these technologies are essential for the transition to more efficient and sustainable transportation and supply chain solutions. These were described in detail in section 3.

4.4. Financial Incentives

Financial incentives or penalties given by public authorities (such as subsidies, tax breaks, etc. for green investments or penalties for non-compliance) or by private service providers (such as a commercial bank providing favourable loan conditions for green investments) are often very important in investment or divestment decisions and to achieve investment recovery. Also, other public entities, such as port authorities, can provide an incentive to decarbonise, as exemplified by Textbox 4.2.

Textbox 4.2. The Environmental Ship Index (ESI)

The Environmental Ship Index (ESI) was created by major ports in cooperation with the International Association of Ports and Harbours (IAPH) and has been fully integrated into the IAPH's governance structure since 2020. The Environmental Ship Index portal enables ports and other interested parties to incentivise ships to use cleaner engines and fuels with preferential treatment offered either through discounts on port dues, bonuses or other benefits commensurate with a specified level of cleanliness. ESI is a voluntary tool that includes a formula-based evaluation of vessels' nitrogen oxide (NOx) and sulphur oxide (SOx) emissions. The calculation also rewards vessels that are equipped to use available onshore power and which demonstrate fuel efficiency improvements over time, reducing carbon dioxide (CO2) and particulate matter (PM) emissions. The ESI has become the established standard by which port authorities and maritime administrations incentivize ship owners and ship owners/operators to continuously improve the environmental performance of the fleets calling at their terminals. ESI has been recognized by the IMO as the standard basis for port incentives for low- and zero-carbon ships. By 2026, ESI's revised and expanded offering will take into account a range of potential emissions, introduce a new GHG methodology, and reward innovation and application of zero-emissions techniques onboard vessels. The new ESI will also address global concerns about the environmental impact of vessels on marine life.

Source: based on IAPH and Notteboom et al. (2022)

On a regional, national and supranational level there is a very broad set of financial incentives that support the digitalisation and process and operational automation. This ranges from the regional funding schemes as provided by VLAIO[47] (Flanders Innovation & Entrepreneurship), covering innovation from the lower Technology Readiness Levels (TRLs) cSBO via ICON and COOCK to market-ready solutions in pure O&O (applicable Research and Development), to the European level with the EU[48] providing several schemes, such as Interreg programmes, Horizon Europe with a specific Cluster focussing on Climate, Energy, and Mobility, and the Connecting Europe Facility (CEF), an EU funding instrument to promote growth, jobs, and competitiveness through targeted infrastructure investment at the European level.

4.5. Technological advances

Emerging technologies and practices hold promise for further reducing emissions. Green hydrogen, ammonia, and other zero-carbon fuels are (slowly) gaining momentum as alternatives to fossil fuels. Strong advances are made in battery technology. Additionally, innovations in carbon capture and storage (CCS) technology could offset emissions that cannot be eliminated.

Digital tools, such as artificial intelligence (AI) and the Internet of Things (IoT), can optimise logistics operations to minimise emissions. Technologies like digital twins enable predictive

[47] https://www.vlaio.be/en/subsidies
[48] https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes_en

maintenance and efficient resource management, while autonomous vehicles and drones reduce fuel consumption. Information and communication technologies (ICT) are playing a key role in the coordination and integration of decarbonisation initiatives. Resource commitment to information technology can help to achieve superior environmental performance. Thus, digital transformation within and between companies may be primarily justified for other reasons, but can also be evaluated from a greening perspective.

Technology advances rapidly, leading to increased electrification of automated solutions for terminal equipment, warehouse facilities, and various transportation modes. Concurrently, operational and process automation are increasingly interconnected, creating new opportunities for equipment and rolling stock to function as communicative devices. This transformation enables them to enhance efficiency in core operations actively. The capabilities of digital tools and technology continue to expand, leveraging data from a growing number of well-structured and organised sources. This advancement will improve all stakeholders' analytical, transport, and supply chain management capabilities.

Additionally, technology offers solutions to address staff shortages, including the need for 24/7 operational staff or drivers. It is particularly well-suited for taking over repetitive tasks while enhancing safety and security, allowing employees to concentrate on more value-added responsibilities that are often more fulfilling. This shift can make jobs in the ports and logistics industry more appealing.

4.6. Cooperation schemes and new governance models

Decarbonisation in the port, transport and logistics industry is a complex but necessary endeavour for addressing climate change and achieving global sustainability goals. While the challenges are significant, advancements in stakeholder collaboration provide a path forward. Successful decarbonisation initiatives often involve many departments within and between companies, and this cooperation and communication are important to successful environmental practices. The inter-organisational sharing of responsibility for various aspects of environmental performance is key to successful decarbonisation strategies. Cooperation between actors is also needed to improve the total quality environmental management within and between organisations.

Collaborative initiatives between governments, private companies, and research institutions can drive innovation and fund large-scale decarbonisation projects. Examples include green ports and eco-industrial clusters.

Not only can individual companies opt for co-operation on a bilateral or multilateral basis. Industry and branch organisations often play an important role in bringing companies together to take joint initiatives. In other cases, private companies (sometimes with different backgrounds) and other organisations (such as public entities) form ‘coalitions of the willing’ to advance the design and implementation of decarbonisation solutions. These coalitions are associated with new models of governance to build trust among the parties involved and to achieve a fair distribution of costs/efforts and revenues/returns. For illustration purposes,

Table 4.1 provides a selection of voluntary cooperation initiatives in the context of shipping decarbonisation.

Table 4.1. Selected voluntary initiatives for decarbonising shipping

Initiative	Members	Purpose
Getting to Zero Coalition	200 organisations, including entities from the maritime, energy, infrastructure, and finance sectors	Decarbonise maritime shipping and develop and deploy commercially viable deep sea zero emission vessels by 2030 and full decarbonisation by 2050
Mission Innovation	Co-led by Denmark, Norway, United States, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Global Maritime Forum	Demonstrate commercially viable zero-emission ships by 2030 and promote zero-emission fuelled vessels
Poseidon Principles	30 banks jointly representing approximately $200 billion in shipping finance	Voluntary principles by global shipping banks to promote shipping decarbonisation, a framework for disclosing the climate alignment of lending portfolios to the shipping industry
	36 charterers and operators	A framework for aligning chartering activities with responsible environmental behaviour and disclosing the climate alignment of global ship chartering activities
Clean Energy Marine Hubs	International Chamber of Shipping, International Association of Ports and Harbours and the Clean Energy Ministerial	A public-private platform across the energy maritime value chains to promote green fuels and support the global energy transition. Includes the governments of Canada, Norway, Panama, Uruguay, and the United Arab Emirates
Green Voyage 2050	Led by IMO and funded by Norway. Aims at selected developing countries	Cooperation between SIDS and the LDCs and maritime-related international associations and the industry
Zero-Emission Waterborne Transport	Horizon Europe, European maritime companies	Provide and demonstrate zero-emission solutions for ships before 2030

Source: adapted from UNCTAD (2023)

Many organisations are concerned about the sensitive issue of sharing data with other stakeholders in the transport and supply chain, particularly regarding data security.

However, international **momentum is growing for next-generation data-sharing mechanisms** between organisations, including business-to-business (B2B) and business-to-government (B2G) models. The European Commission views data sovereignty as critical to the future digital economy. It aims to create data spaces that promote trustworthy data sharing while adhering to societal values and legal frameworks.

Several initiatives led by organisations like the International Data Spaces Association (IDSA), GAIA-X, FIWARE, and the Big Data Value Association (BDVA) are central to this strategy, which seeks to boost innovation in the European data economy (see earlier section 3).

4.7. Summary

Figure 4.4 provides an overview of the main tailwinds and drivers of decarbonisation and digitalisation as identified in the presented literature analysis. The listing does not contain any weighing of the various tailwinds and drivers, as the weights might be context-dependent in terms of the specific decarbonisation or digitalisation initiative, the regional activity of the company concerned, etc. The survey-based approach developed later in this report aims to provide more insight into the relative importance of each identified potential tailwind and driver.

Figure 4.4. Summary of tailwinds and drivers of decarbonisation and digitalisation

1. Environmental goals and policies

- Supranational (UN, IMO, ECE, EU) and national/regional public bodies
- Green Deal, Fit for 55, Corporate Sustainability Reporting (CSR)
- Corporate goals
- Contribution of digitalization and automation to achieve goals

2. Regulatory pressure

- Existing range of policy instruments (reporting requirements, pricing, etc.)
- Examples of concrete policy instruments applied to ports & logistics

3. Market pressure & corporate reputation

- Demands & requirements of customers and supply chain partners
- Push for visibility & transparency of CO2 emissions
- ESG ratings

4. Financial incentives

- Compulsory /voluntary incentive or penalty programs (e.g. ESI)
- Public subsidies/taxes, and funding schemes
- Access to sustainable finance

5. Technological advances

- Alternative fuels, propulsion systems, CCS, digital tools, etc.
- Data use from a growing number of well-structured & organised sources
- Technology as a tool to address staff shortages issues

6. Cooperation schemes & new governance models

- Advances in stakeholder collaboration & collective action regimes
- Inter-organisational sharing of responsibility
- Next-generation data-sharing mechanisms (IDSA, GAIA-X, FIWARE, BDVA,..)

5. Headwinds of Decarbonisation and Digitalisation in Ports, Transport and Logistics

As market actors and policymakers intensify their efforts to combat climate change, the port, transport and logistics industry faces mounting pressure to decarbonise and digitalise. The path to decarbonisation and digitalisation is fraught with challenges. This section of the report explores the difficulties the port, transport and logistics industry might encounter in its quest, focusing on technological, economic, regulatory, and infrastructural barriers.

To overcome these challenges, a coordinated effort is required from governments, industry stakeholders, and the private sector. Policymakers must provide clear and consistent regulations, as well as financial incentives, to support the adoption of low-carbon technologies. Industry players must invest in research and development to overcome technological barriers, while also fostering a culture of sustainability within their organisations. Finally, collaboration between different stakeholders is essential to develop the necessary infrastructure and ensure a smooth transition to a decarbonised port, transport and logistics industry.

5.1. Technological Challenges and Choice of Technology

One of the primary hurdles to decarbonisation in the port, transport and logistics industry is the reliance on fossil fuels, particularly diesel and heavy fuel oil (HFO), for transportation. The sector is heavily dependent on internal combustion engine vehicles, which are inherently carbon-intensive. Transitioning to low-carbon or zero-emission vehicles, such as electric trucks or hydrogen-fuelled vehicles, presents **significant technological challenges**. The current state of battery technology limits the range/working time and payload capacity of electric vehicles and equipment. Long-haul transportation, which is a critical component of the logistics industry, requires vehicles that can travel extended distances without frequent recharging. Moreover, heavily used equipment at terminals and warehouses also requires energy solutions with minimal downtime for recharging. While advancements in battery technology are ongoing, the energy density of batteries remains insufficient to meet the demands of long-haul freight transport and heavy equipment. Additionally, the public charging infrastructure for such vehicles is still in its infancy. For example, there is only a very limited availability of high-capacity charging stations for electric trucks across Europe. Hydrogen fuel cells offer a promising alternative, particularly for heavy-duty vehicles. However, the production of green hydrogen, which is produced using renewable energy, is still in its early stages and is not yet scalable to meet the demands of the logistics industry. Moreover, the infrastructure for hydrogen refuelling is virtually non-existent, further complicating the adoption of hydrogen-fuelled vehicles.

Policymakers often claim to be **technology-neutral** when addressing the decarbonisation of the port, transport and logistics industry, but in practice, this neutrality is often limited or influenced by various factors. Technology neutrality in policymaking has several advantages.

Governments that set emissions reduction targets without prescribing specific technologies allow the market to find the best solutions rather than picking a single winner. Examples include CO_2 standards for trucks or low-carbon fuel standards. A truly technology-neutral approach allows industries to decide on the best approach based on cost, efficiency, and scalability. However, technology neutrality is often not guaranteed, particularly when powerful industry groups or politicians may push policy in favour of one technology over another. By using subsidies and incentives, governments can *de facto* favour specific technologies through tax breaks, grants, or mandates. In this respect, the strong support of EU policy for green hydrogen has been criticised by some. Some policies might even implicitly favour certain solutions, such as bans on internal combustion engines (ICEs), which push battery-electric technology rather than allowing alternatives like biofuels or hydrogen-based ICEs. A strong public investment in specific infrastructure, such as charging networks or specific bunkering solutions, can also signal a preference. Technological solutions require agreement and a legal framework on relevant standards and procedures. Lengthy decision-making processes on the recognition of new fuel types, grades or mixtures, or technical standards on fuelling/charging installations (such as onshore power supply or OPS) can drastically reduce their market potential. Thus, while some policies claim to be neutral, in practice, they might tend to favour technologies that align with political priorities, existing infrastructure, or the interests of influential stakeholders.

In terms of digitalisation, many innovations are being developed in isolation, often without considering their compatibility with other technologies. This can create **a fragmented approach to technological advancement**, which does not lead to smoother or more efficient port and supply chain operations. This issue applies to both logistics automation and digital technologies. Furthermore, integrating these innovations with existing operational and supply chain management legacy systems increases the complexity. At the same time, this siloed approach further complicates the road to standardisation.

The current geopolitical landscape fosters **mistrust in our interconnected world**. It can be challenging to distinguish between cyber-attacks from rogue entities and those supported by governments. This uncertainty is exacerbated by the reality that most prominent technology companies are based outside Europe.

New technologies like AI, quantum computing, and blockchain applications are becoming increasingly popular. However, they are also **consuming a significant amount of energy**. This aspect is often overlooked, which contradicts the efficiency gains these technologies aim to achieve in optimising the port, transport and logistics industry.

5.2. Economic and Financial Barriers

Companies cannot blindly roll out decarbonisation and digitalisation initiatives. The transition to a decarbonised and digital port, transport and logistics industry requires substantial investment in new technologies, infrastructure, and operational changes. However, the economic viability of these investments is a significant concern for logistics companies, particularly small and medium-sized enterprises (SMEs) that operate on thin profit margins.

Logistics and supply chain managers have to balance efforts to reduce costs, improve service quality, increase flexibility, and innovate while maintaining good environmental (ecological) and digital performance. When deciding on decarbonisation initiatives, companies take into account the above strategic performance requirements, which may not be environmentally based, such as cost, return on investment (ROI), service quality, and flexibility. In other words, decarbonisation initiatives should not only best support the green supply chain but also result in a positive business case. Otherwise, the competitive and financial position of the company might be negatively affected. Thus, investment recovery is often cited as a critical aspect of decarbonisation in the port, transport and logistics industry. Such investment recovery typically occurs at the back end of the supply chain cycle.

The port, transport and logistics industry operates in a highly competitive market, where cost efficiency is paramount. Any increase in operational costs, whether due to the adoption of new technologies or compliance with stricter environmental regulations, could erode profit margins and make companies less competitive. This economic pressure creates a reluctance among logistics companies to invest in decarbonisation, particularly when the return on investment is uncertain.

While all cases are unique, substantial cost gaps between traditional and new technologies still exist, as illustrated by the following example. The upfront costs of purchasing **electric or hydrogen-fuelled trucks** are considerably higher than those of traditional diesel trucks (ING, 2021). While operating costs may be lower in the long run due to reduced fuel expenses, the initial capital expenditure can be prohibitive for many companies. Additionally, the total cost of ownership (TCO) for alternative fuel vehicles remains uncertain, as it depends on factors such as battery lifespan, maintenance costs, and the availability of charging or refuelling infrastructure.

Decision-makers and investors are inundated with publications discussing Total Cost of Ownership (TCO), Return on Investment (ROI), Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and various other financial metrics. However, these figures often differ significantly from one source to another. Regardless of the scientific methods behind these results, such discrepancies create confusion and contribute to the perception that many studies are merely academic exercises, disconnected from actual economic and operational realities. This confusion can lead to hesitation in committing to certain automation or digitalisation technologies.

5.3. Regulatory and Policy Challenges

An **unclear, complex, or unstable regulatory framework** creates legal uncertainty for investors in decarbonisation and digitalisation initiatives. In particular, whatever governments and public entities do in terms of environmental policy development, the business world is very sensitive to coherence and continuity in the developed policy, the legal (un)certainty of implemented policies, and the enforcement of policies through inspection and control.

As many investment decisions have a medium to long-term payback time, any **changes in government policy** (for example, the abolition of a subsidy scheme for certain decarbonisation investments) can have large ramifications on the soundness of the initial corporate decision related to a decarbonisation initiative. Thus, government policies and regulations typically have a significant impact on green strategies, investments and initiatives pursued by companies, but should provide legal and investment certainty to the affected companies.

Patchworks of regulations complicate compliance and increase the administrative burden on port and logistics companies. While the EU has set ambitious targets for reducing GHG emissions, the regulatory landscape for the logistics industry is complex and often fragmented. Global decarbonisation requires harmonised regulations and standards to prevent fragmentation. Different countries within the EU have varying levels of commitment to decarbonisation, which may lead to inconsistencies and varying interpretations of regulations and incentives. This lack of harmonisation creates uncertainty for port, transport and logistics companies that often operate across multiple jurisdictions and can even distort the 'level playing field', affecting fair competition between companies.

Uncertainty or lack of clarity in policy can stall investments. For example, the EU's Emissions Trading System (ETS), which is a cornerstone of its climate policy, currently covers maritime shipping, but not road transport. It remains unclear whether ETS will be extended to include road transport, how this could be implemented, or whether other market-based measures (such as a flat CO_2 tax) will be targeted to internalise the external costs related to CO_2 and other emissions in the road sector.

Lengthy and complicated permitting processes can significantly slow down the decarbonisation of the port, transport and logistics industry. It can lead to the delayed installation and deployment of critical infrastructure such as new charging stations, bunkering infrastructure, onshore power systems, or renewable energy projects. For example, ports need grid expansions to support electrification, but permitting delays might prevent the timely rollout of grid connections and onshore power. Also, wind and solar projects at ports or offshore locations can be slowed by environmental and zoning approvals, reducing the availability of clean energy for port operations, and therefore seriously affecting their targeted decarbonisation pathway.

Lengthy and complicated permitting processes are particularly troublesome when the demand side has already committed to using these infrastructures. The resulting extended project timelines add to the overall investment cost due to inflation, regulatory changes, and supply chain disruptions. Thus, complex and lengthy permitting processes add to the uncertainty and risk for private sector investment. Unpredictable and prolonged approval timelines can deter innovation and make companies hesitate to invest in zero-emission technologies. Countries and logistics zones or ports with slow permitting may even lose cargo traffic to other regions that demonstrate faster and more efficient permitting capabilities.

To support decarbonisation in the port, transport and logistics industry, companies require **speedy and streamlined permitting processes**. Simplifying and harmonising permitting across jurisdictions can reduce bureaucracy (i.e., red tape). Governments can introduce fast-track approvals for certain urgent and critical types of projects. Project approvals can be accelerated by enhancing collaboration and dialogue between regulators, businesses, and local communities.

In the digital field, automated or autonomous solutions face a lengthy and complex process of being incorporated into existing legislative and regulatory frameworks. This challenge is particularly evident for solutions being used on public roads, while it is less pronounced for other modes of transport. Examples from North America, such as Kodiak[49] and Embark Trucks (now known as Applied Intuition[50]), illustrate this issue. In contrast, European member states tend to be more cautious, favouring a lane-approved approach rather than a technology-oriented one.

5.4. Spatial and Infrastructural Limitations

The decarbonisation of the logistics industry is heavily dependent on the **availability of supporting infrastructure**. The installation of high-capacity energy infrastructure requires significant investment and coordination between multiple stakeholders, including governments, utility companies, and private sector players. Despite all efforts, the current infrastructure in Europe is still inadequate to support a large-scale transition to a low-carbon port, transport and logistics industry. Developing the necessary infrastructure for alternative fuels remains a challenge. Additionally, technology readiness varies globally, creating disparities between regions.

Land availability concerns and competing land claims pose major challenges to decarbonising the port, transport and logistics industry. The spatial development of Belgium is increasingly facing competing land claims: land needed to accommodate population growth and the associated housing needs; land required for strengthening and preserving nature; space for the water system, and space for biodiversity. Soil and water quality/household aspects (think of the PFOS discussion in Flanders) tend to take up an ever more prominent role in guiding such decisions. Furthermore, the transition to sustainable energy and circularity also requires additional space and new infrastructure, particularly in or near port areas. In a small country where almost all space has already been allocated for different functions, finding space to support the decarbonisation of the port, transport and logistics industry is not an easy task. Spatial planning authorities have a key role to play in making clear and robust choices in the division of space for the longer term.

Ecosystem thinking has gained ground in spatial and infrastructure development. This trend puts more emphasis on the clustered development of energy transition solutions. Seaports as large clusters for energy and industry have a key role to play as they are nodes in an emerging international network for the transport, handling, storage and use of alternative energy sources. This network is supported by long-distance energy corridors (undersea

[49] https://kodiak.ai/industry/trucking
[50] https://www.appliedintuition.com/

cables, power lines, pipelines, etc.) and local grids for energy distribution. Within such ecosystems, **spatial specialisation** is becoming increasingly important due to land scarcity. For example, space within seaport areas should ideally be reserved for companies that can make a demonstrable positive and connecting contribution to the further development and sustainable strengthening of the industrial-logistics ecosystem and the associated value chains, and that themselves also have clear competitive and operational benefits (both economic and in terms of sustainability) through their presence in that ecosystem. The infrastructural and spatial needs associated with decarbonisation in the port, transport and logistics industry should be approached from a broad ecosystem perspective. In other words, the needs of individual companies are still very important. Still, they are secondary to the broader spatial and infrastructural needs of the entire ecosystem and the networks within which it operates.

Social acceptance for spatial and infrastructural developments is increasingly under pressure, even when it concerns decarbonisation initiatives. Social acceptance is not automatically acquired but must be earned through an active approach. Within the context of the 'license to operate', 'license to grow' and 'license to adapt' of port, transport and logistics companies, it is necessary to explain and demonstrate the social added value of each development to the broader community of stakeholders.

The increased digitalisation and automation of logistics technologies will significantly enhance the efficiency of port and terminal operations. This improvement will lead to more effective use of existing infrastructure, reducing the strain on current facilities and delaying the need for expansion to accommodate rising trade volumes, and as such, can be considered a tailwind in this context.

5.5. Operational and Cultural Challenges

A last group of challenges in decarbonising and digitalising the port, transport and logistics industry relates to an array of operational and cultural aspects. Decarbonisation and digitalisation often require significant changes to the operational practices and culture within the port, transport and logistics industry. Many companies have established processes and routines that are deeply ingrained in their operations, making it difficult to adopt new technologies or practices. Training programs, certifications, and collaborative networks can ensure that stakeholders adopt sustainable practices. For example, the adoption of electric or hydrogen-fuelled vehicles may require changes to route planning, scheduling, and driver training. Drivers may need to be trained on how to operate and maintain new types of vehicles, while dispatchers may need to adjust routes to account for the limited range of electric trucks. These changes can be disruptive and may face resistance from employees who are accustomed to traditional practices.

Fostering a culture of sustainability within the port, transport and logistics industry is essential. Industry stakeholders may resist decarbonisation efforts due to uncertainties around the long-term viability of technologies or concerns about competitive disadvantages. Ensuring alignment across governments, port authorities, and private operators is crucial. In this context, not all companies are following the same approach when dealing with the decarbonisation challenge. In fact, companies' attitudes towards decarbonisation can range from reactive monitoring of the general environment management programs to more proactive practices. Kopicki et al. (1993) argued that companies can follow three different approaches:

- *The reactive approach*: Minimal resources are committed to environmental management, and the focus is very much on just meeting compliance in terms of environmental regulation;
- *The proactive approach:* Companies following this approach start to pre-empt new environmental laws by realising a modest resource commitment to, for instance, initiate the decarbonisation of their logistics operations.
- *The value-seeking approach*: In this case, companies integrate environmental initiatives and activities such as green transport as strategic initiatives into their business strategy.

Moreover, the port, transport and logistics industry is often characterised by a culture of cost minimisation and efficiency, which can be at odds with the goals of decarbonisation. Companies may prioritise short-term cost savings over long-term environmental benefits, particularly in a highly competitive market. Changing this mindset requires a shift in corporate culture, as well as greater awareness and education about the importance of decarbonisation.

Internal environmental management is central to improving enterprises' environmental performance. The support of senior managers is necessary and, often, a key driver for successful adoption and implementation of most innovations, technology, programs and activities focused on decarbonisation. For example, a study by Yeung et al. (2003) demonstrated that senior management's confidence is the most influential factor for the development of their quality management system. To ensure progress for environmental management, top management, but also mid-level managers, must be fully committed.

Brewer and Speh (2001) present several concerns when developing decarbonisation initiatives and introducing performance measurement tools and systems across green supply chains:

- *Overcoming mistrust*: Trust in data sharing, acquisition and monitoring needs to be built.
- *Lack of understanding*: Many managers are focused on internal systems, so moving to an inter-organisational scale often demands the development of a deeper understanding of what plays when cooperating with other parties in the chain.
- *Lack of control*: Managers and organisations are often focused on initiatives and measures they can fully control. Inter-organisational measures are difficult to manage and thus control.
- *Different goals and objectives*: The cooperation between organisations might lead to a confrontation between different goals and differing views on how to achieve these goals.

- *Information systems*: Information systems often need to be adapted to include non-traditional information relating to (green) supply chain performance. Also, information exchanges between companies might be complicated by a lack of standards (in terms of units to use, structure, format, etc.), and harmonised protocols and procedures.
- *Difficulty in linking decarbonisation efforts to customer value*: Not all companies see the corporate and stakeholder value of cooperating with other companies in the context of decarbonisation, or have difficulties in identifying and measuring possible value.

Trust is a particularly sensitive issue regarding digitalisation and automation initiatives, as evidenced by the research and survey conducted by VUB in the PILL[51] project. This initiative represents a collaboration among imec, the University of Antwerp, Vlerick Management School, VUB Mobilise, and VIL. A diverse array of stakeholders has articulated a clear need for reliable systems that facilitate integration, a concern that was universally shared. Additionally, stakeholders expressed apprehensions regarding financial returns, the potential for system failures, and disruptions stemming from an unpredictable future. There is also a significant emphasis on the necessity of safeguarding sensitive information while ensuring competitiveness in the market.

Companies might not start to develop practices to decarbonise their supply chains as they fear the emergence of major obstacles, such as a fear of lack of viable markets or customers; expected difficulties in establishing effective project governance; a fear of ambiguous or inequitable distribution of project costs and benefits among partners; expected challenges in securing financing; and anticipated social resistance to change. Such fears can thus result in inertia.

The relentless advancement of digitalisation and automation necessitates **a novel approach to labour** across all organisational levels, from operational to managerial. Attracting highly skilled digital natives, who are redefining the organisation of operations and processes within ports and logistics, is essential; however, it is equally critical for existing staff to engage with and adopt these technologies. Additionally, many organisations tend to address the challenges of digitalisation and automation in a reactive rather than proactively manner, and they frequently lack a coherent digital strategy at the corporate level.

[51] https://www.imec-int.com/en/pill

5.6. Summary

Figure 5.1 provides an overview of the main headwinds and barriers of decarbonisation and digitalisation as identified in the presented literature analysis. The listing does not contain any weighing of the various headwinds and barriers, as the weights might be context-dependent in terms of the specific decarbonisation or digitalisation initiative, the regional activity of the company concerned, etc. The survey-based approach developed later in this report aims to provide more insight into the relative importance of each identified potential headwind and barrier.

Figure 5.1. Summary of headwinds and barriers of decarbonisation and digitalisation

1. Technological Challenges and Choice of Technology

- State of technology and technology choice dilemma
- Lack of technology-neutral policies
- Fragmented approach to technological advancement
- Mistrust fueled by geopolitical tensions at the level of technology
- Energy-intensity of new technologies (e.g., AI)

2. Economic and financial barriers

- Often comparatively high CAPEX and OPEX of green solutions
- ROI concerns, business case approach
- Focus on cost efficiency in a highly competitive market
- Decision-makers and investors are inundated with publications on TCO, ROI, CAPEX, OPEX, and other financial metrics. However, figures often differ creating confusion and investment hesitance.

3. Regulatory and Policy Challenges

- Legal uncertainty: unclear, complex or unstable regulatory frameworks
- Overregulation and patchworks of regulation resulting in lengthy and complicated permitting processes
- Regulatory undermining of the streamlined synchronization of green investments (time gaps), and earlier commitments from customers
- Automated or autonomous solutions, and new energy sources face a lengthy and complex process of being incorporated into existing legislative and regulatory frameworks.

4. Spatial and Infrastructural Limitations

- Availability of supporting infrastructure
- Land availability concerns and competing land claims
- Spatial specialisation in ecosystem thinking
- Poor social acceptance of spatial and infrastructural developments

5. Operational and Cultural Challenges

- Mental shift needed to fight inertia in operational practices and culture
- Alignment across governments, port authorities, and private operators
- Culture of short-term cost savings over long-term environmental benefits, particularly in a highly competitive market.
- Building of trust
- Novel approach to labour needed across all organizational levels

6. Survey on Decarbonisation and Digitalisation

6.1. Survey design

The general objective of the study is to examine the viewpoints of various stakeholders involved in the Belgian port, transport and logistics industry regarding factors that may hinder the implementation of projects aimed at decarbonising and digitalising ports and supply chains, referred to as headwinds. It also identifies factors that can support these efforts, known as tailwinds. The primary focus of the study is on cargo flows and the related information flows. While industrial production processes, such as those in the chemical industry, and passenger mobility are important aspects of decarbonisation and digitalisation, they are not covered in this study.

To achieve the overall objectives of the study, a survey was designed to examine the tailwinds and headwinds in the field of decarbonising and digitalising the port, transport, and logistics industry. In the previous sections, the study analysed the main trends and concepts related to the decarbonisation and digitalisation of supply chains, as well as the key potential tailwinds and headwinds. The survey questions are based on the insights and outcomes from these sections. A few key principles were used when designing the survey:

- The survey questions must allow for maximum quantitative processing, for example, by using statements linked to Likert scales. In addition, space must be provided in which respondents can write down qualitative comments;
- Respondents should be able to fill out the survey in an acceptable timeframe (20 to 40 min);
- Answering the survey should not require the respondents to look up specific data or detailed inputs that would require in-depth data gathering;
- A maximum effort should be made to include a number of questions from the previous ING studies, in particular the 2017 study on "The Future of Port Logistics" and the 2019 study on "Green Supply Chains in Rhine-Scheldt Delta". This allows some results to be compared with the situation and expectations in 2017 and 2019.

The study's editorial board, consisting of professionals in the field (see acknowledgements for a name list), was actively involved in achieving the above goal. A first survey design followed a maximised approach in terms of the number of survey questions, i.e., 30 questions in total. After feedback from the editorial board and a test survey phase, the number of survey questions was reduced from 30 to 23. To make it easier to complete, most questions require respondents to check boxes or indicate their preferences using a Likert-type scale (for example, ranging from 'strongly disagree' to 'strongly agree'). A smaller number of questions include optional text fields where respondents could provide comments or practical examples of initiatives they are developing.

The final set of survey questions focuses on the following sub-themes:

- **Questions 1 to 7** address the current activities and decarbonisation/digitalisation status of the responding companies and organisations. We ask about the type of company or organisation (such as transporter, forwarder, terminal operator, shipper, government, port authority, etc.), as well as questions on their level of development and implementation of decarbonisation and digitalisation efforts in supply chains, and the areas where they are developing initiatives.
- **Questions 8 to 17** form the core of the survey. Here, the survey zooms in on what respondents consider the main drivers and barriers to the decarbonisation of supply chains and the digitalisation of these chains. Potential headwind and tailwind factors are grouped in four sets: (1) business operations and production; (2) external stakeholders; (3) technology; and (4) government regulation and policy. All factors for each group are evaluated by assigning a score from -5 to +5 for each factor. A score of 0 reflects a neutral factor, -5 indicates a significant barrier/headwind, and +5 a significant driver/tailwind for the decarbonisation/digitalisation of supply chains. This part of the survey also includes optional text fields allowing respondents to specify any comments or additions regarding the drivers and barriers.
- **Questions 18 and 19** help to assess how the aspects of decarbonisation/digitalisation of supply chains impact the competitive position of companies, transport mode choice, port choice, and the choice of logistic service providers.
- **Questions 20 to 23** are optional, focusing on respondents' opinions about the speed and impact of robotisation/automation in the port, transport and logistics industry, and the opportunities brought by data-based applications.

Specific survey software was used to compile and process the survey and complete the analysis.

6.2. Survey target group and respondents

The target group of the survey was composed of a wide range of companies. Representatives, mostly at C-level or senior management level, within a total of 572 companies were invited to participate in the survey. The list was compiled based on a selection of members of VIL, input obtained from the port authorities of Antwerp-Bruges and North Sea Port, and mediation of various branch organisations and the ING customer database. The target group was divided into the following sub-categories, under which the respondents could register:

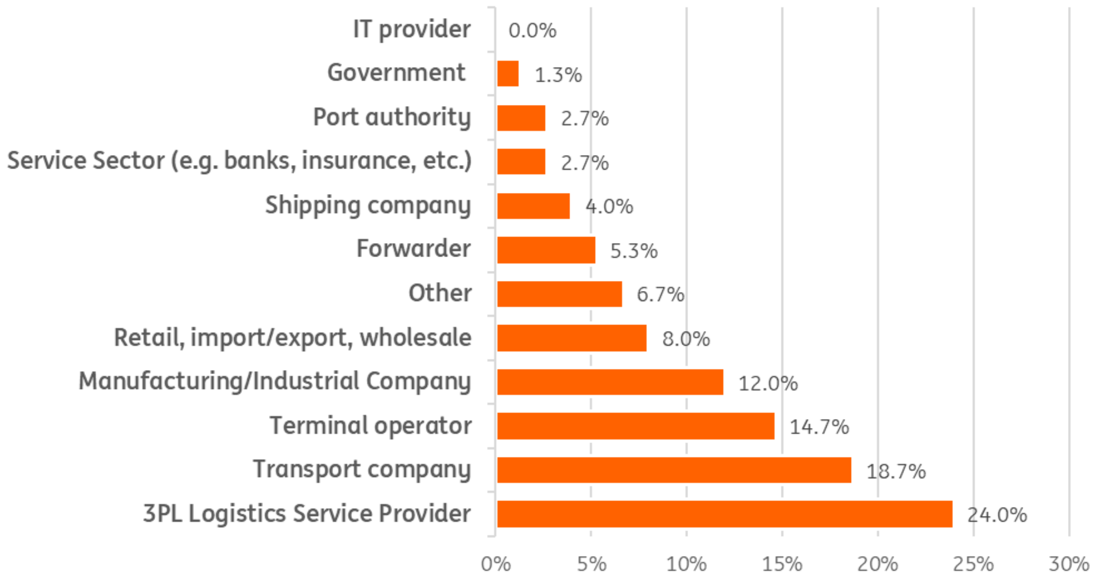
- 3PL Logistics Service Provider
- Transport company
- Terminal operator
- Manufacturing/Industrial Company
- Retail, import/export, wholesale
- Forwarder
- Shipping company
- Service Sector (e.g. banks, insurance, etc.)

- Port authority
- Government
- IT provider
- Other

The survey was made available to respondents through a web-based survey platform and supported by an invitation letter. The online survey was accessible from May 27, 2025, to July 11, 2025. The web-based survey pages received 440 unique visits. These visits resulted in 75 complete and usable survey responses. About 74% of respondents finished the survey in 10 to 30 minutes. Roughly 13% completed it more quickly, while a similar percentage took longer to fill out the survey.

Figure 6.1 illustrates that third-party logistics providers (3PLs) account for nearly one quarter of all responses in absolute terms. They are followed by transport companies, terminal operators, manufacturing/industrial firms, retailers, importers/exporters, and wholesalers - completing the top five respondent groups. However, these group shares should be interpreted with care. For instance, although port authorities constitute only 2.7% of the total completed survey forms, their response rate within the category is notably high, with major ports such as the Port of Antwerp-Bruges and North Sea Port among the respondents.

Figure 6.1. Share of sub-categories in total number of responses (n=75)



While the identities of the companies and organisations that contributed to the survey remain confidential, it is essential to note that the results reflect the perspectives of a more active segment of stakeholders engaged in decarbonisation and digitalisation efforts.

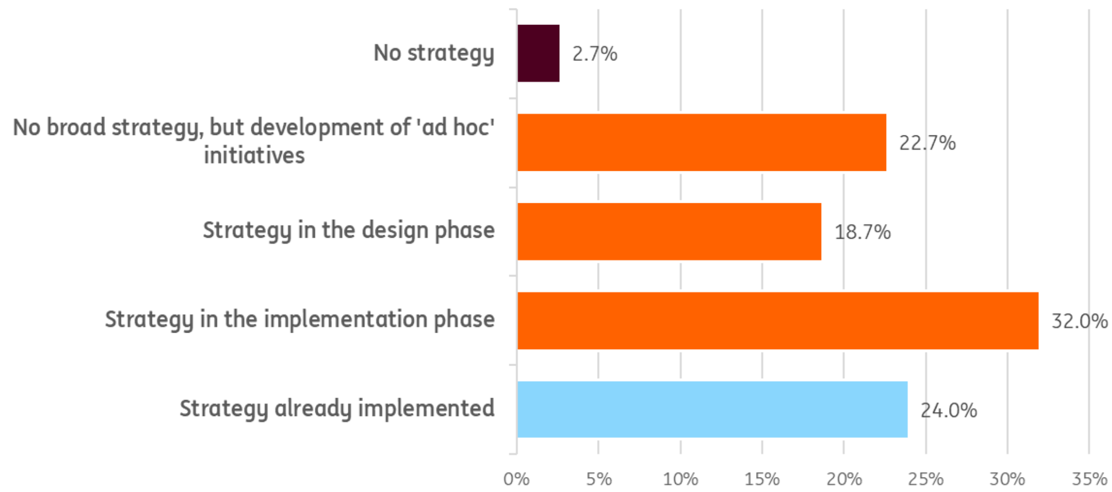
This means that the proportion of frontrunners - those leading the development and implementation of green and innovative solutions - is likely higher among survey respondents than in the broader port, transport, and logistics industry in Belgium and Flanders. Specifically, 45 out of the 75 respondents of this survey are categorised as large companies. This response bias is well-documented in survey-based research and can be attributed to two main factors. First, frontrunners, those with tangible achievements, are generally more inclined to participate in surveys than those who lag. Second, completing surveys requires time and commitment, which larger and more established organisations are typically better equipped to offer compared to small and medium-sized enterprises.

Therefore, the survey results should be interpreted with these considerations in mind.

6.3. Approach of companies/organisations to decarbonisation/digitalisation

The survey results provide insight into the role of decarbonisation/digitalisation in strategy development and implementation at the organisational level.

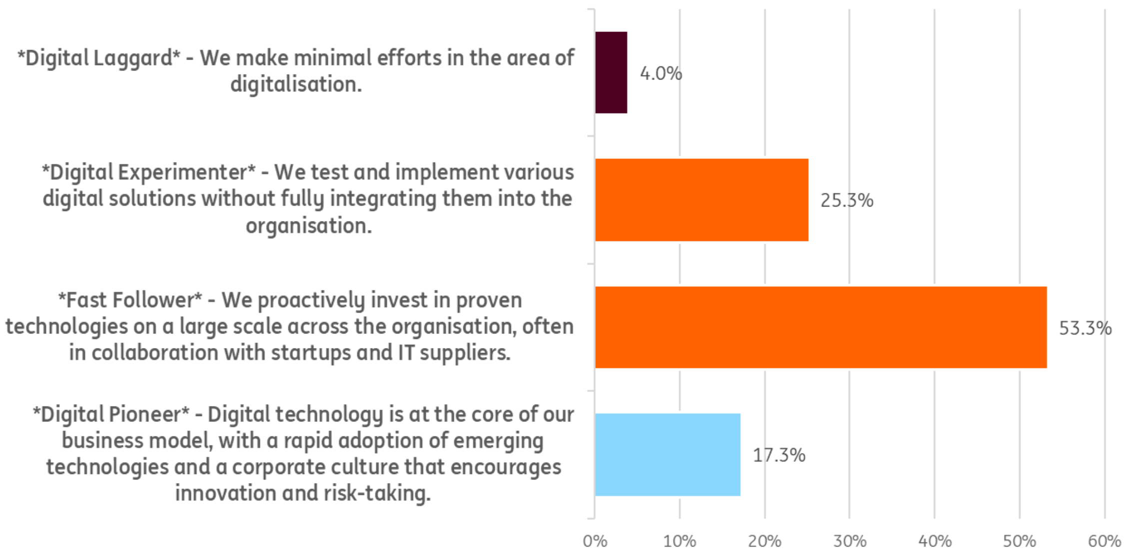
Figure 6.2. Respondents' approach to the development and implementation of a decarbonisation or greening strategy for supply chains (share of total responses)



Approximately one-quarter of respondents have already implemented a decarbonisation or greening strategy, while 32% have progressed to the implementation phase (Figure 6.2). In contrast, around 23% of companies and organisations have not developed a comprehensive greening strategy, but instead focus on ad hoc initiatives and projects aimed at reducing emissions. Fewer than 3% of respondents report having no plan in this area at all.

Figure 6.3 presents the findings related to the digitalisation of supply chains. About 17% of respondents identify as digital pioneers. For these organisations, digital technologies form the core of their business model, characterised by rapid adoption of emerging technologies and a corporate culture that promotes innovation and risk-taking. More than half of the surveyed organisations can be classified as fast followers. These actors actively invest in mature, proven technologies and scale them across their operations—often in collaboration with startups and IT service providers. Roughly a quarter of respondents are categorised as digital experimenters. These organisations explore and test various digital solutions but have yet to fully integrate them into their business processes. Only 4% of respondents can be considered digital laggards, making minimal efforts toward digital transformation. These findings reinforce earlier observations that the survey sample likely represents the more proactive segment of stakeholders, particularly in terms of engagement with digitalisation initiatives.

Figure 6.3. Respondents' approach to the digitalisation of supply chains (share of total responses)



6.4. Areas of decarbonisation/digitalisation initiatives

In which areas are organisations developing initiatives for the **decarbonisation of supply chains**? The answer to this question is captured by Figure 6.4. The implementation level of decarbonisation initiatives is particularly high in the fields of cargo handling equipment in warehouses and distribution centres, and supporting functions, i.e. 26% and 25% of total replies, respectively. The infrastructure in hubs and transport nodes such as quays, locks, warehouses or bunkering/tank infrastructure follows closely behind with 22%. Approximately 41% of respondents indicate their decarbonisation initiatives and projects in this field are in the implementation phase. When it comes to transport vehicles, this percentage amounts to 39% with another 35% of respondents stating they are preparing decarbonisation initiatives in this field. Decarbonisation clearly is a current issue for infrastructure in hubs and transport nodes and transport vehicles, as only 5% and 9% of respondents, respectively, say otherwise. For the other categories, this percentage lies between 15 and 25%.

Figure 6.4. Areas of transport and logistics in which respondents are developing initiatives for the DECARBONISATION of supply chains (share of total responses)

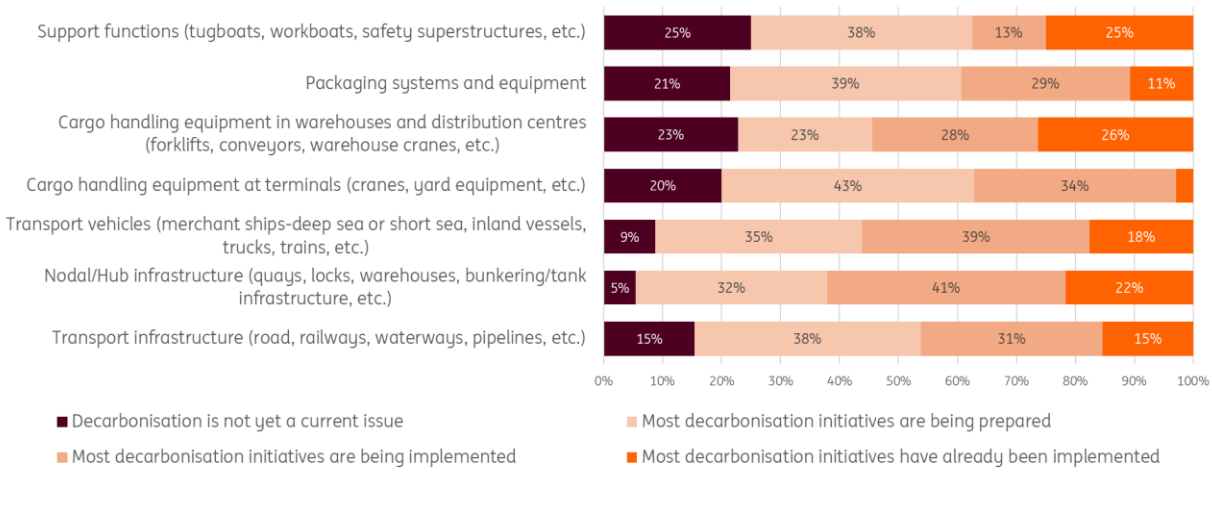


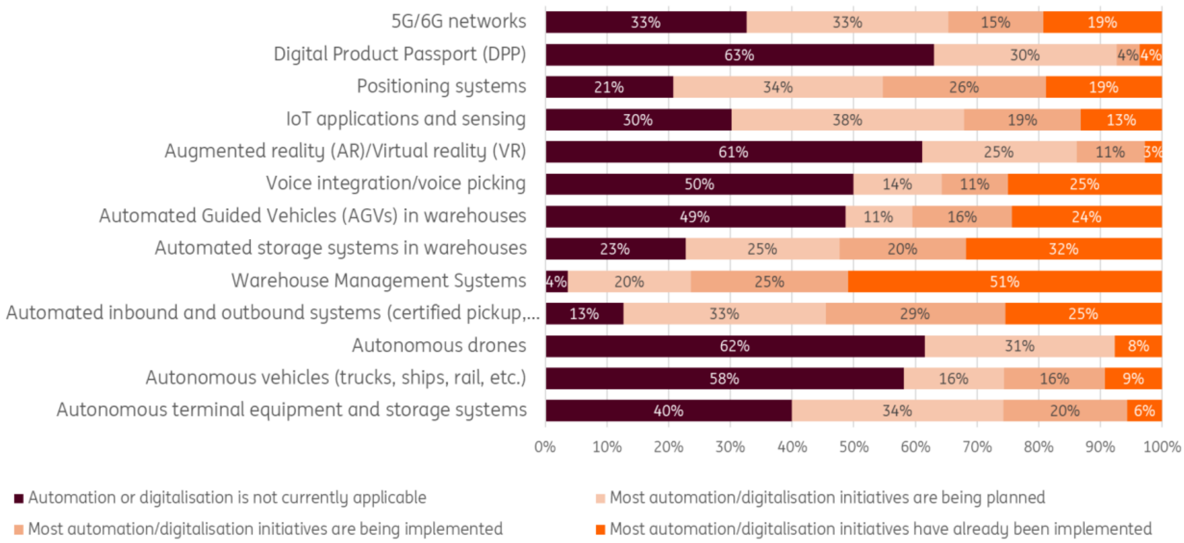
Figure 6.5 illustrates the areas within transport and logistics where respondents are developing **initiatives to digitalise supply chains**. The responses indicate that many technologies are currently considered not applicable to the specific activities of a significant portion of respondents. This is particularly evident for the Digital Product Passport (DPP), with 63% indicating it is not relevant to their operations, followed by autonomous drones (62%), augmented/virtual reality (AR/VR) (61%), and autonomous vehicles (58%).

Warehouse Management Systems (WMS) show the highest level of implementation, with 51% of respondents reporting active use. This is followed by automated storage systems in warehouses (32%), voice integration/voice picking, automated inbound/outbound systems (both at 25%), and Automated Guided Vehicles (AGVs) in warehouses (24%). These figures suggest that warehousing environments are leading in terms of actual digitalisation and automation implementation.

Conversely, technologies such as AR/VR (3%), DPP (4%), and autonomous terminal equipment and storage systems (6%) report the lowest levels of achieved implementation. However, there is momentum building: one in five respondents (20%) are currently moving toward implementing autonomous terminal equipment and storage systems, and another 34% are planning initiatives in this area.

Technologies like IoT applications and sensing, positioning systems, and 5G/6G networks present a more balanced distribution. For instance, 34% of respondents have already implemented or are in the process of implementing 5G/6G, another 33% are planning to do so, while the remaining 33% consider it not currently applicable to their activities.

Figure 6.5. Areas of transport and logistics in which respondents are developing initiatives for the DIGITALISATION of supply chains (share of total responses)



6.5. Headwinds and tailwinds for the decarbonisation/digitalisation of supply chains

As previously mentioned, the analysis of headwinds and tailwinds forms the core of the survey. In this section, we present respondents' views on the key drivers and barriers to both the decarbonisation and digitalisation of supply chains. Potential headwind and tailwind factors are categorised into four thematic groups:

- Business operations and production
- External stakeholders
- Technology
- Government regulation and policy

Respondents evaluated each factor within these groups using a scale from -5 to +5, where 0 indicates a neutral impact, -5 represents a significant barrier or headwind, and +5 signifies a strong driver or tailwind. In addition to the quantitative scores, we also analysed qualitative insights provided by respondents in the optional comment fields.

It is important to note that the assessments reflect the organisation-wide perspective, rather than views tied to specific projects or initiatives. In other words, respondents shared their general perception of what broadly enables or hinders decarbonisation and digitalisation efforts across their organisations.

The next four sections present the results for each group of factors. These are followed by a consolidated overview and ranking of the most significant drivers and barriers to both decarbonisation and digitalisation across all groups.

6.5.1. Headwinds and tailwinds in relation to business operations and production

This category encompasses company-specific headwind and tailwind factors, including elements such as corporate reputation, competitive positioning, and financial health—particularly in terms of profitability and investment capacity. It also covers investment-related considerations, such as the comparative capital and operational expenditures (CAPEX and OPEX) associated with decarbonisation and digitalisation initiatives, as well as uncertainties surrounding the financial viability of related business cases.

In addition, the category addresses social and organisational aspects, including internal company culture and its openness to change or innovation. Finally, several factors pertain to production factors, such as labour availability and required skill levels, the accessibility of supporting infrastructure (e.g., energy networks), and land availability both within and outside port areas.

Figure 6.6. Drivers and barriers for the DECARBONISATION of supply chains
Category BUSINESS OPERATIONS AND PRODUCTION

BUSINESS OPERATIONS AND PRODUCTION	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Reputation of your company (commercial)	2.51	7%	15%	78%	1%	43%
Competitive position of your company	2.27	7%	9%	84%	3%	34%
Profitability of your business operations	0.54	30%	22%	49%	7%	12%
Comparative costs (CAPEX and OPEX) associated with decarbonisation initiatives	-0.59	53%	18%	30%	12%	12%
Investment potential of your company	-0.34	47%	19%	34%	9%	7%
Uncertainty regarding financial aspects for the business case of decarbonisation initiatives	-0.64	50%	23%	27%	11%	1%
Internal company culture	0.69	26%	26%	49%	5%	9%
HR availability and skill requirements	0.82	22%	30%	49%	3%	11%
Availability of supporting infrastructure (e.g. energy networks, etc.)	-0.07	36%	27%	36%	11%	7%
Land availability within port areas	-0.51	36%	39%	24%	12%	1%
Land availability outside port areas	-0.54	27%	61%	12%	12%	1%

An overall assessment of the role of company-specific factors in the **decarbonisation of supply chains** is presented in Figure 6.6. The average scores indicate that maintaining and enhancing corporate reputation and competitive positioning are clear drivers for engaging in decarbonisation initiatives, with average scores of +2.51 and +2.27, respectively. Approximately 78% of respondents view company reputation as a tailwind (i.e. a score above 0), and 43% rate it as a strong tailwind (score of +4 or +5). Similarly, 84% consider competitive position a tailwind, with 34% viewing it as a strong driver. While many companies face the challenge of reducing emissions without compromising competitiveness, the findings suggest that competitive positioning itself is increasingly seen as a motivating factor for decarbonisation. Put differently, failing to invest in decarbonisation may significantly undermine a company's competitive standing in the medium to long term.

Profitability, internal company culture and HR availability and skill requirements are viewed as modest drivers, with only 9 to 12% of respondents identifying them as strong tailwinds.

The remaining factors in this category are generally perceived as weak headwinds. Although their average scores are slightly negative, the responses reflect diverse opinions on their overall impact. For instance, while 53% see the comparative CAPEX and OPEX of decarbonisation initiatives as a headwind, 30% consider it a tailwind, and only 12% rate it as a strong headwind. This seems to suggest that the comparative costs of decarbonisation initiatives vary greatly depending on the market segment and project characteristics. As discussed earlier in this report, there are, for example, many areas where green non-fossil-based investments remain extremely challenging due to the cost differential with fossil-based solutions and the resulting lack of demand. In other cases and application fields, a green investment may present a clear and positive business case.

Regarding land availability outside port areas, 61% take a neutral stance, while 27% identify it as a headwind. Opinions are also divided on the availability of supporting infrastructure: 36% consider insufficient infrastructure a headwind (with 12% rating it as a strong headwind), yet an equal proportion report that available infrastructure is facilitating their decarbonisation efforts.

Figure 6.7. Drivers and barriers for the DIGITALISATION of supply chains

Category BUSINESS OPERATIONS AND PRODUCTION

BUSINESS OPERATIONS AND PRODUCTION	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Reputation of your company (commercial)	2.66	0%	10%	90%	0%	35%
Competitive position of your company	3.21	1%	6%	93%	0%	52%
Profitability of your business operations	2.89	6%	7%	87%	0%	45%
Comparative costs (CAPEX and OPEX) associated with digitalisation initiatives	0.94	24%	20%	56%	1%	14%
Investment potential of your company	1.03	21%	21%	58%	0%	14%
Uncertainty regarding financial aspects for business cases of automation/digitalisation initiatives	0.10	32%	28%	39%	4%	4%
Internal company culture	1.27	15%	20%	65%	1%	15%
HR needs (availability, skills, etc.)	0.75	25%	21%	54%	4%	13%
Availability of digital infrastructure (5G/6G, IoT, sensors, etc.)	0.90	24%	24%	52%	1%	14%

The results for factors related to business operations and production differ significantly when it comes to **digitalisation initiatives** (Figure 6.7). All factors in this category received positive average scores, although there is notable variation in the extent to which each factor is perceived as a driver. As in the case of decarbonisation, corporate reputation and competitive position remain strong tailwinds, with average scores of +2.66 and +3.21, respectively. Approximately 93% of respondents view competitive position as a tailwind, and 52% rate it as a strong tailwind (score of +4 or +5).

In contrast to the decarbonisation results, profitability emerges as a significant driver for digitalisation, with an average score of +2.89, instead of a weak driver. Nearly 45% of respondents consider it a strong tailwind. This suggests that the majority of surveyed organisations see a clear positive impact of digitalisation initiatives on their profitability, a link that appears much weaker in the context of decarbonisation. The comparative capital and operational expenditures (CAPEX and OPEX) associated with digitalisation initiatives are viewed as a (weak) tailwind, in contrast to their role as a weak headwind in decarbonisation. A comparable shift is observed regarding perceptions of a company's investment potential, which is also seen more positively in the context of digitalisation. In summary, digitalisation initiatives are widely perceived as financially beneficial, with stronger positive associations in terms of profitability, investment potential, and cost-efficiency. By contrast, decarbonisation initiatives tend to carry more financial uncertainty and are perceived less favourably in the investment sphere.

6.5.2. Headwinds and tailwinds in relation to external stakeholders

The second group of factors concerns the position, expectations, and actions of stakeholders with whom respondents interact either directly or indirectly. Upstream and downstream supply chain partners may integrate environmental or digitalisation requirements into their contract allocation criteria, influencing companies' strategic decisions. These partners, as well as regulators, can also impose demands related to emission visibility and data transparency, for example, through ESG ratings and sustainability reporting obligations.

Broader societal expectations also play a role. The community at large can shape the social license to operate, influencing the acceptance of decarbonisation or digitalisation investments. Geopolitical tensions further contribute to uncertainty, potentially accelerating or obstructing initiatives depending on their nature and context.

In addition, a company's stance on decarbonisation and digitalisation may impact its ability to attract and retain young talent, who increasingly value environmental and technological engagement in the workplace.

The level of cooperation, alignment, and trust among stakeholders is another factor. Effective action often depends on a well-structured and transparent governance model that facilitates coordination among stakeholders. Finally, access to and use of sustainable finance solutions, such as green loans or sustainability-linked financing offered by financial institutions, can serve as a driver of a company's greening agenda.

An overall assessment of the role of stakeholder-specific factors in the **decarbonisation of supply chains** is presented in Figure 6.8. All factors obtain a positive average score. Geopolitical tensions are the only exception with a mildly negative score, but in this case the views are very mixed: 36% consider it a headwind (with 11% rating it as a strong headwind), yet a fairly equal proportion report that geopolitical tensions are facilitating their decarbonisation efforts. Despite scoring mildly above zero, the two factors related to the need for synchronisation and trust between different stakeholders also show a mixed picture in terms of respondents' answers.

Figure 6.8. Drivers and barriers for the DECARBONISATION of supply chains

Category EXTERNAL STAKEHOLDERS

EXTERNAL STAKEHOLDERS	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Role of greening desires/requirements in contract allocation decisions	2.06	3%	19%	78%	1%	24%
Social/societal influence and expectations	2.32	3%	15%	82%	1%	25%
Social acceptance of investments in decarbonisation projects	1.69	6%	17%	78%	1%	11%
Geopolitical tensions	-0.32	36%	29%	35%	11%	3%
Ability to attract young people/employees based on green image	1.25	10%	31%	60%	1%	14%
New forms of cooperation and governance between actors/stakeholders	1.40	8%	24%	68%	1%	8%
Need for synchronisation between the efforts of different stakeholders	0.38	25%	31%	44%	4%	10%
Need for trust between involved partners	0.21	31%	26%	43%	4%	8%
Need for visibility and transparency of CO2 emissions	1.13	18%	25%	57%	1%	17%
ESG ratings and sustainability-related reporting requirements	1.99	8%	21%	71%	1%	29%
Access to and use of sustainable finance solutions	1.18	13%	22%	65%	3%	11%

The average scores indicate that broader societal expectations and project acceptance, the (contractual) requirements imposed by supply chain partners, and ESG ratings and sustainability-related reporting requirements are the strongest drivers of decarbonisation efforts in this category. For these four factors, the share of respondents giving a score below zero is very small (3 to 8%).

The ability to attract young people/employees based on green image, new forms of cooperation and governance between actors/stakeholders, need for visibility and transparency of CO_2 emissions, and access to and use of sustainable finance solutions obtained average scores between 1.1 and 1.4, pointing to fairly strong headwinds.

The results for **digitalisation initiatives** within the stakeholder-related category (Figure 6.9) show some notable differences compared to those for decarbonisation. All factors in this category received positive average scores, though the strength of each perceived driver varies.

Broader societal expectations and project acceptance, along with (contractual) requirements imposed by supply chain partners, remain relatively strong drivers of digitalisation. However, their average scores are slightly lower than those reported for decarbonisation, suggesting that these factors are seen as somewhat less influential in the context of digital transformation.

Figure 6.9. Drivers and barriers for the DIGITALISATION of supply chains

Category EXTERNAL STAKEHOLDERS

EXTERNAL STAKEHOLDERS	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Role of automation/digtalisation initiatives in decisions on contract awards	1.54	7%	26%	67%	0%	13%
Social/societal influence and expectations	1.34	4%	36%	60%	0%	11%
Social acceptance of investments in automation/digitalisation projects	1.36	1%	34%	64%	1%	7%
Geopolitical tensions (cybersecurity)	0.61	24%	27%	49%	3%	14%
Ability to attract young people/employees based on digital innovator image	1.76	4%	21%	74%	1%	17%
New forms of cooperation and governance between actors/stakeholders	1.30	13%	29%	59%	0%	11%
Need for synchronisation between the efforts of different stakeholders	0.86	23%	24%	53%	3%	11%
Need for trust between involved partners	0.16	37%	30%	33%	4%	11%

In contrast, the ability to attract young employees scores higher in the context of digitalisation, with an average score of +1.76, compared to +1.25 for decarbonisation initiatives. This suggests that companies see digital advancements as a slightly more effective tool for attracting talent than environmental initiatives alone.

As with decarbonisation, the need for trust and collaboration among stakeholders receives a largely neutral overall score, indicating a limited perceived impact in either direction.

Interestingly, while geopolitical tensions generated mixed views and a mildly negative score in the context of decarbonisation, they are seen more positively in relation to digitalisation. This implies that companies perceive geopolitical uncertainty as a driver or catalyst for digital investment, particularly in areas such as cybersecurity, data resilience, and technological sovereignty, rather than as a barrier.

6.5.3. Headwinds and tailwinds in relation to technology

Technology plays a critical role in enabling both decarbonisation and digitalisation initiatives. The third group of factors in the analysis focuses specifically on technology-related aspects. These include the pace and maturity of technological development, the emergence of energy-intensive technologies, and the availability of data and new opportunities for data sharing across the supply chain.

In addition to these functional aspects, the analysis also considers factors related to the governance of technological progress, such as the need to avoid a fragmented approach and the importance of clear, consistent, and accessible metrics and publications on technological innovations.

Finally, labour-related issues are included in this group as well, recognising that the integration of new technologies may be influenced by the availability of skilled personnel and the broader implications for workforce management.

Figure 6.10 confirms that technology is a positive driver of **decarbonisation** within the port, transport, and logistics industry. Technological advancements in alternative fuels and green energy are viewed as a fairly strong tailwind in the pathway towards decarbonisation, with an average score of +1.73 and 25% of respondents assigning a score of +4 or +5. Data availability and new opportunities for data sharing also contribute meaningfully to decarbonisation efforts. Approximately two-thirds of respondents identified this factor as a driver, highlighting the growing importance of data-driven solutions in supporting emission reduction strategies.

Figure 6.10. Drivers and barriers for the DECARBONISATION of supply chains

Category TECHNOLOGY

TECHNOLOGY	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Technological progress in the field of alternative fuels and green energy	1.73	21%	4%	75%	7%	25%
Rise of energy-intensive technologies	0.95	13%	27%	60%	4%	5%
Data availability and new possibilities for data sharing	1.11	19%	15%	67%	4%	15%

Figure 6.11. Drivers and barriers for the DIGITALISATION of supply chains

Category TECHNOLOGY

TECHNOLOGY	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Energy-intensity of new technologies (e.g. AI, Blockchain, etc.)	0.11	29%	37%	33%	3%	5%
Data availability and new opportunities for data sharing	1.33	13%	25%	61%	0%	12%
Speed of technological development	1.39	15%	23%	63%	1%	12%
Fragmented approach to technological developments	0.32	28%	33%	39%	3%	8%
Abundance of publications on TCO, ROI, CAPEX, OPEX, and other metrics on technological innovations (deviant)	0.17	27%	41%	32%	0%	1%
Automation/digitalisation as a solution for labor shortages	1.76	5%	27%	68%	0%	20%
Entirely different approach to labor due to automation/digitalisation	1.23	7%	36%	57%	0%	8%

As shown in Figure 6.11, all technology-related factors received positive average scores in the context of **digitalisation**, although the perceived strength of each driver varies. Several factors stand out as particularly influential. Notably, data availability and new opportunities for data sharing, along with the pace of technological development, are regarded as fairly strong tailwinds supporting digitalisation efforts across the port, transport, and logistics industry.

The labour dimension—specifically the role of automation and digitalisation in addressing labour shortages—emerged as the most significant driver in this group, with an average score of +1.76. More than two-thirds of respondents rated this factor positively, and one in five assigned it a strong tailwind score of +4 or +5.

However, there is no clear consensus regarding the impact of certain governance-related factors. For example, issues such as a fragmented approach to technological development and the proliferation of publications on innovation metrics receive mixed evaluations. In both cases, around 28–29% of respondents perceive these as headwinds, while over 30% consider them to be facilitating digitalisation efforts.

6.5.4. Headwinds and tailwinds in relation to government regulation and policy

The final group of potential drivers and barriers relates to the role of government regulation and policy in supporting or hindering decarbonisation and digitalisation initiatives. Rather than focusing on specific laws, policies, or levels of government (regional, national, or supranational), the survey explores how companies and organisations in the port, transport, and logistics industry perceive the overall influence of policy and regulatory frameworks on their ambitions to decarbonise and digitalise supply chains.

As anticipated, climate targets set by supranational and national/regional governments are generally viewed as drivers of decarbonisation (Figure 6.12). However, their perceived strength is moderate at best. Only 20% of respondents view supranational targets as a strong tailwind, while 16% say the same for national or regional targets. This suggests that, while government targets are taken into consideration, companies usually do not allow these targets to fully dictate their decarbonisation strategies.

Figure 6.12. Drivers and barriers for the DECARBONISATION of supply chains

Category GOVERNMENT REGULATION AND POLICY

GOVERNMENT REGULATION AND POLICY	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Climate targets of supranational governments	1.15	24%	7%	69%	8%	20%
Climate targets of national/regional governments	1.04	27%	8%	65%	7%	16%
Licensing/permit policy of governments	-0.27	45%	12%	43%	25%	17%
Subsidy policy of governments	-0.15	40%	19%	41%	13%	8%
Level of continuity in government policy regarding incentives	-0.77	44%	21%	35%	23%	7%
Fiscal policy/taxation authorities	-0.45	44%	23%	33%	15%	7%
Technology policy and level of technological neutrality of authorities	-0.12	32%	28%	40%	11%	4%

All other policy-related factors in this group receive mildly negative average scores, classifying them as weak headwinds. Importantly, the responses reveal no clear consensus on the role of these factors. For example, the continuity of government incentive policies scores an average of -0.77. While 44% of respondents assign it a negative score - and 23% consider it a strong headwind (score of -4 or -5) - over one-third actually regard it as a (weak) driver of decarbonisation. This pattern of mixed views is also evident in respondents' assessments of licensing and permitting policies, subsidy schemes, fiscal and tax policies, and technology policies, including concerns about the technological neutrality of government frameworks.

As with decarbonisation, most policy- and regulation-related factors in the context of digitalisation received mildly negative average scores (Figure 6.13). The continuity of government policy once again registered the lowest score, followed closely by licensing and permitting policies. The only factor to score marginally above zero was technology policy.

Figure 6.13. Drivers and barriers for the DIGITALISATION of supply chains
Category GOVERNMENT REGULATION AND POLICY

GOVERNMENT REGULATION AND POLICY	Average (Range: -5 to +5)	% Headwind Score < 0	% Neutral Score 0	% Tailwind Score > 0	% Strong Headwind Score -5 or -4	% Strong Tailwind Score 5 or 4
Licensing/permit policies of governments	-0.43	39%	36%	25%	8%	4%
Subsidy policies of governments	-0.12	33%	35%	32%	5%	3%
Degree of continuity in policy concerning government incentives	-0.52	40%	31%	29%	11%	4%
Technology policy and the degree of technology neutrality of governments	0.11	27%	40%	33%	4%	5%
Alignment between governments, ports, and private players regarding automation/digitalisation initiatives	-0.25	36%	31%	33%	12%	7%

However, respondents are divided in their assessments. The distribution of scores across the headwind, neutral, and tailwind categories reflects a lack of consensus. Notably, even when comparing strong headwind versus strong tailwind responses, the difference is only slightly tilted toward the former, indicating no overwhelming agreement in either direction.

In summary, the policy and regulation category received the lowest overall average score across all four factor groups, by a significant margin. Yet, the proximity of most scores to zero conceals a deeper issue: there is no clear agreement among respondents on whether current government policies are facilitating or obstructing digitalisation and decarbonisation efforts. This diversity of opinion highlights the uncertain and contested nature of regulatory influence in the transition to greener and smarter supply chains.

6.5.5. Summary of headwinds and tailwinds of decarbonisation initiatives

The previous paragraphs reviewed at great length the headwinds and tailwinds concerning the four thematic groups. Figure 6.14 summarises those that most respondents subscribed to. The parameters in bold are those that are supported most strongly.

Several respondents expressed concern about the unstable and uncertain international context surrounding decarbonisation requirements and initiatives. Climate change resilience is a topic that should be approached from a global angle. Additionally, regional and national authorities should align clearly with European ambitions to move towards a level playing field across Europe. Such alignment could also help in developing a focus on the right projects and improve and accelerate focused and networked decarbonisation initiatives.

Figure 6.14. Summary of headwinds and tailwinds of DECARBONISATION

AFFECTING	HEADWINDS FOR DECARBONISATION	TAILWINDS FOR DECARBONISATION
BUSINESS OPERATIONS & PRODUCTION	1. Space availability in and outside the port 2. Uncertainty regarding the financials of the business case 3. Comparative costs (CAPEX & OPEX) associated with initiatives	**1. Commercial reputation** **2. Competitive position** 3. Profitability of business operations
EXTERNAL STAKEHOLDERS	1. Geopolitical tensions 2. Need for trust between partners * 3. Need for synchronisation between the efforts of different stakeholders*	**1. Social influence and expectations** **2. ESG ratings and reporting requirements** **3. Role of greening requirements in contract allocation decisions**
TECHNOLOGY		**1. Technological progress of technology of alternative fuels and green energy** 2. Data availability & new possibilities for data sharing 3. Rise of energy-intensive technologies**
GOVERNMENT REGULATION AND POLICY	1. Permits and licences policy 2. Level of continuity in policy regarding incentives 2. Fiscal policy/taxation by authorities	**1. Climate targets of governments** 2. Permits and licences policy 3. Subsidy policies

* Indicates that the majority of respondents still viewed it as a driver for taking decarbonisation initiatives.

** Indicates that, regardless of energy requirements, AI is viewed as a driver that supports decarbonisation initiatives.

6.5.6. Summary of headwinds and tailwinds of digitalisation initiatives

Figure 6.15 summarises those headwinds and tailwinds that most respondents subscribed to. The parameters in bold are those that are supported most strongly by the group of respondents.

It should be noted that, preponderantly, the group identified most of the headwinds or tailwinds as potential tailwinds to some degree.

Some participants emphasise the importance of ongoing collaboration with customs regarding the digitalisation of the Belgian ports, transport, and logistics sector.

Figure 6.15. Summary of headwinds and tailwinds of DIGITALISATION

AFFECTING	HEADWINDS FOR DIGITALISATION	TAILWINDS FOR DIGITALISATION
BUSINESS OPERATIONS & PRODUCTION	1. Uncertainty regarding the financials of the business case (=)	**1. Competitive position** **2. Profitability of business operations** **3. Commercial reputation**
EXTERNAL STAKEHOLDERS	1. Geopolitical tensions 2. Need for trust between partners * 3. Need for synchronisation between the efforts of different stakeholders *	**1. Ability to attract young people as digital innovator** **2. Role of greening requirements in contract allocation decisions** **3. Social acceptance of investment in decarbonisation projects**
TECHNOLOGY	1. Rise of energy-intensive technologies * 2. Abundance of (deviating) publications on TCO, ROI, CAPEX, OPEX & other metrics * 3. Fragmented approach to technological developments *	**1. Automation/digitalisation as a solution for labour shortages** **2. Speed of technological development** **2. Data availability & new possibilities for data sharing**
GOVERNMENT REGULATION AND POLICY	**1. Level of continuity in policy regarding incentives** 2. Permits and license policy 3. Alignment between governments, ports and private palyers	1. Technology policy and degree of technology neutrality of governments 1. Subsidy policy of governments (=) 1. Alignment between governments, ports and private players

* Indicates that most respondents still viewed it as a driver for taking digitalisation initiatives.

6.6. Impact of decarbonisation/digitalisation on competition and logistics choices

This section addresses a set of survey questions that help to assess how the aspects of decarbonisation/digitalisation of supply chains impact the competitive position of companies, transport mode choice, port choice, and the choice of logistics service providers.

Figure 6.16 presents the results for the **decarbonisation** case, with the following key conclusions:

- 64% of respondents agree or strongly agree that decarbonisation positively contributes to their company's competitive position, while only 12% express some level of disagreement. This complements the earlier findings in Section 6.5.1, confirming that maintaining and enhancing competitiveness is a clear driver of decarbonisation initiatives.
- Only 14% agree with the statement that decarbonisation influences port choice, while 28% disagree, and a significant 57% remain neutral or express no opinion. These results indicate that port choice is largely unaffected by decarbonisation efforts.
- 53% of respondents state that decarbonisation impacts their modal choice decisions, compared to 14% who disagree, with the remainder (less than one-third) remaining neutral.
- Regarding the influence of decarbonisation on the choice of (port) logistics service providers, 36% agree (including only 3% who strongly agree), 16% disagree, and nearly half of the respondents remain neutral or undecided.
- Finally, 52% agree that decarbonisation is not a competitive domain but rather an opportunity for greater collaboration, although 12% of respondents disagree with this view.

The survey included a question identical to one from the 2019 ING port study on "Green supply chains: implications and challenges for Rhine-Scheldt Delta seaports" (Notteboom et al., 2019), allowing for direct comparison between Figure 6.17 (situation in 2019) and Figure 6.16 (situation in 2025):

- In 2019, 66% of respondents indicated that decarbonisation positively affected competitiveness, very close to the 64% reported in 2025. However, the share of respondents stating that decarbonisation influences modal choice has declined from 60% in 2019 to 53% in 2025.
- Regarding port choice, the 2019 study found that 33% believed decarbonisation did not influence this decision, while 45% had no clear opinion. In 2025, 28% disagree with the influence of decarbonisation on port choice, and a higher 57% remain neutral or undecided. This confirms a consistent finding: decarbonisation is not seen as a major factor in port selection.
- For the statement "decarbonisation impacts the choice of (port) logistics service providers", the level of agreement is fairly consistent, with 33% agreeing in 2019 versus 36% in 2025.

- The perception of decarbonisation as an opportunity for collaboration rather than competition has also remained steady: 53% of respondents in 2019 shared this view, compared to 52% in 2025.

Figure 6.16. Impact of DECARBONISATION on competition between companies and ports
Results from this study (n=75, share of total responses)

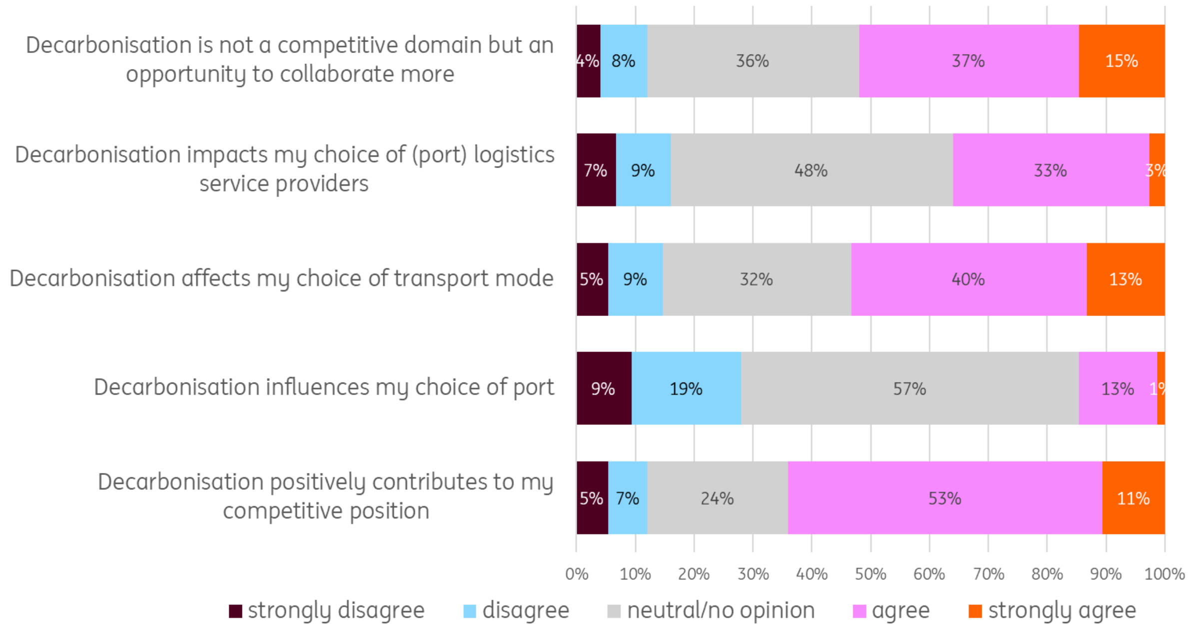
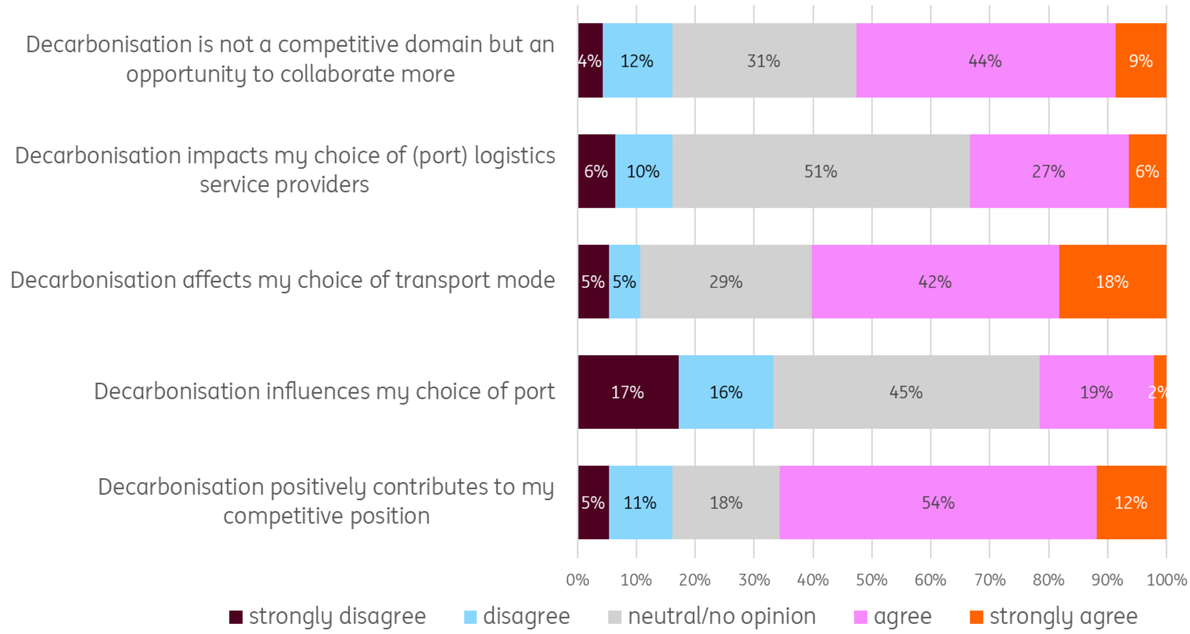


Figure 6.17. Impact of DECARBONISATION on competition between companies and ports
Results from the ING port study of 2019 (n=93, share of total responses)



Note: The survey of the ING port study of 2019 also included a set of answers from the Rotterdam port, transport and logistics community, next to the answers of Belgian companies and organisations.

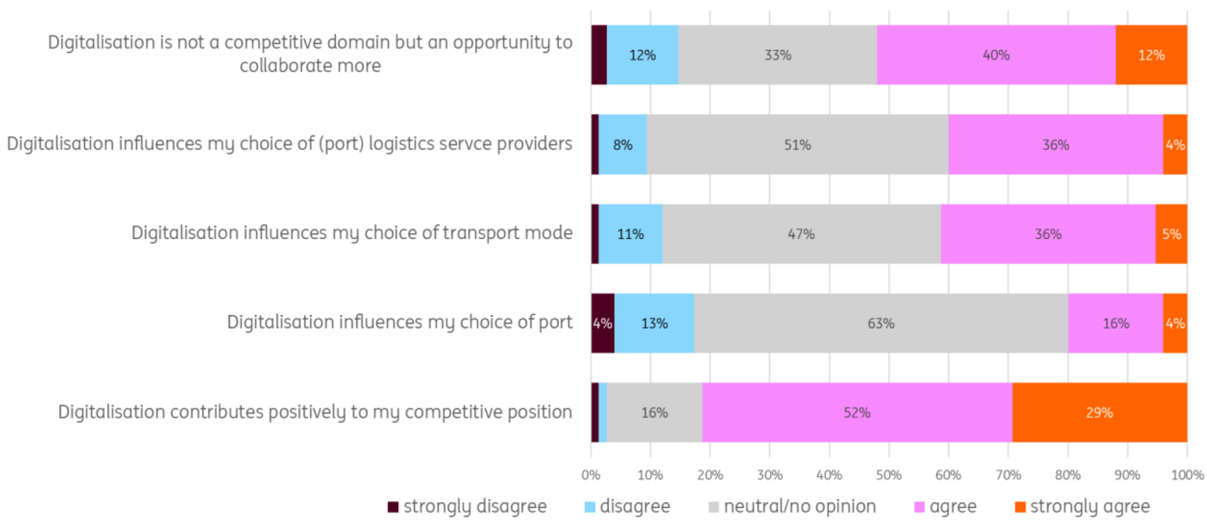
Source: adapted from Notteboom et al. (2019)

Similar statements were presented to the respondents on the impact of **digitalisation** (Figure 6.18), leading to the following conclusions:

- An impressive 81% of respondents agree or strongly agree that digitalisation positively contributes to their company's competitive position, while only 2% express some level of disagreement. This clear result supports the earlier findings in Section 6.5.1, where 93% of respondents view competitive position as a tailwind for digitalisation, and 52% rate it as a strong tailwind (score of +4 or +5).
- Only one in five agrees with the statement that digitalisation influences port choice, while 17% disagree. A significant 63% remain neutral or express no opinion. These results indicate that, similar to the decarbonisation aspect, port choice seems to be largely unaffected by digitalisation efforts. This result can also be attributed to the fact that virtually all competing ports are actively engaging in digitalisation efforts.
- 41% of respondents state that digitalisation impacts their modal choice decisions, compared to 12% who disagree, with the remainder (47%) remaining neutral.
- Regarding the influence of digitalisation on the choice of (port) logistics service providers, 40% agree (including only 4% who strongly agree), 9% disagree, and more than half of the respondents remain neutral or undecided.
- Finally, 52% agree that digitalisation is not a competitive domain but rather an opportunity for greater collaboration, although 14% of respondents disagree with this view. These figures are comparable to the decarbonisation case presented in Figure 6.14.

Figure 6.18. Impact of DIGITALISATION on competition between companies and ports

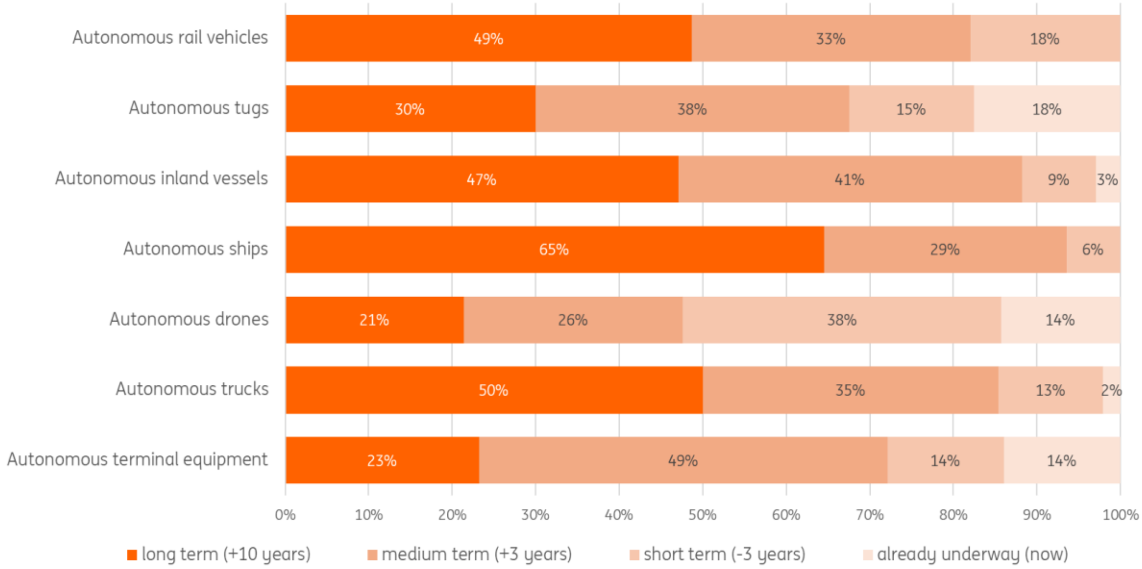
(share of total responses)



6.7. Impact of data-based applications, robotisation and automation

The final four questions of the survey were optional and explored respondents' views on the speed and impact of robotisation and automation in the port, transport, and logistics industry, as well as the opportunities offered by data-driven applications.

Figure 6.19. Speed of implementation of robotisation/automation in relation to business activities
(share of total responses)



One area of focus was the expected pace of implementation of autonomous technologies and the perceived need for a supporting regulatory framework. As illustrated in Figure 6.19, opinions are divided regarding when these technologies will be widely adopted in the sector:

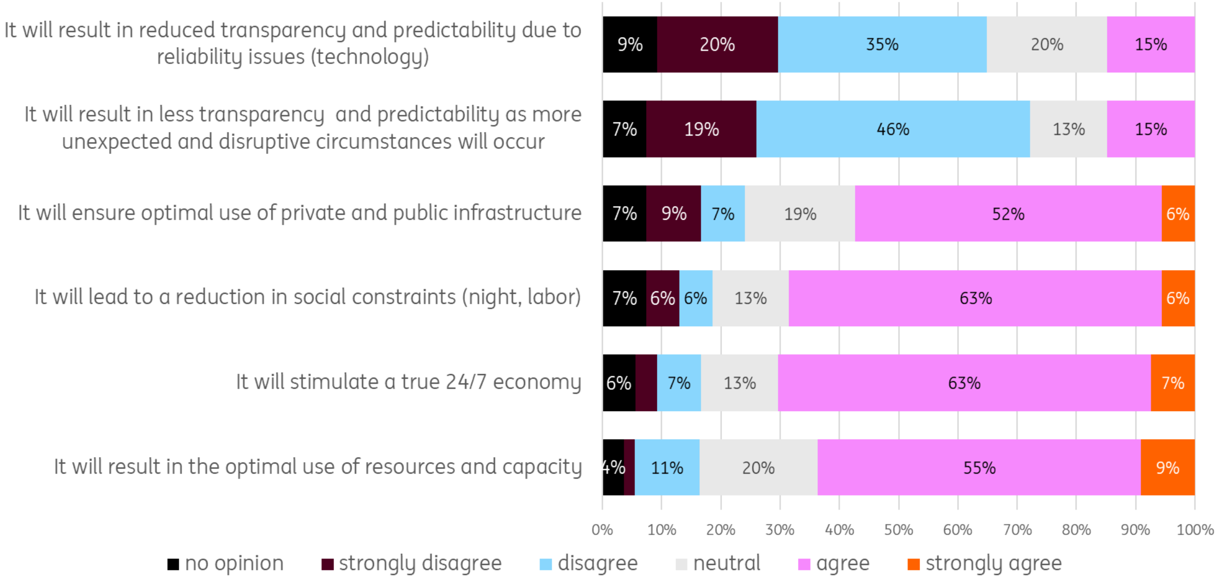
- Among the technologies considered, **autonomous drones** emerged as the most ready for deployment. Currently, 14% of companies see active use of drones, while another 38% expect implementation within the next three years, indicating strong short-term potential.
- **Autonomous tugs** and **autonomous terminal equipment** also rank high in terms of readiness, with 33% and 28% of respondents, respectively, indicating either current use or planned implementation within a three-year timeframe.
- In contrast, expectations surrounding **autonomous trucks** are more fragmented. Half of the respondents (50%) view widespread use as a long-term development (beyond 10 years), while 35% anticipate implementation in the medium term (3–10 years), and 15% believe it could be realised in the short term (within 3 years). As expanded upon in the study, this strongly correlates with the effective use cases and the technology's domain of implementation.
- A similarly diverse outlook applies to **autonomous inland vessels**. Although pilot projects are already in place, most respondents expect broader application in the long term (47%) or medium term (41%).

- When it comes to **autonomous deep-sea vessels**, optimism is more limited. Nearly two-thirds of respondents believe these will not see widespread use within the next decade, while 29% expect progress over the medium term.

The robotisation/automatisation of ships, inland vessels, road transport and terminal operations will potentially bring disruptive change in port, transport and logistics operations. Figure 6.20 captures the expectations of companies and organisations active in the Belgian port, transport and logistics industry on this matter.

Figure 6.20. Expected impact of the robotisation/autonomous of ships, inland vessels, road transport and terminal operations on port, transport and logistics operations

(share of total responses)

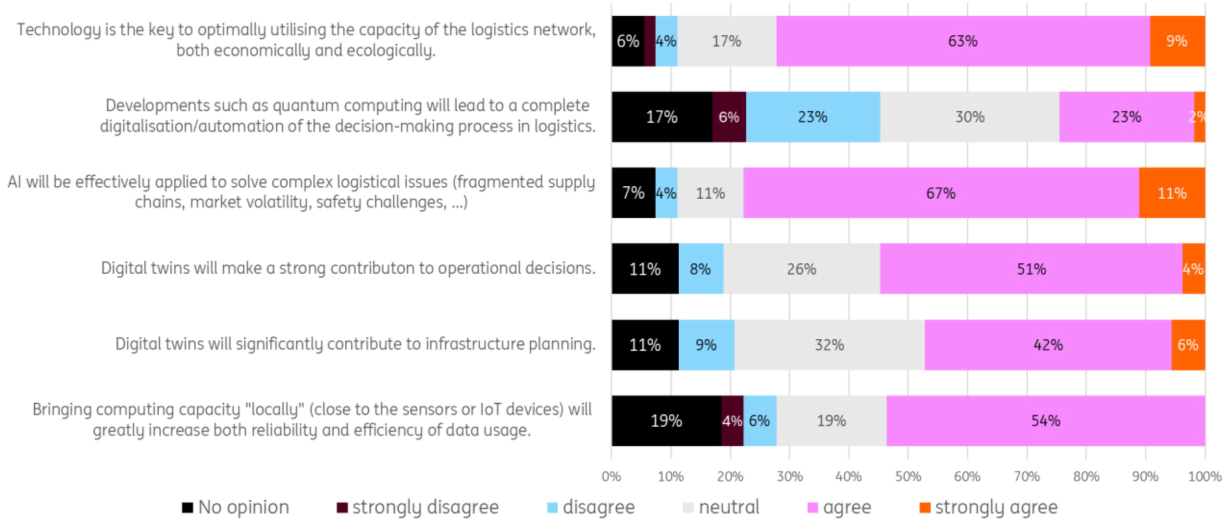


Quite clearly, survey participants have expectations concerning the impact of robotisation of ships, inland vessels, road transport and operations and the disruptive change it will entail. It will stimulate an actual 24/7 economy (70% of respondents agree or strongly agree), while also leading to a reduction in social constraints on night work and port labour (69%), with an optimal use of resources and capacity (64%). This, in turn, is expected to lead to an optimal use of private and public infrastructure (58%).

Most respondents do not expect unexpected and disruptive circumstances to hurt transparency and predictability (65% disagree or strongly disagree). The impact of potential reliability issues (technology) is also less evident to the participants, with 55% of survey actors disagreeing or strongly disagreeing with the statement that robotisation/automation will result in reduced transparency and predictability due to technological reliability issues.

The increasingly precise and up-to-date data, along with growing expertise in collecting, distributing, and managing it reliably, has the potential to result in a virtually limitless number of application possibilities, including the use of digital twins or AI applications. Figure 6.21 reveals how companies and organisations in the port, transport and logistics industry assess the possibilities based on their experience.

Figure 6.21. Possibilities offered by technologies supporting data collection, distribution, and management (share of total responses)



A significant majority of respondents (78%) believe that Artificial Intelligence (AI) holds strong potential for practical application in addressing complex logistical challenges such as fragmented supply chains, market volatility, and safety risks. In parallel, 72% of respondents agree or strongly agree that technology is a key enabler in optimising the economic and ecological capacity of logistics networks.

More than half of the respondents expect that the increased use of sensors and Internet of Things (IoT) devices will lead to greater reliability and efficiency in data utilisation, although 10% disagree with this view.

There is considerable interest in the potential of digital twin applications. While 48% of respondents see opportunities for infrastructure planning and 55% for operational decision-making, nearly one-third remain neutral or express no opinion. This indicates that the full potential and value of digital twins are not yet widely understood across the industry.

Opinions diverge sharply on the future impact of quantum computing on decision-making in logistics. 25% of respondents believe it will eventually enable full automation and digitalisation of the decision-making process, while 29% disagree. The rest are either neutral or undecided, underscoring the uncertainty and limited awareness surrounding this emerging technology.

7. Conclusions and Recommendations

7.1. General findings

The Belgian port, transport, and logistics industry stands at a pivotal moment. This report underscores the urgency and complexity of the twin transitions toward decarbonisation and digitalisation. The sector, which is foundational to Belgium's open economy and vital to its role as a European logistics hub, faces mounting pressures from regulatory, environmental, technological, and market factors. Market expectations and regulatory frameworks are rapidly evolving. Shippers and end customers increasingly demand green logistics solutions, not only for regulatory compliance but also for reputational reasons. This shift in market behaviour is reshaping procurement and service design throughout the logistics ecosystem. Forward-thinking companies are capitalising on this momentum to differentiate themselves and gain a competitive edge. Yet, these pressures are also catalysts for innovation and transformation.

A central finding is that the sector has entered a **phase of active transformation**, with many companies no longer treating sustainability and digital innovation as abstract goals but as operational imperatives. Technologies such as AI, IoT, robotics, and digital twins are no longer viewed as future tools; they are being applied in areas such as predictive maintenance, cargo handling, and traffic flow optimisation. These technologies are enabling more responsive, data-driven operations across terminals, warehouses, and transport modes. Simultaneously, energy efficiency measures, alternative fuels, and innovative logistics concepts are gaining traction in efforts to reduce emissions.

Still, the findings reveal a **diverse landscape**. While some companies have moved beyond experimentation and are actively implementing low-emission technologies and digital platforms, others remain in earlier stages, hindered by uncertainty, lack of resources, or misaligned incentives. Thus, a marked disparity exists between front-running firms and those still in the early stages of transformation. Across the sector, there is a clear understanding that the challenges are no longer hypothetical - climate goals, client expectations, and evolving legislation are making decarbonisation and digitalisation **operational necessities rather than strategic options**.

Collaboration and governance remain underdeveloped. Many decarbonisation and digitalisation initiatives are hampered not by a lack of ideas but by poor coordination among stakeholders and unclear cost-sharing models. Public-private partnerships, knowledge-sharing platforms, and common standards are considered essential to overcoming these governance challenges and facilitating system-wide change.

Technological uncertainties, lengthy permitting processes, inconsistent regulations, and inadequate infrastructure act as **barriers**. Financial challenges also remain acute, especially for SMEs and firms operating on thin margins. Many businesses still struggle to establish a compelling business case for large-scale green or – to a lesser extent - digital investments, particularly when return on investment is unclear or delayed.

This report also notes that **modal shift and multimodal solutions**, long touted as key decarbonisation strategies, remain underutilised. Structural and operational constraints - such as inadequate terminal connectivity, inefficiencies in intermodal transfers, and the dominance of road transport in short-haul operations - continue to inhibit widespread adoption. However, inland terminals, pipelines, and digital collaboration platforms are emerging as enablers of greener transport chains.

While the journey toward decarbonisation and digitalisation is fraught with challenges, it presents a **critical window of opportunity**. Firms that successfully align technological innovation with environmental responsibility can benefit from stronger market positioning, enhanced regulatory readiness, and improved long-term cost efficiency.

7.2. Specific survey-based findings

The **survey section of this report** examined decarbonisation and digitalisation in the Belgian port, transport, and logistics sector. The survey offers critical insights into how organisations perceive, approach, and experience the ongoing transitions toward decarbonisation and digitalisation. The findings, derived from a targeted survey of 75 industry stakeholders, offer a detailed picture of how companies are navigating the transition to more sustainable and technologically advanced supply chains. The responses reveal a complex and varied landscape, marked by ambition, experimentation, uncertainty, and uneven progress.

A key conclusion from the survey is that **decarbonisation and digitalisation are indeed gaining traction**, but their implementation remains uneven across the sector. About one-quarter of the respondents report having fully implemented a decarbonisation strategy, while another third is currently executing their plans. However, a notable share of companies rely on ad hoc initiatives or have yet to formulate a comprehensive approach. In the digital domain, only a small group can be considered digital pioneers. At the same time, the majority are fast followers or experimenters, suggesting that digital transformation is somewhat more advanced than decarbonisation in terms of organisational uptake.

Decarbonisation initiatives are most actively implemented in areas such as cargo handling equipment and transport vehicles. Warehousing and distribution centres are also leading zones for **digitalisation**, with widespread use of warehouse management systems, automated storage, and inbound/outbound systems. However, advanced technologies such as Digital Product Passports, autonomous vehicles, and AR/VR remain in early adoption stages, as they are perceived as not yet relevant for many respondents' operations.

A key objective was to identify both **tailwinds (enabling factors) and headwinds (barriers)** affecting the adoption of green and digital strategies across the industry. Potential headwind and tailwind factors were categorised into four thematic groups: (1) Business operations and production; (2) External stakeholders; (3) Technology; and (4) Government regulation and policy. The analysis of headwinds and tailwinds highlights distinct contrasts between decarbonisation and digitalisation:

- The analysis of the factors at the level of **business operations and production** level revealed some interesting results. While decarbonisation and digitalisation processes benefit from a company's reputation, competitive pressure, and stakeholder expectations, financial barriers weigh more heavily on decarbonisation efforts. Uncertainty about the business case, high capital expenditures, and insufficient supporting infrastructure often inhibit decarbonisation efforts. In contrast, digitalisation is widely seen as a financially sound investment, with clear benefits in profitability and efficiency.
- From a **stakeholder perspective**, external actors - including customers, societal expectations, and ESG-related requirements - play an increasingly influential role in promoting both green and digital transitions. However, trust and coordination among stakeholders remain underdeveloped, with mixed views on the effectiveness of current collaborative models.
- **Technological advancements**, particularly in green energy, data sharing, and automation, are broadly seen as enablers for both transitions. Yet the sector still faces uncertainty in areas like the energy intensity of new technologies, fragmented innovation trajectories, and workforce readiness. Interestingly, respondents believe that automation and robotisation will foster a more continuous (24/7) logistics economy while enhancing infrastructure efficiency.
- The most consistent and problematic headwinds lie in the domain of **government policy and regulation.** While respondents did not provide any details on specific policies, they express in general terms mixed or negative views on the continuity, predictability, and effectiveness of subsidy regimes, licensing frameworks, and fiscal policies. Although supranational and national climate targets are seen as modest drivers of change, the broader regulatory landscape is often perceived as ambiguous and inconsistent, lacking the alignment and clarity needed to guide long-term investments.

The survey also assessed how decarbonisation and digitalisation influence **competitive dynamics and operational choices**. Most respondents see both transitions as enhancing competitiveness. However, neither decarbonisation nor digitalisation currently plays a decisive role in port choice. Modal choice and the selection of logistics service providers are influenced to a moderate extent, while both trends are increasingly regarded as areas for collaboration rather than direct competition.

Finally, the sector is cautiously optimistic about the **potential of data-driven technologies and autonomous systems**. Respondents anticipate that AI, digital twins, and IoT will significantly improve supply chain efficiency; however, awareness and understanding of emerging technologies, such as quantum computing, remain limited.

7.3. Recommendations

The pathway to successful transition will not be uniform. A single solution or blueprint will not suffice. Instead, companies must develop tailored roadmaps that reflect their specific operational contexts, market positions, and innovation capacities. Several concrete recommendations can be made for companies and organisations active in the sector.

Use ESG and societal expectations as strategic levers - Instead of seeing sustainability requirements as mere compliance obligations, companies can leverage their environmental and digital credentials to attract customers, investors, and talent. Decarbonisation and digitalisation are essential strategies; thus, being transparent about emissions and digital maturity should be integral to a company's brand values.

Toward more robust business cases for green investment - From a technological perspective, priority should be given to fleet renewal, operational energy efficiency, and infrastructure modernisation. Companies are encouraged to adopt low- and zero-emission vehicles and explore the use of alternative fuels. Electrification, where feasible, should be accelerated, particularly in short-haul transport and warehousing. However, this investment path is likely to be bumpy. Therefore, companies should focus on improving their internal financial assessments of decarbonisation projects, identifying segments where the transition away from fossil fuels presents both a clear ROI and long-term resilience. This includes leveraging data and benchmarking tools to reduce perceived uncertainty and communicate value across departments. Given the capital-intensive nature of many decarbonisation projects, businesses should also explore the use of sustainable finance and ESG financing instruments, and innovation subsidies, to align investment decisions with long-term environmental goals. Still, there is a clear need for external support and coordination, as well as more transparent and more coherent public policy, improved access to funding and subsidies, and more substantial support for pilot projects and knowledge exchange. This is also true for small and medium-sized enterprises. Concepts as pool procurement, shared services or simplified reporting tools could be interesting avenues to pursue. Many companies also point to the role of industry associations and cluster organisations in facilitating collaboration and aligning interests across the value chain. Additionally, port authorities and terminal operators play a crucial role in facilitating this shift, for instance, by providing shore power and bunkering infrastructure for alternative fuels.

Collaboration and governance models must mature - The survey findings reveal that many companies struggle to transition from pilot projects to full-scale implementation due to governance bottlenecks and unclear cost-benefit analyses. A more coordinated approach among supply chain partners is needed to unlock synergies, especially for decarbonisation. This includes aligning efforts through shared metrics, joint governance structures, and sector-wide platforms for data sharing and innovation. Public-private partnerships and sector-wide consortia can help overcome obstacles by fostering shared risk, pooling expertise, and aligning stakeholder interests. Given the relative dissatisfaction with current government support mechanisms, industry actors should actively engage in policy dialogues, pressing for greater clarity, continuity, and technology-neutral support schemes. Strategic alliances between ports, logistics firms, and industry associations can amplify the sector's voice in shaping a regulatory environment that enables growth. This is equally true for digitalisation and automation efforts, where engaging in data-sharing platforms and logistics dataspaces will improve automated operational interconnectivity, visibility and coordination. Multiple coordinated efforts in this domain across various sectors in Europe are being developed; however, there is still a risk of fragmentation.

Embrace digitalisation as a driver of competitiveness - Digitalisation offers transformative potential across the value chain. Therefore, digital transformation should not be seen as a secondary goal but as an enabler of operational excellence, cost reduction, and supply chain visibility. Fast followers should accelerate their integration of proven technologies, particularly in warehousing and data analytics, while remaining open to experimental solutions such as AI, digital twins, real-time tracking, predictive analytics, and platform-based ecosystems. These technologies do more than optimise flows. They also enhance transparency, support emissions reporting, and facilitate collaboration with stakeholders. The integration of digital tools into decision-making processes can enhance resilience and adaptability, particularly in contexts of geopolitical and supply chain volatility. Fast followers should particularly consider emerging initiatives towards standardisation and interoperability by supporting or adopting open standards for data sharing and system interoperability. With clear expectations of a 24/7 logistics economy, companies should start developing pilot programs for autonomous systems and AI applications that enhance efficiency, reduce labour constraints, and improve infrastructure utilisation.

Invest in workforce development and cultural change - Both decarbonisation and digitalisation require new skill sets and a shift in organisational mindsets. Companies should prioritise training programs and change management strategies to prepare employees for a more automated, data-intensive, and sustainability-focused industry, and this across all levels. Many organisations struggle with recruiting and retaining talent in areas such as IT, sustainability management, and automation. Smaller companies, in particular, cite limited human resources as a barrier to innovation. A workforce equipped with both green and digital competencies is critical to translating strategy into practice. Building these capabilities requires leadership commitment and structured investment in human capital. As automation and AI redefine logistics processes, companies should anticipate shifting job profiles and proactively manage this transition through upskilling, recruitment, and change management strategies.

Reassess supply chain design - Companies should increasingly consider modal shift and synchromodal solutions as a viable path toward reducing transport emissions. This includes strengthening multimodal connections, improving terminal access, and leveraging inland hubs. Policymakers have a role in ensuring that infrastructure and regulatory frameworks support these alternatives. Additionally, logistics players should pursue cargo bundling, load optimisation, and reverse logistics as operational strategies to reduce emissions and increase efficiency. By embracing existing and emerging digital tools, companies can transition to become agile, intelligent, and interconnected service providers within a networked supply chain.

Companies that move decisively, invest strategically, and collaborate effectively will not only meet regulatory expectations but will also enhance their competitiveness, build resilience, and help shape the future of logistics in a low-carbon economy. By actively addressing these areas, the port, transport, and logistics industry in Belgium - and by extension, in comparable regions - can take further steps in transforming current headwinds into long-term strategic advantages.

References and further reading

Alam, M.S., Duffy, P., Hyde, B. and McNabola, A., 2017. Improvement in the estimation and back-extrapolation of CO2 emissions from the Irish road transport sector using a bottom-up data modelling approach. Transportation Research Part D: Transport and Environment, 56, 18-32.

AUTOSUP, 2024. Classification of automation technologies, https://www.autosup-project.eu/wp-content/uploads/2024/12/AUTOSUP_D1.1_Classification-of-logistics-automation-technologies-V1.0-1.pdf

Cariou, P., Parola, F. and Notteboom, T., 2019. Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. International Journal of Production Economics, 208, 17-28.

Churchill, S.A., Inekwe, J., Ivanovski, K. and Smyth, R., 2021. Transport infrastructure and CO2 emissions in the OECD over the long run. Transportation Research Part D: Transport and Environment, 95, p.102857.

Deutsche Bahn, 2025. Resource protection, accessed January 30, 2025.

ECMT, 1998. Report on the Current State of Combined Transport in Europe. European Conference of Ministers of Transport, OECD Publications: Paris.

EFTE, 2018. Road map to decarbonizing European shipping, European Federation for Transport and Environment

European Commission, 2006. Keep Europe moving – Sustainable mobility for our continent. Mid-term review of the European Commission's 2001 Transport White Paper [COM(2006)314]. Office for Official Publications of the European Communities, Luxembourg.

Fan, A., Xiong, Y., Yang, L., Zhang, H. and He, Y., 2023. Carbon footprint model and low–carbon pathway of inland shipping based on micro–macro analysis. Energy, 263, 126150.

Flemish Government, 2025. Vlaams Energie- en Klimaatplan 2021-2030. Definitief geactualiseerde versie zoals goedgekeurd door de Vlaamse Regering op 18 juli 2025, VR 2025 1807 DOC.0747/2

Frosch, R.A. and Gallopoulos, N.E., 1989. Strategies for manufacturing. Scientific American, 261(3), 144-153.

Ge, J., Zhu, M., Sha, M., Notteboom, T., Shi, W. and Wang, X., 2021. Towards 25,000 TEU vessels? A comparative economic analysis of ultra-large containership sizes under different market and operational conditions. Maritime Economics & Logistics, 23, 587-614.

IMO, 2015. Third IMO Greenhouse Gas Study 2014 : Safe, secure and efficient shipping on clean oceans. https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx

IMO, 2023. 2023 IMO Strategy on Reduction of GHG Emissions From Ships, Annex 1 - Resolution MEPC.377(80), Marine Environment Protection Committee (MEPC), Adopted on 7 July 2023, International Maritime Organisation: London

IMO, 2025. https://www.imo.org/en/OurWork/Safety/Pages/VesselTrafficServices.aspx

ING, 2021. Fuel for the Future: Alternatieve brandstoffen voor wegtransport, ING Bank, June 2021.

Krantz, J., 2017. Reducing carbon dioxide emissions in transport infrastructure projects (Doctoral dissertation, Luleå University of Technology).

Mallouppas, G. and Yfantis, E.A., 2021. Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. Journal of Marine Science And Engineering, 9(4), 415.

McKinnon, A., 2007. CO2 emissions from freight transport: an analysis of UK data. In: Logistics Research Network-2007 Conference Global Supply Chains: Developing Skills, Capabilities and Networks.

Merk, O., 2014. Shipping emissions in ports, International Transport Forum Discussion Papers 2014/20, OECD, Paris, December 2014

Mueller, D., Uibel, S., Takemura, M., Klingelhoefer, D. and Groneberg, D.A., 2011. Ships, ports and particulate air pollution-an analysis of recent studies. Journal of Occupational Medicine and Toxicology, 6, 1-6.

Notteboom, T., Pallis, A. and Rodrigue, J.P., 2022. Port economics, management and policy. First Edition, Routledge.

Notteboom, T., Van Der Lugt, L., Van Saase, N., Sel, S., Neyens, K., 2019. Green supply chains: implications and challenges for Rhine-Scheldt Delta seaports, final report prepared for ING Belgium, UAntwerpen/VIL/Erasmus Universiteit Rotterdam, 17 July 2019, 121 p.

OECD, 2018. Decarbonizing maritime transport: pathways to zero-carbon shipping by 2035, OECD-International Transport Forum, Paris

Pfoser, S., Treiblmaier, H. and Schauer, O., 2016. Critical success factors of synchromodality: Results from a case study and literature review. Transportation Research Procedia, 14, 1463-1471.

Porter, M.E. and Linde, C.V.D., 1995. Toward a new conception of the environment-competitiveness relationship. Journal of Economic Perspectives, 9(4), 97-118.

Psaraftis, H.N., Zis, T. and Lagouvardou, S., 2021. A comparative evaluation of market based measures for shipping decarbonization. Maritime Transport Research, 2, 100019.

Rodrigue, J.P., 2024. The Geography of Transport Systems, Routledge

TNO, 2016. Using a simplified Willans line approach as a means to evaluate the savings potential of CO2 reduction measures in heavy-duty transport, TNO, Delft

TNO, 2017. Great challenges lie ahead for low-carbon long-haul transport, TNO, Delft, September 2017 - TNO 2017 R10953

TNO, 2017b. Towards zero-emission city logistics, TNO, Delft, September 2017 - TNO 2017 R10954

Transport & Environment, 2022. EU Ports' Climate Performance: An analysis of maritime supply chain and at berth emissions, Transport & Environment, February 2022

UIRR, 2024. Combined transport operation: a new definition. Press Release, International Union for Road-Rail Combined Transport (UIRR), Brussels, 27 February 2024.

UNCTAD, 2023. Review of Maritime Transport, UNCTAD, Geneva

UNCTAD, 2024. Review of Maritime Transport, UNCTAD, Geneva

Van Hoek, R.I., 1999. From reversed logistics to green supply chains. Supply chain management: An international Journal, 4(3), 129-135

Vandenberghe, K., 1997. The Commission's Intermodal Transport Policy: a systems approach to transport, European Commission DGVII, ESTI conference, Brussel

Wilkerson, T., 2005. Best practices in implementing green supply chains. In North America Supply Chain World Conference and Exposition, Vol. 5.

WSP, 2024. Rail Decarbonisation: Global Outlook. What are the next steps to achieve net zero by 2050 for rail stakeholders in various parts of the world?, WSP, June 2024

Yuan, S., Jia, P., Notteboom, T., Ma, Q., 2024. Emerging trends and developments in multimodal freight transportation: a scientometric analysis using CiteSpace, International Journal of Transport Economics, Vol. L (3-4).

Zhang, X., Zeng, Q. and Yang, Z., 2019. Optimization of truck appointments in container terminals. Maritime Economics & Logistics, 21(1), 125-145.

ABOUT THE AUTHORS

Theo Notteboom is professor of maritime and port economics. He is affiliated with Faculty of Business and Economics of University of Antwerp and Faculty of Sciences of Antwerp Maritime Academy, and is chair professor 'North Sea Port' at Maritime Institute, Faculty of Law and Criminology of Ghent University. He is co-founder and co-director of Porteconomics.eu and member of Risk and Resilience Committee of International Association of Ports & Harbors (IAPH). He is former vice-president (2022-2024) and past president (2010-2014) of International Association of Maritime Economists (IAME). He is Associate Editor of Maritime Economics & Logistics, Editor of Journal of Shipping and Trade and a member of the editorial boards of eight other leading academic journals in the field. He previously held positions as full professor and 'High-end Foreign Expert' at Dalian Maritime University in China and research professor and director at Shanghai Maritime University. Theo has published widely on ports and maritime logistics and his work is highly cited. He is editor/author of about a dozen academic books, including the handbook 'Port Economics, management and policy' (Notteboom, Pallis and Rodrigue, 2022; Routledge). He is a regular speaker at international academic and business conferences and received a dozen international awards for his research and achievements in the field. Theo Notteboom acts a rapporteur/expert to leading organisations and corporations in the field.

Kris Neyens is the Manager of Internationalisation at VIL, Flanders' sole innovation spearhead cluster for logistics. He is involved in international innovation projects focusing on new alternative logistics concepts, transport routes, and modes. As a supply chain expert, he has a long track record in managing change and innovation projects, both in the private sector and in public-private collaboration initiatives, particularly in challenging and competitive environments. He also gained experience in inspection, stevedoring, and warehousing environments. In his role as Manager of Internationalisation, he leverages his extensive experience in supply chain innovation, specialising in designing and implementing innovative logistics concepts such as supply chain resilience, transcontinental rail transport, nearshoring, and autonomous transport. Additionally, he served as the Hyperloop Theme Manager for VIL, a position commissioned by the Flanders government, where he informed Flanders' innovation stakeholders—both in industry and academia—about the opportunities presented by Hyperloop technology and its potential spillover applications. Currently, he also serves as the vice-chair of TG2, focusing on hubs, corridors, and networks at ETP-Alice, the European technology platform dedicated to realising the Physical Internet concept.

FURTHER INFORMATION

This publication was prepared for ING Belgium. For further information on the services of ING Belgium in transport and logistics, please visit www.ing.be .

ING Belgium S.A./nv • Bank/Lender • Marnixlaan/Avenue Marnix 24, B-1000 Brussels • RLP Brussels • VAT: BE 0403.200.393 • BIC: BBRUBEBB • IBAN: BE45 3109 1560 2789
www.ing.be • Contact us via ing.be/contact • Insurance broker, registered with the FSMA under the number 0403.200.393 • Publisher responsible: Saskia Bauters • Marnixlaan/
Avenue Marnix 24, B-1000 Brussels • 731630E • 09/2025