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Smart logistics nodes: concept and classification

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ABSTRACT
This paper presents the Smart Logistics Node concept, which combines the physical infrastructure of logistics nodes with digital systems to enhance collaboration. The Smart Logistics Node benefits from data sharing, supporting infrastructure, and Connected and Automated Transport (CAT) technologies. Based on a literature review on logistics nodes and CAT, we propose a general classification of Smart Logistics Nodes distinguishing upon the node function, degree of organisational (de-)centralisation, digital integration, and infrastructure support for automated driving. Then, we classify sixteen logistics nodes and find that high digital integration is common while automation is lacking. Further automation entails mixed traffic on public roads and requires organisational changes that do not always align with current business models. Our work supports the adoption of emerging technology at logistics nodes and the comparability of business cases. Ultimately, node authorities can use our concept and classification to draw a roadmap to develop CAT capabilities.

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1. Introduction

Freight transport is a fundamental part of modern society and will become increasingly essential. In fact, freight transport is forecasted to more than double by 2050, resulting in CO_2 emissions increasing by at least 22% despite current transport decarbonisation policies (ITF 2021). Due to freight transport growth, logistics networks face challenges regarding shorter delivery times, driver shortage (IRU 2021), traffic congestion, and safety and sustainability concerns. Furthermore, the COVID-19 pandemic, with its subsequent factory shutdowns and nationwide lockdowns, worsened the situation by causing a ripple of disruptions in supply chains (Hald and Coslugeanu 2021; Magableh 2021), especially for containerised trade (UNCTAD 2021). Being at the core of containerised trade and freight networks, logistics nodes, such as ports, risk bearing the brunt of the increasing freight volumes and disruptions along the supply chain.

Given the need to make global trade more efficient, resilient, and sustainable, the freight sector is looking at emerging and transformative technologies. The most impactful are self-driving vehicles, drones, the Internet of Things (IoT), big data analytics, cloud computing, and artificial intelligence (Dong et al. 2021; Toy 2020). Moreover, these technologies can reduce epidemic-related risks and uncertainties by lowering human intervention, thus increasing supply chain resilience (Chowdhury et al. 2021; Gultekin et al. 2022). However, their value and implementation process are uncertain to logistics operators (e.g. see Heilig, Lalla-Ruiz, and Voß 2017a). This is partly due to a lack of comprehensive studies on emerging technologies in the freight sector, as emerging technologies

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are typically studied within specific scenarios and as standalone tools. Consequently, research streams on emerging technologies in logistics are fragmented and do not consider the full complexity and scope of real implementation scenarios (Dong et al. 2021). Also, studies on using emergent technologies to handle disruptions and boost logistics resilience are scarce (Chowdhury et al. 2021). Next to emerging technologies, and because of those technologies' assumed impact on business models, logistics players are looking at new organisational approaches to increase resource utilisation and lower emissions further. Horizontal collaboration, i.e. collaboration among (competing) companies operating in the same segment of different supply chains, has been considered one of the significant innovations in logistics for quite some time now (e.g. see Tavasszy and Ruijgrok 2013). Still, applications of such collaborations in the freight sector are lagging (Cruijssen 2020). Moreover, a lack of cooperation and standardisation also hinders the practical use of advanced planning tools and information technology (IT) systems, which are considered essential to reap the full benefits of economies of scale in collaboration (Tavasszy and Ruijgrok 2013).

Following the trends in digitalisation and transport systems (see also Dong et al. 2021; Pernestål et al. 2021; Wang and Sarkis 2021), logistics nodes need to adjust and transform into Smart Logistics Nodes (SLNs). Our view of an SLN is that of a logistics node, e.g. seaport, airport, or freight village, using data integration and information-sharing technologies to improve and automate processes. A specific example of automation at these nodes is the use of Connected and Automated Vehicles (CAVs) for the internal handling of freight. These CAVs could also benefit from a decoupling point (DP) to separate inbound road modalities from the internal traffic, i.e. a pre-gate parking area. In addition, SLNs could improve the processes of other logistics service providers by supporting collaborative transport, trailer swapping, and truck platooning for long-haul transport. The transition to an SLN is expected to improve logistics nodes' operational efficiency and environmental footprint.

The final goal of the SLN is to be the cornerstone of an open, global, and integrated transport system, similar to what was envisioned in SETRIS (2017). Such a transport system would achieve a seamless, flexible, and efficient supply chain connected on a physical, digital, and operational level. In fact, a synchronised and seamless logistics network supports the modal shift to slower and cheaper modalities (Groothedde 2005), e.g. to trains and barges, which in turn could also be more environmentally friendly. Therefore, the change to the SLN is even more crucial to support synchronised planning and the seamless modal shift at logistics nodes. This seamless connection of logistics operations and freight flows requires ample use of IT, requiring shared protocols and standards, and a higher degree of information exchange. These requirements are also part of the Physical Internet (PI) as defined by Montreuil, Meller, and Ballot (2012). The PI is an open, global logistics system aiming to achieve physical, digital, and operational interconnectivity via encapsulation, interfaces, and protocols, e.g. using modular containers. The concept of PI is inspired by the digital internet, as in freight units seamlessly finding their way through a network of routes connected by logistics hubs, like emails moving through virtual network of servers. A fundamental aspect of achieving these requirements is through the IoT (Atzori, Iera, and Morabito 2010), as it provides real-time information on the state, position, and arrival time of a shipment, container, or even a product at any step of the supply chain. Tran-Dang et al. (2020) theorise an IoT ecosystem for the PI (π-IoT), where IoT offers end-to-end visibility of the PI objects and processes, while the PI achieves sustainability and efficiency through interoperability and interconnectedness. The IoT services support PI decision-making with real-time, accurate data. Drawing inspirations from integrated systems like in the PI, the SLN could employ shared resources and collaborative planning, where we would have a shared CAV fleet for internal transport or where we could allocate jobs among a consortium of logistics service providers, e.g. re-assigning a job to another partner to improve efficiency or increase the timeliness of transport.

The increasing freight flows, supply chain disruptions, and technology trends we described push logistics nodes to develop new capabilities and change their operations. Connected and Automated Transport (European Commission 2018), termed CAT, promises to answer the need for increased efficiency and collaboration at logistics nodes by harnessing emerging technologies; we introduce and extensively discuss CAT later in Section 2.2. However, theoretical research is lagging behind the implementation of CAT in practice. For example, research regarding CAV ownership, sharing, and collaboration models at logistics nodes is lacking (Cruijssen 2020; Fritschy and Spinler 2019; Monios and Bergqvist 2020). Consequently, the economic value of CAT at logistics nodes needs further analysis to convince all stakeholders to commit (Heilig, Lalla-Ruiz, and Voß 2017a). Also, the uncertain economic value of CAT is often the cause of derailed implementation projects. A prerequisite for analysing the value of CAT would be a proper classification of the technological capabilities at logistics nodes. Such a classification would benefit the development of logistics nodes by directing research efforts and investments into their best-fit CAT concepts. Yet, to the best of our knowledge, a classification of technological capabilities at logistic nodes is missing.

The contribution of this paper is threefold. First, we provide an overview of the literature on logistics nodes and CAT. Specifically, we discuss collaboration approaches, novel concepts and equipment, IT systems, and developments around IoT and the PI. Second, we define the concept of the SLN and provide a classification of SLNs based on their characteristics and scope. Finally, we apply our classification to multiple existing logistics nodes to validate our classification and assess the status of globally relevant nodes toward their transition to SLNs. Through our classification, we identify an SLN class for each logistics node, which includes a list of technological capabilities aligned to the node's organisational approach and business goals. The SLN concept is being developed as part of the CATALYST (Connected Automated Transport And Logistics Yielding SustainabiliTy) project funded by the Dutch government and a consortium of research and logistics partners. Four of the sixteen logistics nodes we classify belong to the CATALYST consortium.

The remainder of this paper is structured as follows. First, we explore the literature regarding logistics nodes and CAT in Section 2. In Section 3, we present the concept of SLN and our classification. In Section 4, we classify various logistics nodes and provide general insights through the SLN classification. We end with conclusions and directions for further research in Section 5.

2. Overview of logistics nodes and CAT

This section presents the groundwork for our definition and classification of the SLN. First, we dive into the logistics nodes' literature to provide a clear definition and scope of SLNs (Section 2.1). Second, we define CAT, multiple CAT technologies, and their practical implementations to identify CAT's transformative effects on logistics operations (Section 2.2).

2.1. Logistics nodes

Logistics areas are referred to by multiple, sometimes overlapping terms, and logistics nodes face the same ambiguity. However, settling on a logistics term for the SLN is essential to establish the concept. Therefore, we build on the literature defining logistics areas, going from general to specific, to reach a consensus on the definition of the SLN. Then, we present concepts applicable to logistics nodes from theory and practice and relate them to the SLN in that they use data to improve operations and boost collaboration. Lastly, we describe the major challenges logistics nodes face in rolling out CAT concepts.

A widely-used term to refer to logistics areas is *logistics center*, although its definition is ambiguous, fragmented, and has been the scope of several works of literature in the last decades (see Higgins, Ferguson, and Kanaroglou 2012; Notteboom et al. 2017; Rimienė and Grundey 2007; Wagener 2015). The European Logistics Platforms Association (EUROPLATFORMS 2015) defines a logistics centre as an area where various operators perform all activities related to transport, logistics, and distribution of goods with a commercial scope. Noticeably, the EUROPLATFORMS mentions multimodality as a preferable characteristic of logistics centres, thus not mandatory. However, this definition is extensive and potentially includes all logistics areas with multiple actors. Following this, logistics nodes can be seen as a subset of logistics centres. Specifically as large-scale, semi-public, intermodal hubs with tight connections to inland logistics centres (Rimienė and Grundey 2007). In this context, 'semi-public' refers to the public-private partnerships constituting the neutral and legal body in charge of managing, developing, and regulating these large logistics areas. Regarding their scope, logistics nodes can be included in the gateway or freight distribution cluster categories as defined by Notteboom and Rodrigue (2009), thus connecting global freight flows to a large regional network and providing a range of logistics services.

Higgins, Ferguson, and Kanaroglou (2012) merge the work of the previous authors with the size categorisation of Wiegmans, Masurel, and Nijkamp (1999) to create a consolidated classification. In this, the updated freight distribution cluster and main port terminal concepts are most relevant to us. The first concept relates to a medium to large inland cluster of industrial, intermodal, and logistics infrastructures, e.g. a freight village or dry port. Moreover, freight distribution clusters provide high-quality multimodal connections, industrial value-adding services, and share logistics and IT services between its partners, e.g. special equipment, customs, IT platforms, and rest areas. The second concept relates to a major node between inland logistics and maritime or airborne transport, i.e. large ports and airports. Mainport terminals handle large volumes of freight, rely heavily on IT and other technologies, and provide all kinds of logistics and value-adding services. Based on the two definitions, we further frame a logistics node as ranging between wide-scope freight distribution clusters and mainport terminals, being of medium to large size. We could adhere to the consolidated classification and call our augmented concept smart mainport terminal; however, we dismiss this option for two main reasons. First, we do not want to limit the scope of the SLN to air- or seaports, as it could be applicable to freight villages, inland ports, or future, undefined logistics areas. Second, the term *node* better fits into the Physical Internet (PI) setting and helps convey the idea of a seamless, connected, global logistics network. Hence, we settle on the term *logistics node* to identify a medium to large, semi-public, multimodal hub that connects international freight flows to a large regional network and provides value-adding services and technologies shared between its partners at the node.

Regarding theoretical concepts applicable to logistics nodes, we start with the Smart Port concept. Molavi, Lim, and Race (2020) define a Smart Port as a port with a skilled and educated workforce, automation, and intelligent infrastructure, where its goal is to promote the optimisation, safety, and sustainability of port operations, facilitated by knowledge development and sharing. The Smart Port concept overlaps in scope and characteristics with the SLN, especially regarding automated equipment. However, the authors focus on developing a Smart Port Index to assess ports' operational, environmental, and security performance. For example, they suggest a list of metrics and perform a detailed analysis of ecological and energy-related activities. Therefore, their work can be considered a tool to assess port performance at an operational level. Finally, as obvious from its name, the Smart Port concept limits itself to ports.

Next is the Cross-Chain Collaboration Center (4C). De Kok, Van Dalen, and Van Hillegersberg (2015) define a 4C as a legal entity providing a supply chain management service to independent partners in one or more supply chains, i.e. a cross-supply-chain orchestrator managing a collaboration platform. The 4C performs a crucial task that we consider part of an SLN's scope. In fact, a 4C could be located at an SLN or be remotely connected to multiple SLNs, since logistics nodes are the location where multiple supply chains cross.

A further concept related to the SLN is the use of PI nodes (or π-nodes). Montreuil, Meller, and Ballot (2010) define the PI nodes as a variety of locations interconnected to logistics activities, delivering different services, and openly sharing information on their performances, e.g. modal interfaces, service levels, and capacity. PI nodes range from simple storage or sorting areas (PI store and PI sorters, respectively) to multimodal areas for container cross-docking and exchange (PI hubs) between material handling systems. Moreover, PI nodes include PI gateways, which function as entry and exit points between the larger PI network and private logistics networks. Although PI hubs could be seen as SLNs with limited scope, an SLN would include many, if not all, kinds of PI nodes and other non-PI agents. We discuss PI elements in more detail in Section 2.2.

Other relevant concepts related to SLNs are the framework for Logistics Center 4.0 (Yavas and Ozkan-Ozen 2020) and the Hyperconnected City Logistics concept (Crainic and Montreuil 2016). Regarding the first, the authors describe, among others, logistics centres featuring online platforms, autonomous vehicles, and real-time location data. Regarding the second, the authors describe a system of collaborating urban logistics hubs supported by PI technology. In both concepts, the authors propose a combination of digital and physical technologies to enhance logistics interoperability, connectivity, and flexibility at areas with intense freight flows.

Regarding logistics nodes in practice, ports, and freight distribution clusters are already implementing concepts related to connectivity, data-driven planning, and collaboration. Ports are likely to feature larger-scale IT systems and a more comprehensive set of technologies, equipment, and services. Therefore, we first discuss significant development at ports. Specifically, we examine the concept of Port Community Systems, i.e. the digital ecosystem of a port, and provide an extensive state-of-the-art discussion on CAVs, IoT, PI, and other digital services in Section 2.2. A Port Community System (Long 2009) is an information system to support collaboration and data sharing between logistics stakeholders. For example, community systems might include a Gate Appointment System (GAS), see Guan and Liu (2009), to match the arrival of freight transport modalities with timeslots at terminals and warehouses. Due to their scheduling function, GASs reduce congestion and port emissions (Chen, Govindan, and Yang 2013). Port Community Systems are now present on all continents and feature online services, mobile applications, and intelligent systems of self-executing agents, to support efficient and green operations (Moros-Daza, Amaya-Mier, and Paternina-Arboleda 2020). Moros-Daza, Amaya-Mier, and Paternina-Arboleda (2020) surveyed the literature on Port Community Systems and formulated a research taxonomy. The taxonomy highlights three main design themes: business, integration, and legal governance. The first covers evaluating the business model, with aspects such as the business scope, the processes, and the relationships with stakeholders. The second covers the IT capabilities, interconnectivity, interoperability, and the organisational interdependence of functions and duties. The third covers cargo security and the governance models for the IT system. Regarding governance models, we refer to Tijan et al. (2021) for port systems, to Chandra and Van Hillegersberg (2016) for supply chain systems, and to Provan and Kenis (2008) for networks in general. Furthermore, Srour et al. (2008) support the extension of community systems over the physical boundaries of a port to achieve chain-wide visibility and planning. This goal is included in the scope of an SLN, and indeed, a Port Community System (or logistics node community system) is an essential step to realise an SLN in practice. We refer to Heilig and Voß (2017a) for an overview of well-established information systems and technologies implemented at ports, e.g. automation, traffic control, and real-time freight location.

Logistics nodes encounter multiple challenges when implementing CAT concepts, with the goal of increasing logistics efficiency and resiliency. The main challenges can be categorised by the adoption of new forms of collaboration, the adoption of new technological developments, and embracing new business models. In the following paragraphs, we delve into a comprehensive examination of these challenges, the specific obstacles, and the role of the SLN concept in overcoming them. Table 1 presents a summary of said paragraphs.

Cruijssen (2020) suggests that (horizontal) collaboration lags behind former expectations because companies are waiting for the right data-sharing support model. Also, the author identifies the need for more research on macro-level standardisation, full collaboration scenarios, and profit-sharing. In this respect, the SLN represents a large logistics area with many actors where various degrees of standardisation and collaboration could be studied theoretically and practically. Similarly, mechanisms for profit-sharing could be tailored upon the SLN and its stakeholder composition to support data sharing and interoperability.

Regarding the aspect of technology adoption, Heilig, Lalla-Ruiz, and Voß (2017a) identify challenges for smart ports in the field of real-time data analysis and faster decision-making. Interestingly, the authors report how the implementation of intermodal support systems at the Port of

Table 1. Challenges at logistics nodes and the role of the SLN concept.

Challenge	Authors	Obstacle	Role of the SLN concept
Collaboration	Cruijssen (2020)	Need for studies on standardisation, collaboration, and profit-sharing	Large-scale environment with various collaboration degrees
Technology	Giuliano and O'Brien (2007)	Lack of interest by stakeholders, a multitude of non-integrated systems	Development of processes and algorithms for integrated planning. Study on centralised vs. decentralised systems
	Heilig, Lalla-Ruiz, and Voß (2017a)	Lack of commitment by stakeholders, uncertain value of technology	Assessing the value of CAT technology in complex settings
Business models	Monios and Bergqvist (2020)	Research on ownership and resource sharing are neglected in freight transport	Case study for business model research of freight transport at logistics nodes
	Fritschy and Spinler (2019)	Uncertain future of ownership: leased by manufacturers vs. owned by new logistics players	Testbed for ownership models
	Monios and Bergqvist (2020)	Rapid technical obsolescence and high vehicle cost	Testbed for vehicle characteristics and management strategies
	Monios and Bergqvist (2020)	Evolving business models with maturing of the technology. Value in vehicles, infrastructure, and data	Facilitates scenario analysis. Combines vehicles, infrastructure, and use of data

Hamburg failed due to stakeholders' lack of willingness to collaborate. In this case, technology was ready, but its value was uncertain to logistics stakeholders. Another example of failed technology implementation is the GAS at the port of Los Angeles and Long Beach (Giuliano and O'Brien 2007). The authors identify the coexistence of several appointment systems and a lack of interest by relevant logistics players, i.e. the port terminals, as the main issues. The first issue led to confusion about what system to use and increased complexity for the truck drivers in approaching the port. The second resulted in a faulty integration and misalignment of the GAS with the internal logistics operations at terminals, e.g. terminal resources were not ready for the scheduled appointment. The SLN is a prime logistics environment to assess the value of CAT technology in complex settings, thus boosting the stakeholders' commitment toward technology adoption projects. For example, distinct types of SLNs will require technologies for integrated or distributed planning, depending on their (de-)centralised organisational structure, in combination with the supporting infrastructure, e.g. a truck parking and CAVs. This complexity and a wider range of studied applications can offer more suitable and credible solutions, again improving the willingness of stakeholders to commit.

Regarding convincing business models, the main challenges are the ownership and sharing of CAVs, although these have been neglected in freight transport research (Monios and Bergqvist 2020). As discussed later, the SLN concept can be the theoretical frame for many case studies regarding logistics nodes and freight transport between locations inside the nodes. Different business models can be theorised and assessed in practice or via simulations, especially regarding the management of CAV fleets. We now focus on the ownership and sharing of CAVs.

Fritschy and Spinler (2019) performed a Delphi study focusing on freight transport by CAVs in Germany – one of the most advanced countries in the legal acceptance of CAVs (BMVI 2021) – that included 30 logistics experts. The experts reached consensus on multiple sector directions resulting in a few future scenarios. In these scenarios, vehicle manufacturers retain ownership of CAVs and orchestrate fleet sharing, or new logistics players emerge to fill this role. Monios and Bergqvist (2020) claim that the change in ownership models will result in a higher risk of technical obsolescence and increased costs of vehicles.

Concerning CAV sharing, Fritschy and Spinler (2019) and Monios and Bergqvist (2020) see data-enabled collaboration in freight transport as an important leverage for value creation in supply chains. Specifically, the latter authors foresee three transitional business models. First, the value will come from costly and rapidly improving truck technology. In this phase, we have a traditional ownership model where manufacturers shoulder the obsolescence risk and intensify vehicle leasing to logistics players. Second, the charging infrastructure will become crucial. This will lead to the emergence of network operators that own the CAVs, possibly aided by an asset manager, which also handles the battery charging or swapping, enabling 24/7 operations. Also, network operators will organise collaborative transport and data sharing. Finally, following the PI and IoT paradigms, data availability and IT will become the source of value. At this stage, we will see full collaboration and fleet sharing. Furthermore, IT actors will gain importance and network operators may transform their core business into the management of software and real-time data. Also, network operators may be renting CAVs and other assets, e.g. charging stations, from manufacturers or asset managers. Interestingly, the authors identify hub operators, e.g. logistics node operators, as potentially fulfilling the role of network operators. For CAV ownership and sharing, the SLN could fulfil the role of a testbed for ownership models, CAVs' characteristics, and CAVs' management strategies, e.g. for optimal battery recharging and fair dispatching rules. Finally, the SLN and its variants could support a broad scenario analysis. In such analysis, it is possible to combine several types of vehicles, supporting infrastructure, IT systems, and the processing and sharing of data among stakeholders. Also, the scenario analysis could consider the evolution and obsolescence of technology as well as the transformation of logistics operators, as described above.

2.2. Connected and automated transport

Based on the description of the European Commission (2018), we define Connected and Automated Transport (CAT) as a field of transportation technology whose goal is the development of fully unmanned and automated vehicles capable of sharing and receiving information in real-time, thus enabling the realisation of innovative, efficient, and sustainable transport systems. Connectivity refers to wireless information exchange among the vehicle manufacturer, third-party logistics service providers, users, infrastructure operators, and other vehicles. On the other hand, automation refers to various degrees of vehicle-initiated actions without driver input, ranging from safety-critical functions, e.g. braking, to open road driving and real-time route choice. Furthermore, CAT applies to vehicles as well as infrastructures and digital platforms. In fact, infrastructures are enhanced to communicate with the vehicle and facilitate its operations, while digital platforms support collaboration and data sharing. Hence, examples of CAT technologies include automated trucks or vessels, smart traffic lights, and matchmaking platforms for transport requests.

CAT affects all transport modes, however, with different potential impacts and challenges. The European Commission (2019) provides an overview of each transport modality. CAT has many benefits for road transport, such as the reduction of accidents and emissions and the effective use of travelling time. In logistics, an important aspect is the removal of (long-haul) drivers or the possibility of taking a break while the truck moves. Road transport challenges include the complete mapping and engineering of vehicle interactions with drivers, passengers, and other road users; the definition of suitable business and operational models; and the consideration of societal needs and expectations, among others. For rail transport, CAT can potentially increase the capacity of the current railway infrastructure and reduce energy consumption. There, the main challenge lies in deploying recent technology in such a long-life asset sector. For waterborne transport, the main benefits are an increase in safety due to accident avoidance and operational efficiency, thanks to automation and real-time data sharing. Also, automation and real-time data sharing improve intermodal operations and enable the creation of new business models. Waterborne transport challenges are similar to the other modalities' regarding technology development and human interaction; the full benefits of waterborne CAT will be reaped when the whole logistics chain's operations are connected and automated. For airborne transport, CAT introduces transformative concepts such as drones and unmanned aerial vehicles (UAV) for the on-demand transport of people and goods. Obviously, airborne CAT faces a challenging regulatory process as well as the same difficulties in mapping interactions with the environment as road transport. Note that UAVs can be automated or remotely operated, with the latter being either always or at crucial moments such as take-off and landing. For further discussion on the opportunities and limitations of CAT for each transport modality, we refer to Daduna (2020).

Scoping down on the transport of containers at logistics nodes, we see that road, water, and rail modalities are employed to different extents. However, UAVs are currently limited to safety inspections and the transport of parcels, e.g. in the drone programme of the Port of Rotterdam (Römers 2021). Nonetheless, the use of UAVs is being investigated for heavier loads, such as the unmanned cargo aircraft by Meincke (2022) and the high-load drones by Volocopter and Griff Aviation. Returning to modalities employed in container transport, Hu et al. (2019a) summarise how road modalities are the most used due to their speed and flexibility. However, automated road vehicles face implementation challenges regarding the required control system and potentially the requirement of dedicated lanes (Gharehgozli, de Koster, and Jansen 2017). These drawbacks could be overcome by deregulating mixed autonomous-manned traffic and an integrated IT platform at the logistics node. Conversely, water and rail modalities are more economical (Hu et al. 2019a) and easier to implement in restricted networks, such as port areas (Daduna 2020). However, they require longer transport times and additional handling operations (Hu et al. 2019a). Moreover, rail transport is hardly researched or applied in internal transport settings at logistics nodes but has been studied as a promising concept that would benefit from automation, achieving time savings and boosting sustainability (Hansen 2004; Hu et al. 2019b; Krämer 2019; Truong et al. 2020).

Due to the extensive use of road vehicles for internal freight transport at logistics nodes and the complexity of road automation, we focus on road CAT, also called Connected, Cooperative, and Automated Mobility (CCAM), in Section 2.2.1. Moreover, road transport is common to all logistics nodes, while water and rail transport might not always be both available at the same node. Nevertheless, most concepts and insights apply to other modalities; thus, differences will be mentioned. Next, Section 2.2.2 lists relevant CAT technologies for logistics nodes and summarises the research gaps resulting from our literature review.

2.2.1. Connected, cooperative, and automated mobility

In 2019, the European Road Transport Research Advisory Council (ERTRAC) updated its roadmap on automated driving, i.e. the automation of driving tasks such as speed control, steering, and road awareness. Also, they added the notion of connectivity, i.e. technology-enabled communication between the vehicle and other agents or elements on the road. This addition happened because of the increasing importance of connectivity in automated driving, especially for communication with other vehicles and the infrastructure (ERTRAC 2019). Two years later, the ERTRAC (2021) further extended connected and automated driving with cooperativity: managing traffic, mobility, and functional safety for the system of vehicles as a whole through connectivity-enabled coordination and intelligent traffic infrastructure. Therefore, we define *CCAM* as a vehicle's automated and cooperative operations, with or without human control or supervision, where communicating agents support or mandate the vehicle's decision-making process. Such agents could be other vehicles, smart road elements, a high-level orchestrating infrastructure, or pedestrians. CCAM should enable automated and fully orchestrated vehicle maneuvers and new mobility services for passengers and goods, thus supporting safety, reduction of congestion, and sustainability goals (ERTRAC 2020). Also, CCAM should improve operational efficiency at logistics hubs, e.g. by supporting yard planning with anticipatory information (ERTRAC 2020). Thus, this section discusses automation levels, connectivity and cooperation, and the use of CAVs in CCAM.

The Society of Automobile Engineers (SAE 2018) defines six levels of driving automation, which we summarise in Table 2. To achieve a functional classification, they focus on four concepts. First is the Operational Design Domain (ODD), defined as the scope of the automated driving system. Second is the Dynamic Driving Task (DDT), defined as the actions performed by the CAV or the user, e.g. a driver, remote driver, or dispatcher. Third, the Object and Event Detection Response

Table 2. Summary of the SAE levels of automation.

Level	System features[a]	User role within ODD	Example system
0 – No Automation	Warning or safety intervention in limited ODD	(Remote) entire DDT and OEDR	Anti-blocking system, blind-spot warning
1 – Driver Assistance	Sustained lat or lon motion control in limited ODD	(Remote) remainder of DDT, OEDR	Adaptive cruise control (ACC), steering-only parking assist
2 – Partial Automation	Sustained lat and lon motion control in limited ODD	(Remote) remainder of DDT, OEDR	ACC with lane centreing, parking/ traffic jam assist
3 – Conditional Automation	Complete DDT in limited ODD and OEDR	May spend time freely but prepared for (remote) fallback	Highway traffic pilot
4 – High Automation	Complete DDT in limited ODD and automated fallback	Passenger or dispatcher, may perform DDT at OOD limit	City pilot, automated shuttles on tracks, valet parking
5 – Full Automation	Complete DDT in any OOD and automated fallback	Passenger or dispatcher, may perform DDT if requested	Automated taxi, automated and free-ranging vehicle

[a]lat = latitude, lon = longitude

(OEDR) is defined as detecting an obstacle and taking corrective action. Last is the fallback, defined as the safety response after a system failure, an unexpected event, or DDTs out of the ODD.

The ERTRAC (2019) classifies the automated transport of freight in confined areas, hub-to-hub operations, and open roads as level 4 automation, namely high driving automation. To avoid ambiguity, we refer to (i) confined area operations as movements inside the same private logistics yard, (ii) hub-to-hub operations as transport on roads between locations in the same industrial area, e.g. terminals and warehouses at a logistics node, and (iii) open road operations as long-haul transport on highways and corridors. Moreover, the ERTRAC (2019) considers level 4 automation a priority target for the three types of operations to increase transshipment efficiency, load factors, and CO_2 reductions. In the SLN, confined area operations and hub-to-hub operations occur. The latter entails a more complex but also more impactful implementation (ERTRAC 2021) and, thus, is our focus. Also, indirectly the DP can facilitate open road operations, e.g. by matching parked trucks for platooning and providing service areas for repairs and recharging.

For water and rail transport, we have slightly different classifications of automation. The alternative classifications of automated water transport summarised by Bratić et al. (2019) include intermediate levels of remotely controlled vessels, either for normal operations or in case of fallback to human control. Lloyd's Register (2017) produced a fundamental classification for inland (and short-sea) water transport (Daduna 2020), which is the ODD of a logistics node, and features seven levels of autonomy. The levels roughly correspond to the SAE levels with the addition of the aforementioned remote control options. Rail transport automation is best summarised by Lagay and Adell (2018). The authors describe the four automation levels of the International Electrotechnical Commission, from no automation to fully automated and unmanned trains, and three functional layers of automation: train protection, i.e. safety systems for speed control; train operation, i.e. performing the DDT with the support of trackside systems; and train supervision, i.e. operation notification and traffic control by manager-level infrastructure. We refer to Yin et al. (2017) for more information on train trackside automation. Also, we refer to Vagia and Rødseth (2019) for a list of modality-specific taxonomies, e.g. sea ships, small automated guided vehicles, and drones, and to Vagia, Transeth, and Fjerdingen (2016) for a general taxonomy encompassing all modes.

Regarding connectivity and cooperation, Shladover (2018) summarises how connected vehicles interact with external agents or systems in five categories: vehicle-to-vehicle (V2 V), vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2 V), vehicle-to-pedestrian (V2P), and vehicle to anything (V2X). Also, the author lists a range of wireless technologies that support these interactions, e.g. Wi-Fi, 4G and 5G, satellite, and Bluetooth. For an SLN, V2I and I2 V interactions are highly interesting regarding real-time information sharing and fleet routing and scheduling, e.g. when sharing data on traffic conditions or bidding for a transportation job in a (de-)centralised auction. Carreras et al. (2018) present the five levels of road Infrastructure Support for Automated

Driving (ISAD), which support vehicle cooperation. They range from no CAV support (level E) to cooperative driving (level A), where the infrastructure guides CAVs in real-time to optimise traffic flow at bottlenecks. In between, there are static information and map support (level D), dynamic information support (level C), and cooperative perception of the traffic situation (level B). The authors report implementations of ISAD level C and potentially level B on highways in Spain and Austria, with mixed automated and traditional traffic. The testing sites employ cameras, radars, fibre-optic networks, image-processing algorithms for traffic flows, and 3-D simulation tools. Although the ISAD levels were initially designed for extended road networks such as highways and main roads, the ERTRAC (2021) already foresees its use in all areas of transportation to achieve cooperation. From our side, we see clear applicability to logistics nodes. In fact, Carreras et al. (2018) suggest that higher automation support levels will be applied at complex intersections, where traffic awareness and CAV guidance are most useful. Furthermore, the automated driving support could be extended to other modalities for hub-to-hub transport. We further discuss the link between logistics nodes and the ISAD levels in Section 3.1.

CAVs are used to transport goods in many environments, e.g. production plants, warehouses, container terminals, and external transportation systems (Vis 2006). In all these environments, CAVs showed great potential in reducing costs and increasing the flow of goods at container terminals (Liu, Jula, and Ioannou 2002). Also, Aria, Olstam, and Schwietering (2016) studied the effects of CAVs on human drivers and mixed (manned and automated) traffic in road networks. The authors highlight how CAVs outperform conventional vehicles in terms of vehicle density and reduction of travel time, especially for more complex traffic scenarios, e.g. during peak hours. For the sake of simplicity, we use the term CAV to refer to any type of automated, autonomous, or self-driving vehicle for freight transport at SLNs. In fact, based on the definition of Wood et al. (2012), the connection and collaboration between CAVs and other entities at SLNs exclude a completely autonomous behaviour. For freight transport on the road, CAVs could be automated guided vehicles, automated lifting vehicles, or more advanced concepts like the Volvo Vera. Carlo, Vis, and Roodbergen (2014) provide an overview of research trends and challenges for (automated) transport operations at container terminals, which can be generalised to CAVs operations at logistics nodes. Typical challenges of CAVs at logistics nodes are dispatching and routing strategies (e.g. Erdelic and Carić 2019; Grunow, Günther, and Lehmann 2006), fleet selection and dimensioning (e.g. Bae et al. 2011; Vis and Harika 2004), collision and deadlock prevention (e.g. Li et al. 2016; Lombard et al. 2016; Zhou et al. 2017), and planning of battery charging (Schneider, Stenger, and Goeke 2014) or battery swapping (e.g. Hof, Schneider, and Goeke 2017; Yang and Sun 2015). Regarding dispatching, Ichoua, Gendreau, and Potvin (2006) study the impact of dynamic dispatching strategies based on forecasted arrivals, significantly reducing travel times and lateness for harder problems, e.g. when we have fewer resources. Regarding routing, the Inter-terminal Truck Routing Problem (ITTRP, Heilig, Lalla-Ruiz, and Voß 2017b; Tierney, Voß, and Stahlbock 2014) is a variant of the multi-depot pickup and delivery problem with time windows at port areas. It models homogeneous fleets servicing multiple logistics companies at ports, i.e. a shared manned or CAV fleet servicing terminals, and it may be extended to include the previous challenges. Moreover, Heilig and Voß (2017b) suggest studying the ITTRP to transport networks other than ports to further investigate fleet management in logistics stakeholders' coalitions with real-time information exchange. A final topic of interest is CAV relocation (or rebalancing) and dwell point strategy. However, to the best of our knowledge, most research in this field focuses on shared mobility services for urban logistics (e.g. Fagnant and Kockelman 2014; Huang, Correia, and An 2018) and warehousing (e.g. Roy et al. 2015; Ventura and Lee 2003) without considering logistics nodes.

2.2.2. CAT-related technologies for logistics

Next to CAVs, many CAT-related technologies are being developed for logistics. Most relevant are those relying on Blockchain and PI concepts such as the PI container and IoT technology, e.g. vehicle and cargo monitoring, smart packaging and labelling, smart traffic lights, and infrastructure.

We refer to Song et al. (2021) and Avatefipour and Sadry (2018) for an overview of IoT technology in logistics and traffic management.

A Blockchain is a series of connected information blocks, composing an electronic ledger distributed and maintained by the entire system (Zheng et al. 2018). Although popularised by Bitcoin and highly relevant for the financial sector (Nofer et al. 2017), Blockchain is seen as increasingly suitable for digital supply chains (Cheung, Bell, and Bhattacharjya 2021; Kuhi, Kaare, and Koppel 2018; Sobb, Turnbull, and Moustafa 2020; Toy 2020). For example, it enables smart contracts for non-monetary transactions, e.g. for validating product flow and thus increasing traceability (Sobb, Turnbull, and Moustafa 2020). Furthermore, it could remove organisational PI barriers such as fast, trustworthy exchange of sensitive data and creating a robust, secure network (Meyer, Kuhn, and Hartmann 2019). The SmartLog project studied Blockchain in Baltic supply chains, showing significant interest from the logistics sector and a potential reduction in lead times (Pilvik, Kaare, and Koppel 2021). However, Pilvik, Kaare, and Koppel (2021) noticed a low level of digitalisation, technical know-how, and standardisation in logistics, which hinders the adoption of Blockchain solutions in the short term. We refer to Imeri, Khadraoui, and Agoulmine (2019) for a survey of Blockchain projects in supply chains and to the Port of Shanghai's Blockchain platform (SIPG 2020) for a more recent, large-scale example.

The aim of a PI-based logistics system is to enhance interoperability via encapsulation, interfaces, and protocols. An example of physical encapsulation and the use of interfaces is the PI container. Montreuil, Meller, and Ballot (2010) define PI containers as unit loads with varying modular dimensions that can be combined and disassembled to move through and be stored in PI infrastructures. Moreover, the PI container has an information part analogous to the header in the digital internet's packets. This header includes, among others, a unique worldwide identifier, a client identifier, a logistician identifier, container dimensions, and data on the container content. The goal of the PI container is (i) to encapsulate its contents to make them irrelevant to the PI system and (ii) to transport them as efficiently and environmentally friendly as possible through modularisation and standardisation of interfaces. Sallez et al. (2016) add product activeness to the capabilities of PI containers: the capacity of PI containers to schedule reports, trigger events, and make decisions. Examples of product activeness are data collection through its own sensors, self-triggered requests to partners, defining or adapting goals, negotiating with handling devices and routing software, and learning from experience. As an example of negotiation and learning, van Heeswijk (2020) describes smart containers with bidding capabilities for auctioning transport services and cooperative learning for improving bidding policies.

Other CAT-related technologies at logistics nodes include tracking and tracing, geofencing, and digital platforms or ecosystems. On a product level, tracking and tracing technology (Shamsuzzoha and Helo 2011) is widely used and allows customers and shippers to know past and current locations of goods and receive notifications on arrival and departure times. Moreover, Shamsuzzoha et al. (2013) see tracking and tracing as fundamental for customer satisfaction and collaboration through the supply chain. This collaboration can be further enhanced by integrating tracking and tracing with Blockchain technology, thus supporting decentralisation, scalability, and information security (Helo and Shamsuzzoha 2020). On a spatial level, geofencing technology allows the creation of virtual fences to remotely monitor tracked entities entering or exiting an area (Reclus and Drouard 2009), e.g. a logistics node. On a network level, digital platforms or ecosystems (McIntyre and Srinivasan 2017) are relevant enablers of collaboration and data sharing inside and outside logistics areas, primarily to support multimodal transport (Ding 2020). Simple multi-sided digital platforms are already used to auction freight transport between shippers and carriers. Advanced cloud-based, real-time platforms are being developed, with adaptive planning features for the auction of freight transport, to achieve quicker decision loops and shorter processing times of large trading volumes (Helo and Shamsuzzoha 2020; Kong et al. 2015). Srour et al. (2008) list various advanced platforms integrated into Port Community Systems, which are a type of digital ecosystem, among which are Dakosy for the Port of Hamburg, Portbase for the Port of Rotterdam and the Port of Amsterdam, Portnet for the Port of Singapore, and OnePort for the Port of Hong Kong. Furthermore, these platforms could be enhanced to become a Digital Twin (Grieves and Vickers 2016; Jones et al. 2020) for logistics operations (e.g. Hofmann and Branding 2019; Pan et al. 2021). Specifically, Hofmann and Branding (2019) implement an IoT- and cloud-based digital twin to provide real-time support for truck dispatching at port areas, using performance forecasts based on the system status. The authors suggest a GAS and a parking area as potential extensions for their Digital Twin. Cloud ecosystems, digital twins, and their extension to cyber-physical systems (Alam and El Saddik 2017) promise operational benefits but pose important cybersecurity concerns. Although relevant, these concerns are out of the scope of this paper; we refer to Sobb, Turnbull, and Moustafa (2020) and Cheung, Bell, and Bhattacharjya (2021) for an overview on cybersecurity in logistics and supply chains, and to Gupta et al. (2020) and Senarak (2021) for new approaches to CAV security by Blockchain and port cybersecurity, respectively.

Based on the discussed literature on logistics nodes and CAT, we highlight several research gaps:

- Sections 2.1 and 2.2 presented various new smart logistics concepts and technologies for logistics areas, mostly arising directly from practice and being documented ex-post in the scientific literature. However, we find no holistic classifications of smartness (as defined by Alter 2020) and technological capabilities at logistics nodes. As a result, the discussion on applications of smart logistics concepts at logistics nodes is currently fragmented and ambiguous.
- Research on ownership, sharing, and collaboration models at logistics nodes is lacking, as summarised in Table 1. Therefore, implementation projects of CAT concepts often fail or require prohibitive costs for individual logistics players.
- The economic value of CAT at logistics nodes needs further analysis to convince all stakeholders to adopt the technology (Heilig, Lalla-Ruiz, and Voß 2017a), especially regarding shared fleets of CAVs and hub-to-hub transport planning with real-time information; for example, with smart, active containers (Sallez et al. 2016). In addition, the quick adoption of CAVs in confined areas and hub-to-hub transport is also supported by the ERTRAC (2019). Therefore, we find that the goals of both practitioners and researchers are aligned in quantifying the economic value of CAT.
- Most research on shared fleets at logistics nodes focuses on terminals and makes simplifying assumptions regarding information availability and technical interoperability (see He et al. 2013; Li, Udding, and Pogromsky 2015). However, these studies do not accurately represent the value of CAT at logistics nodes, nor are they helpful in solving the challenges encountered in designing new logistics processes employing CAT. Therefore, there is a need for studies on shared fleets servicing many heterogeneous partners and adding realistic details on interoperability.
- Studies at logistics nodes other than ports and with real-time planning are lacking for the hub-to-hub transport of freight. Therefore, they are particularly interesting for future research (Heilig, Lalla-Ruiz, and Voß 2017b). Moreover, in the same field, we notice that the analyses of cooperation with non-monetary incentives and freight vehicle relocation are lacking.

Following the highlighted research gaps, we provide a definition of the Smart Logistics Node and a classification of its possible variants in the next section, considering different CAT technologies, organisational approaches, and scope. This provides an answer to the first research gap and supports future studies on the remaining ones.

3. Smart logistics nodes

This section introduces the general concept of Smart Logistics Nodes (SLNs) and the classification of SLNs.

As discussed in Section 2.1, we use the term *logistics node* to refer to a medium to large, semi-public, multimodal hub that connects international freight flows to a large regional network and provides value-adding services and technologies that are shared between its partners at the node. Additionally, logistics nodes comprise various stakeholders, transport modalities, terminals, and warehouses for transshipment operations and value-adding services. We use the term logistics company (LC) to refer to any terminal, warehouse, cross-docking centre, or area for consolidating goods by freight forwarders. The number and type of stakeholders being part of an SLN differs. Typically, an SLN would have dozens to hundreds of LCs (including one to several terminals), a logistics node authority, a customs authority, manufacturing and chemical companies, financial and insurance agencies, and any other agent usually present at a large hub.

To be considered *smart*, a logistics node must collect, process, interpret, and share data among its stakeholders to improve and automate operations. Such technical capabilities include hub-to-hub CAV dispatching, lookahead planning under uncertainty, and freight matchmaking. Also, an SLN preferably features predictive, learning, and self-configuring capabilities concerning operations planning and disruptions. This definition of smartness for SLNs is based on the definition of smart devices and smart systems by Alter (2020), who extensively defines devices, sociotechnical systems, and fully automated systems. An SLN is a sociotechnical system ranging from no automation, at its basic level, to full automation in its most advanced version. We adapted the definition of Alter (2020) by adding the sharing aspect, which is fundamental for the collaboration of stakeholders and systems at an SLN. Moreover, we scoped the predictive, learning, and self-configuring capabilities to plan operations and handle disruptions. The main type of information used and shared in an SLN is related to logistics operations, e.g. the arrival time of modalities, the expected (un-)loading time at LCs, and congestion levels. To fully use its data-collection and planning capabilities, an SLN shares such data and relevant planning information between actors inside the node and, to a certain extent, over the supply chain. The overarching SLN's IT system should include all entities that affect the flow of goods. Moreover, an SLN should support these entities via digital platforms to allow for the planning of operations and the efficient use of pooled resources.

Next, an SLN might feature beneficial (smart) infrastructures and CAT technologies. Figure 1 depicts a general SLN, including LCs, modalities, CAVs, a Decoupling Point (DP), and information-sharing capabilities. These (smart) infrastructures and CAT technologies support the SLN's goal of seamless and automated operations. Let us focus on two prominent examples of (smart) infrastructure and CAT: the DP, i.e. a truck parking with services for drivers and containers, and the CAVs. Other applicable and beneficial technologies for an SLN were already discussed in Section 2.2.

Regarding the DP, it could be used by an SLN to separate long-haul transport from hub-to-hub transport, allowing for better control of the internal freight flows. Here, inbound road modalities can park and detach their trailer or chassis with a container to be picked up by internal vehicles. The DP facilitates the implementation of a GAS and removes larger, heavy-duty trucks from the busy and smaller internal roads. Furthermore, additional services might be present at the DP, such as a rest area with tank or container cleaning stations, plugs for reefer containers, showers and restoration areas for drivers, container repairs, or even custom activities to avoid bottlenecks at the (un-)loading warehouses. A rest area could improve the willingness of drivers to accept transport requests to and from a certain SLN.

Regarding CAVs, an SLN could employ a shared CAV fleet to handle internal freight transport. Specifically, an SLN uses CAVs whose main task is hub-to-hub operations, which may also operate in confined areas. Examples of such operations are the inter-terminal transport of containers with either the hand-over to a terminal's (automated) yard tractor or the direct (un-)loading at a container stack or quay crane. Furthermore, the notion of CAVs could be extended to other modalities such as drones, autonomous surface vessels (Devaraju, Chen, and Negenborn 2018), autonomous shunting locomotives (Krämer 2019), or smart freight wagons (Gattuso et al. 2017). Among these, water CAVs are only applicable to hub-to-hub transport, whereas drones and rail CAVs apply both

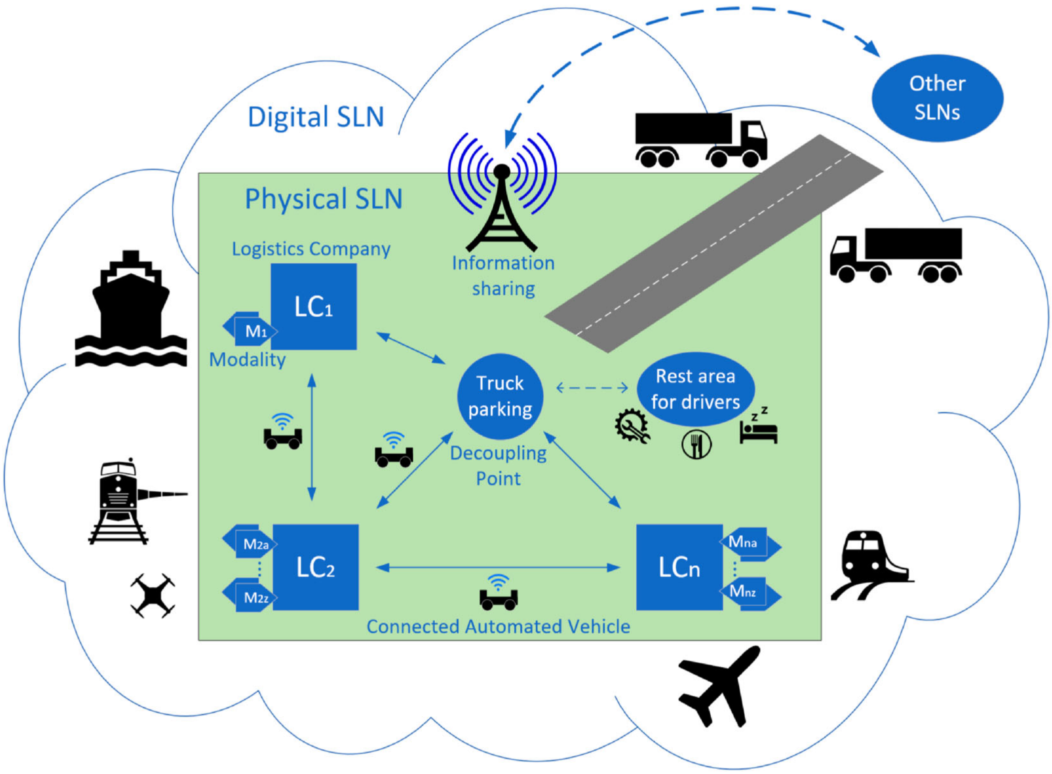

Figure 1. General representation of the smart logistics node.

to hub-to-hub and confined area operations, although with apparent differences in transport units: parcels and pallet-like loads for the first, containers and other freight wagons for the second. Automated hub-to-hub transport, supported by data and the separation of internal and external flows, can reduce congestion at the node, improve sustainability, increase safety, and allow for higher utilisation of resources by continuous operations.

Now that the general concept of SLNs has been defined, Section 3.1 further describes the physical, digital, and CAT elements of the SLN. Then, Section 3.2 presents our classification. There, we explain how our classification is rooted in the scientific literature and describe our adaptations and additions to existing works. Ultimately, our classification links traditional business functions and organisational structures at logistics nodes to emerging technologies and collaboration approaches.

3.1. Physical, digital, and technological aspects of the SLN

As shown in Figure 1, we distinguish between the digital and physical levels of an SLN. The digital SLN can be seen as a cloud platform to store and share information and optimise logistics flows. On the other hand, the digital level is similar to the intelligent transportation system described by Heilig, Negenborn, and Voß (2015) and the cloud-based platform implemented by Heilig, Lalla-Ruiz, and Voß (2017b). This cloud platform can be extended to become a complete digital ecosystem, i.e. an SLN community system. Moreover, a Blockchain could connect all incoming modalities, upstream locations in the supply chain, and freight destinations to the digital SLN through secure and fast technologies. The digital level of an SLN could include functionalities of cyber-physical systems, effectively creating a digital twin of the physical operations (Alam and El Saddik 2017). For example, after obtaining awareness of the state of the connected transport modalities and the LCs – effectively forming a cyber-physical system – an integrated simulation and analysis of future scenarios could be achieved (a digital twin). The goal would be self-configuration, optimisation, and more robust logistics operations planning. Different CAV dispatching and routing algorithms could be used by the SLN system based on the current congestion levels and forecasts, e.g. see Ichoua, Gendreau, and Potvin (2006). This planning process can be enhanced or directed through communication with smart or PI containers to obtain real-time, accurate data on the location, freight status, and operational constraints, e.g. an updated due date. Also, transport operations, e.g. the loading and unloading of containers, could be rescheduled after notification of a late shipment.

The physical level of an SLN can be identified with the node stakeholders, the internal transport vehicles, and the infrastructure at the node. Depending on its layout and scope, the SLN area can be open or (semi-)confined, which means controlling vehicles entering the system is harder or easier. For example, a freight village could control access to most of its roads, while a large seaport will have many open roads where private vehicles are mixed with yard tractors that transfer goods between terminals and the surrounding LCs. A confined SLN would ease the separation of manned and automated traffic, thereby increasing safety and easing CAVs implementation. However, a complete separation of the two traffic flows is often unrealistic. Nevertheless, using a DP to separate incoming road modalities could reduce the number of manned vehicles in the SLN. Therefore, we focus on hub-to-hub transport and first- and last-mile drayage operations at the SLN. These operations include the incoming and outgoing long-haul transport flows, the transport of freight between LCs, and the transport between the LCs and the DP. The operations within the LCs at the SLN are only implicitly considered in this paper, as terminal operations and consolidation of goods have already been extensively analysed, both for manned operations and with automated equipment, e.g. with automated quay cranes (de Koster, Le-Duc, and Roodbergen 2007; Steenken, Voß, and Stahlbock 2004).

Based on the discussion above, Figure 2 shows all the elements of an SLN, separated into three categories and eight subcategories. The three categories are the physical and digital levels of the SLN and the CAT technologies. The latter category has transformative and enabling relationships with either the physical or digital level, represented by dashed lines. The three subcategories of the physical level are the stakeholders, the freight flows, and the decoupling point. For the digital level, the three subcategories are information sharing, data collection, and fleet management services. For CAT, the two subcategories are automation and connectivity. Nonetheless, although desirable, most elements and subcategories are not strictly necessary to obtain a basic SLN. The fundamental elements and subcategories of the SLN at the physical level are the stakeholders and freight flows, with vertical or horizontal collaboration. The fundamental elements at the digital level are the digital platforms or ecosystems, at least a few data collection options, and basic transport planning capabilities. Regarding CAT, the fundamental elements all relate to technologies supporting connectivity. Therefore, CAVs and ISAD are not required for a basic SLN. As technologies and equipment for logistics are constantly under development, this will inevitably lead to extensions of the elements and subcategories in Figure 2.

Before moving to the SLN classification, we clarify the relationship between logistics centres, logistics nodes, and SLNs. Here, we use summarised definitions to compare the three concepts. First, a logistics centre is the most general concept among the three. We previously defined it in Section 2.1 as an area where various operators perform all kinds of logistics activities with a commercial scope. This definition does not exclude activities related to the flow of information, which are a crucial element of an SLN, yet it focuses on physical freight flows. Therefore, logistics nodes and SLNs can be considered subsets of logistics centres. Second, we defined a logistic node as a major and multimodal hub that is a gateway to regional freight networks and provides multiple services to its stakeholders. This definition specifies the characteristics that logistics centres must exhibit to be considered nodes: to be relevant hubs in larger distribution networks, with a minimum set of value-adding services and information-sharing technologies. Once more, the focus is on the physical freight flows, with collaboration only partially dependent on technology. Last, we defined an SLN as a logistics node that processes and shares data among its stakeholders to improve operations. Moreover, an SLN may feature automated fleets for inter-terminal transport and

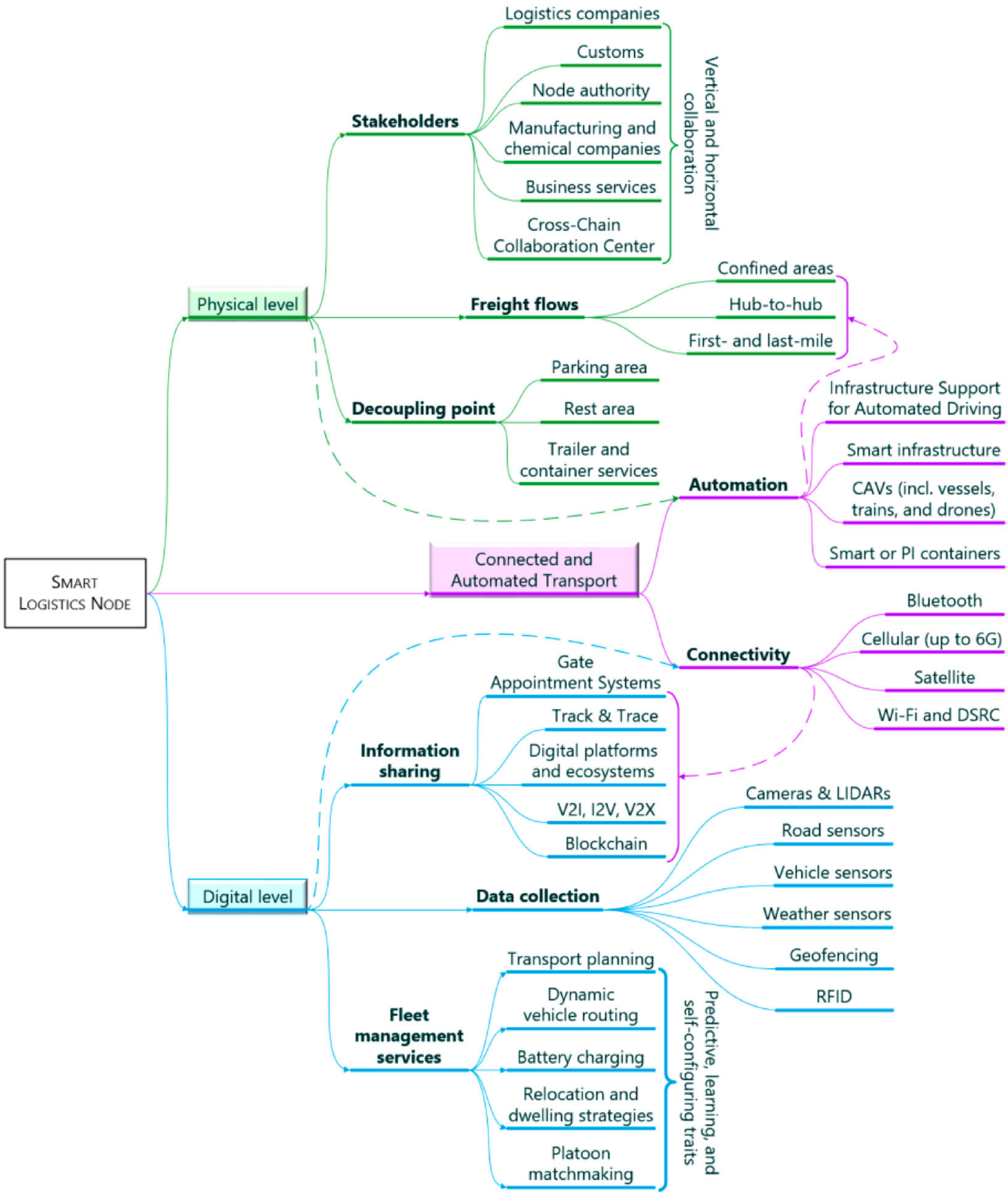

Figure 2. Physical, digital, and CAT elements of a smart logistics node.

supporting infrastructure. Hence, an SLN is basically a smart and technologically upgraded logistics node with capabilities such as advanced operations planning, matchmaking freight platforms, and possibly CAVs. As a subset of logistics centres, the SLN focuses on the flow of information and automation to increase efficiency and respond to uncertainty, e.g. disruptions.

3.2. SLN classification

An SLN is a multi-disciplinary concept encompassing a variety of aspects. Therefore, to create the SLN classification, we considered elements from the classification of logistics centres by Notteboom et al. (2017), from the taxonomy of Port Community Systems by Moros-Daza, Amaya-Mier, and Paternina-Arboleda (2020), from the coordination approaches for automated vehicles by Mariani, Cabri, and Zambonelli (2021), and the ISAD levels by Carreras et al. (2018). These categorizations are informative but either limited in scope or applied to specific research fields, e.g. automated driving on highways. Hence, we merge the categorizations, expand their scope, and add new dimensions. Ultimately, we obtain new, technologically updated categories for logistics and smart logistics nodes. Using these updated categories, we classify logistics functions and plot a potential evolution of the nodes' technological and coordination capabilities.

From Notteboom et al. (2017), we adapt the division between functions and dimensions of logistics centres. The authors indicate that the primary function of a logistics centre is either to provide (i) value-adding services and manufacturing operations, (ii) transloading of freight and rapid transit, or (iii) storage and warehousing. Due to the size of an SLN and the importance of transshipment operations at logistics nodes, e.g. the movement of containers without transloading their contents, we modify the second function to 'transloading, transshipment, and rapid freight transit'. Moreover, we consider the storage and warehousing function implicitly satisfied, thus dropping it from our classification. Also, the function of a logistics node overlaps with the business scope and processes described by Moros-Daza, Amaya-Mier, and Paternina-Arboleda (2020). The authors chose several dimensions: size, geographic market coverage, position in supply chains, strategy, organisation, technology, and governance settings. While most of these dimensions are already fixed by our definition of a logistics node, we differentiate SLNs based on the organisation and technology dimensions, plus the integration and governance designs further specified by Moros-Daza, Amaya-Mier, and Paternina-Arboleda (2020). Therefore, we express the organisation and technology of the SLN using the dichotomy centralised vs. decentralised, as (de-)centralised organisational interdependency and (de-)centralised governance models for IT systems.

To further specify the degree of (de-)centralisation, we combine elements from the classification of coordination approaches from Mariani, Cabri, and Zambonelli (2021): centralised, negotiation, agreement, and emergent. Each coordination approach requires specific negotiation protocols, e.g. a central coordinator, auctions, argumentation, and collaboration emerging from game theory. The four coordination approaches are originally meant for automated vehicles on the road, supported by communicating infrastructure. Similarly, our LCs and, in general, our SLN stakeholders are agents of a physical and digital system, cooperating through connected IT systems and possibly sharing the same CAV fleet for hub-to-hub transport. Therefore, these stakeholders are affected by each other's decisions, also resulting in coordination approaches and protocols. Nevertheless, each stakeholder retains its autonomy. Therefore, once the coordinated decision is made, each agent of the coordinated system is allowed operational freedom to best adhere to that decision (Mariani, Cabri, and Zambonelli 2021). Since an SLN is a system of independent stakeholders, i.e. a human organisation, opposing the coordinated decision is possible. However, the authority of an SLN could disincentivize this behaviour, e.g. via monetary incentives or profit-sharing mechanisms.

In Figure 3, we use the SLN function and the organisation approach as y and x axes, respectively, thus dividing the y-axis between freight transport and value-adding operations and the x-axis between a centralised and decentralised organisational structure. The x-axis is further divided into four coordination approaches. Hence, we distinguish four general classes of SLNs: the integrated freight flow, the integrated services, the freight flow agents, and the service agents. Obviously, a real SLN may have diverse functions and a hybrid organisation structure leading to in-between solutions, as is often the case in practice. Therefore, the four classes are defined as follows:

- **Integrated freight flows**: an SLN where freight throughput is maximised by central coordination through the digital ecosystem; however, the plans of an individual LC may have to adapt to the overall SLN plan, e.g. considering penalties and incentives by the SLN authority.

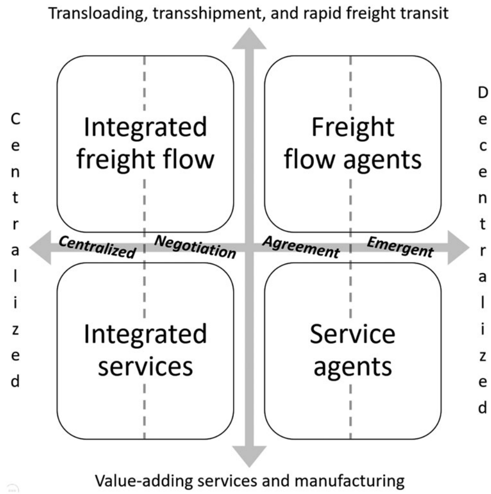

Figure 3. The four general SLN classes.

- **Integrated services**: an SLN where complex value-adding services and manufacturing operations can be performed by transporting a unit of freight to multiple manufacturing companies. Ultimately, the IT integration between manufacturing companies turns the SLN into a cross-company job shop. Also, the portfolio of services is tailored to the overall goals of the node.
- **Freight flow agents**: an SLN where the freight throughput is optimised by continuous, self-initiated interactions between LCs, transport modalities, and the rest of the supply chain, using matchmaking platforms and self-organising algorithms.
- **Service agents**: an SLN where a wide variety of services are offered and where multiple digital platforms are developed by different (groups of) stakeholders. These platforms form a marketplace for actors from multiple supply chains, who bid on value-adding services and manufacturing operations at the nodes.

Considering Carreras et al. (2018), we transpose the infrastructure support levels for automated driving to the SLN and combine them with the degree of digital integration at the node, i.e. how information is shared. Automated driving support refers to any level of vehicle automation, including both completely driverless CAVs and manned CAVs with limited automated tasks, as described in Section 2.2 and SAE (2018). We further translate the ISAD levels to logistics nodes: a conventional logistics node without CAV support would be level E; a logistics node with CAVs and fixed guidance (e.g. embedded wires and local regulatory information at confined areas) would be providing a static route and environmental information, thus level D; free-range guidance of CAVs with dynamic information would be level C; lastly, level B and A are directly transferable to logistics nodes with cooperative traffic awareness and cooperative driving, respectively. An SLN might not desire level A capabilities and implement up to level B, for example, at nodes with little mixed traffic and congestion. That is because infrastructure guidance has the largest benefits in traffic environments where the CAVs' self-decision-making process would be suboptimal, e.g. in heavily congested and mixed-traffic areas. In a decentralised system of smart agents, the CAVs would be learning how to optimally maneuver through traffic to reach their destination, following the most effective route from the perspective of the individual CAV. Unless the environment is heavily congested and with multiple operational restrictions, e.g. safety rules in mixed traffic areas, the CAVs could outperform the centralised guidance or perform similarly but with a lower computational burden on the system. Moreover, other tasks would be absorbing computational resources, e.g. the fleet management services for freight matchmaking and battery charging, thus discouraging computationally heavy tasks such as microscopic traffic management.

Regarding IT integration, we simplify the spectrum of solutions to three levels: silos software, digital platforms, and digital ecosystem. First, with silos software, each LC at the SLN has its own IT system with limited communication capabilities; planning is mostly based on the LC's information and forecasts, and transport modalities interact exclusively with their LC of arrival. Second, digital platforms allow multiple players to communicate simultaneously and share functional data to plan and bid on logistics tasks. Multiple platforms may coexist without any connection, offering different services but potentially hindering operations planners with unnecessary complexity and a lack of standardisation. Third, multiple platforms are integrated into a digital ecosystem offering cross-service transfer of information. Planners will benefit from powerful, integrated tools but may occasionally rely on external IT platforms due to a limited IT portfolio of the digital ecosystem, e.g. because of services that are hard to integrate or of interest to a limited number of LCs.

We combine the adapted ISAD levels and the simplified spectrum of digital integration in Figure 4 to show possible configurations of SLNs. A general evolution path for SLNs is drawn from no automated driving support and silos software up to complete cooperative driving and integrated digital ecosystems over the whole SLN. We expect SLNs with higher ISAD levels to be more interconnected on the digital level to fully reap the benefits of dynamic information sharing, collective (cooperative) perception via CAVs' sensors, and cooperative driving. Looking back at the organisational approaches in Figure 3, we want to clarify that the coordination approach denotes the decision-making process, not the digital environment connecting the agents (Mariani, Cabri, and Zambonelli 2021). Therefore, a centralised SLN may prefer any digital integration level as long as sufficient information is relayed to the central decision-maker. Still, this may lead to centralised SLNs preferring a digital ecosystem as this allows for seamless information sharing and better use of advanced ISAD. Ultimately, practical applications of the SLN concept depend on the characteristics of individual nodes and may require different combinations of digital integration and ISAD levels, deviating from our general development path. Examples of such SLN configurations are described in the next section.

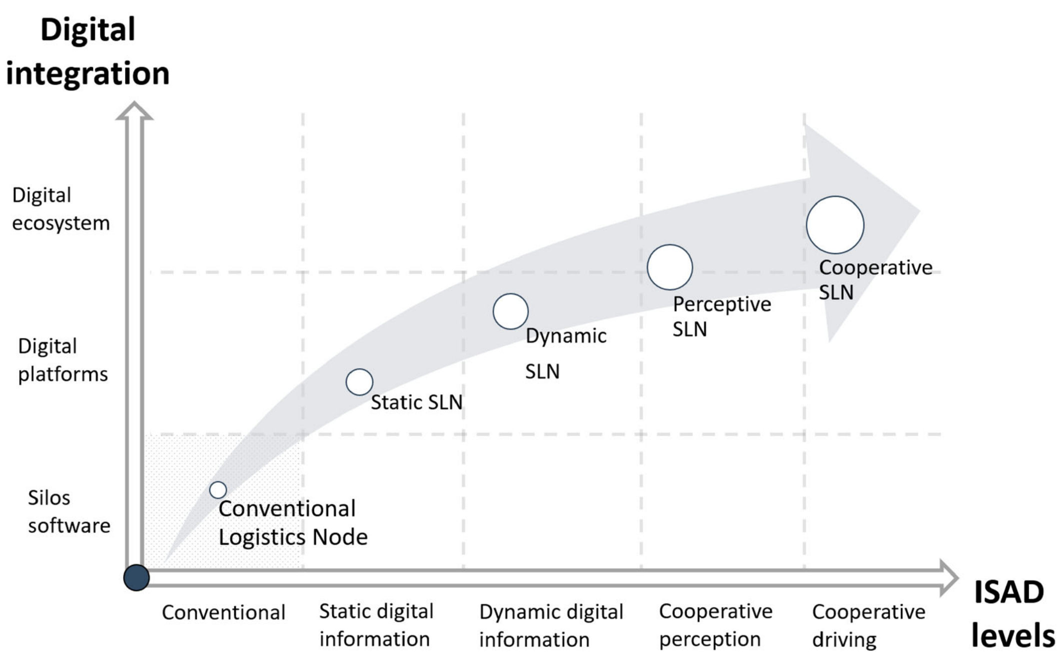

Figure 4. Digital and automation support capabilities of the SLN with a proposed path of evolving technological configurations.

4. Classifying existing logistics nodes

Here, we show various forms of SLNs from practice regarding their class, objectives, and digital and automation capabilities. Then, we apply our classification from Section 3 at two levels of detail: general and in-depth. The two levels of classification detail relate to the amount of information available on the logistics nodes. Information on the logistics nodes was collected through each node's official websites, reports, media, and press releases, and from direct conversations with representatives of the nodes in the CATALYST (Connected Automated Transport And Logistics Yielding SustainabiliTy) consortium. The CATALYST project is funded by the Dutch government and a consortium of research and logistics partners in the Netherlands, e.g. universities, port areas, and legislators.

The four logistics nodes from the CATALYST consortium are Port of Moerdijk (PoM), Port of Vlissingen East (PoV), Amsterdam Airport Schiphol (AAS), and XL Business Park Almelo (XL-A), all located in the Netherlands. These logistics nodes have common interests in the potential benefits of the SLN concept. These interests include congestion reduction, round-the-clock handling by CAVs, and improved planning through the smart use of data. Additionally, each logistics node has a different focus: (i) PoM aims to evaluate the buffering and decoupling effect of a DP, thus using smaller vehicles for hub-to-hub transport, (ii) PoV aims to increase road safety and become a preferable transit location for truck drivers, e.g. by offering extra services at the DP, (iii) AAS aims to reduce congestion and the impact of operational disruptions, as well as to create tighter, robust schedules, thanks to improved real-time information sharing between all logistics actors, and (iv) XL-A aims to be an innovation hotspot for logistics and to be an early adopter of CAVs for hub-to-hub operations. The remaining twelve nodes are: Port of Rotterdam (PoR), Port of Hamburg (PoH), Port of Antwerp (PoA), Port of Singapore (PoSi), Port of Shanghai (PoSh), Port of Busan (PoB), Port of Long Beach (PoLB), Freight Village of Bremen (GVZ-B), Freight Village Vorsino (FVV), Tahoe Reno Industrial Center (TRIC), TGS Cedar Port (CP), and Interporto Quadrante Europa of Verona (IQE-V), an intermodal logistics centre.

The characteristics and goals of the sixteen logistics nodes are summarised in Table 3. Ten logistics nodes are port areas, with nine seaports and one airport. The other six are freight distribution clusters, including freight villages and intermodal, industrial, and logistics parks. In the table, size values are related to the land hectares (ha) of the node: small is up to 50 ha, medium is up to 250 ha, large is up to 1000 ha, extra-large is up to 5000 ha, and extra-extra-large for anything over 5000 ha. Note that we chose land ha for size ranking because freight distribution clusters usually neglect other size measures, e.g. yearly tonnage or container traffic. In addition, note that in our size ranking, 'small' refers to the relative scale of SLNs, which are by definition medium- to large-scale hubs. In other words, a 50 ha distribution centre may be a small SLN but is by no means a small logistics centre (hub). For the SLN classes, all nodes have a general class, i.e. integrated freight flow (IFF), freight flow agents (FFA), integrated services (IS), and service agents (SA), while the four CATALYST's nodes also feature the coordination approach, i.e. centralised (C), negotiation (N), agreement (A), emergent (E). Also, the SLN class column includes the type of automated driving support: conventional SLN (Cn-SLN), static (S-SLN), dynamic (D-SLN), perceptive (P-SLN), and Cooperative SLN (Cp-SLN). Last, for brevity, the phrase 'freight flow' is used instead of 'transloading, transshipment, and rapid freight transit' when referring to the main function of a logistics node.

Now that the sixteen logistics nodes have been introduced, we provide a general classification of the logistics nodes in Section 4.1. The nodes were chosen for their relevance in international logistics networks and the literature (e.g. from Molavi, Lim, and Race 2020) and for their node type, size, and general goals. Then, in Section 4.2., we classify the four logistics nodes that are part of the CATALYST project consortium in greater detail, i.e. the in-depth classification, to assess their current SLN elements from Figure 2 and specific goals.

Table 3. Summary of the sixteen logistics nodes.

Node	Type	Modalities[a]	Size	Main function	SLN class[b]	Technologies	Goals
PoM	Industrial seaport	Barge, ship, train, truck	XL	Freight flow, manufacturing	IFF-N, Cn-SLN	Digital ecosystem, Simple transport planning	Avoid infrastructural congestion, evaluate DP, CAVs, and GAS
PoV	Seaport	Barge, ship, train, truck	L	Freight flow, value-adding services	FFA-A, Cn-SLN	Digital ecosystem, transport planning	Competitive advantage, solving workforce shortage, safety, preferred transit location, 5G teleoperations
AAS	Airport	Plane, train, truck	XL	Freight flow	FFA-C, S-SLN	Digital ecosystem, transport planning, static ISAD	Reduction of planning disruptions, reduction of road congestion, tighter and more robust schedules, at least level B ISAD, and the implementation of drones for freight inspection and passenger transport
XL-A	Intermodal business park	Barge, truck	M	Freight flow	IS-N, Cn-SLN	Silos software	Competitive advantage, future-proof, CAVs- and PI-ready
PoR	Seaport	Barge, ship, train, truck,	XXL	Freight flow, value-adding services	FFA, D-SLN	Digital ecosystem, CAVs on dedicated lanes for hub-to-hub transport, GAS, inspection drones, transport planning	Becoming the 'smartest port', future-proof infrastructure and advanced IT and connectivity, IoT, automated vehicles, vessels, and freight drones
PoH	Seaport	Barge, ship, train, truck	XXL	Freight flow	IFF, S-SLN	Digital ecosystem, CAVs in a confined area, inspection drones	Smart infrastructure and traffic flow, electrification, hyperloop train, and freight drones
PoSi	Seaport	Barge, ship, train, truck	XXL	Freight flow	FFA, Cn-SLN	Digital ecosystem, AI for container handling at terminals	Efficiency, crew satisfaction, cellular and Wi-Fi technologies, mobile apps, highly automated and digital port enterprises, IoT
PoSh	Seaport	Barge, ship, train, truck	XXL	Freight flow	FFA, S-SLN	Digital ecosystem, CAVs in confined area, AI, Blockchain	Maintain a leading position as port, strengthen transshipment, modal shift, and inland transport, achieve a port service platform, automation of all terminals
PoA	Seaport	Barge, ship, train, truck	XXL	Freight flow, value-adding services	FFA, Cn-SLN	Digital ecosystem, freight drones, transport planning	Implementation of automated inland shipping, artificial intelligence, Digital Twin, smart asphalt, 5G network, and teleoperations.
PoB	Seaport	Barge, ship, train, truck	XXL	Freight flow	FFA, Cn-SLN	Digital ecosystem, transport planning, Digital Twin	Productivity and efficiency of operations, addition of a business park for value-adding logistics services and freight distribution
PoLB	Seaport	Barge, ship, train, truck,	XL	Freight flow	FFA, S-SLN	Digital ecosystem, CAVs in confined area, freight forecasts	Future-proof infrastructure, seamless supply chains
GVZ-B	Freight village	Barge, plane train, truck	L	Freight flow, value-adding services	FFA, Cn-SLN	Silos software	Autonomous driving in confined areas, electrification, digitalisation
FVV	Freight village	Train, truck	L	Freight flow and manufacturing	IFF, C-SLN	Digital platform, GAS	Dynamic routing with AI, Digital Twin of warehouses, increase infrastructure's capacity

(*Continued*)

Table 3. Continued.

Node	Type	Modalities[a]	Size	Main function	SLN class[b]	Technologies	Goals
TRIC	Intermodal industrial park	Plane, train, truck	XXL	Value-adding services and manufacturing	IS, Cn-SLN	Silos software	Expansion of infrastructure and companies
CP	Port industrial park	Barge, train, truck	XL	Freight flow, value-adding services, and manufacturing	IFF, Cn-SLN	Silos software	DP for rail, new value-adding logistics, and warehousing
IQE	Intermodal logistics park	Plane, train, truck	L	Freight flow, value-adding services	FFA, Cn-SLN	Wired network connecting silos software	Smart parking areas with GAS, increase modal shift, real-time traffic system for road and rail, expand infrastructure

[a]Excluding pipelines; [b]IFF = Integrated freight flow, IS = Integrated services, FFA = Freight flow agents, SA = Service agents; C= Centralized, N = Negotiation, A = Agreement, E = Emergent; Cn = Conventional, S = Static, D = Dynamic, *P* = Perceptive, C*p* = Cooperative

4.1. General classification

Following our SLN classification from Section 3.2, we visualise the data from Table 3 using the general division into four SLN classes of Figure 3 and the assessment of technological capabilities of Figure 4. From Figure 3, the four SLN classes, we position the sixteen logistics node based on their function and organisation approach, obtaining Figure 5. Next, from Figure 4, the nodes' digital and automation support capabilities, we position the nodes based on the digital integration degree and the ISAD levels, obtaining Figure 6. In both Figure 5 and Figure 6, the size of the circles indicates the size of the SLNs in our sample, which ranges from medium, e.g. XL-A, to extra-extra-large, e.g. PoR.

From Figure 5, we make three observations. First, the vast majority of logistics nodes focus on rapid freight transport. This is likely partially the result of our search for logistics nodes that are important hubs for international and regional freight networks. Another cause is that large logistics areas, such as logistics nodes, would focus on the inevitably complex freight flows rather than developing manufacturing operations and value-adding services. Even more so for seaports, which constitute most of our sample, since manufacturing industries are land-intensive, and land is a scarce

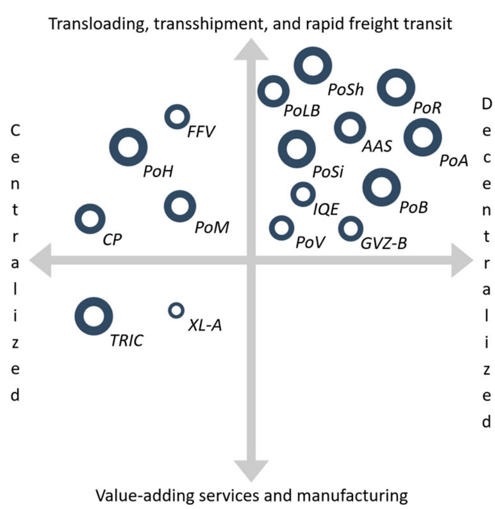

Figure 5. Function and organisation of the logistics nodes.

and costly resource at ports. Second, logistics nodes are spread over the whole x-axis, showing that any centralised and decentralised SLN approach could be effective. Moreover, we see that extensive port areas are mainly on the decentralised area of the chart, probably due to the complexity of managing a large set of stakeholders. In this regard, we also mention that PoH, the only centralised XXL node, is the smallest of the XXL nodes in our sample, closer to the XL boundary. Third, we lack examples of decentralised SLNs focusing on value-adding services, i.e. the service agent class. Again, this may be due to our selection criteria of logistics nodes, leading to the size-function bias mentioned earlier. However, our nodes' sample includes some of the world's largest and busiest logistics areas. Therefore, the following two aspects might explain the absence of a service agent SLN. First, it might not be recommended to coordinate a large number of independent stakeholders over multiple value-adding services in a decentralised fashion, e.g. due to its complexity or to supply chains not requiring such a node configuration. Second, current IT systems at logistics nodes may not yet support the coordination of decentralised, value-adding operations. Due to its complexity, the service agent SLN would require advanced data-sharing technologies and coordination approaches, e.g. via automation and smart algorithms, to ease the coordination burden. Technologies like Blockchain and hub-to-hub CAVs could make the service agent SLN a reality. Such technologies are currently being rolled out for logistics but are yet to be implemented to their full potential at logistics nodes.

From Figure 6, we again make three observations. First, the logistics nodes' digital integration capabilities are correlated to their node type: freight distribution clusters mostly rely on silos software, while ports employ digital ecosystems to support information sharing among the many freight handling stakeholders. Second, one would expect a link between the size and the digital integration of a node. In fact, digital ecosystems would be unnecessarily expensive and complex to manage for smaller nodes. However, that connection is difficult to infer. On the one hand, ports in our sample are, on average, larger than freight distribution clusters and feature digital ecosystems. On the other hand, the larger freight clusters do not employ a digital ecosystem, nor a platform, e.g. the CP and the TRIC. Therefore, we advocate that port areas had a different IT evolution process than

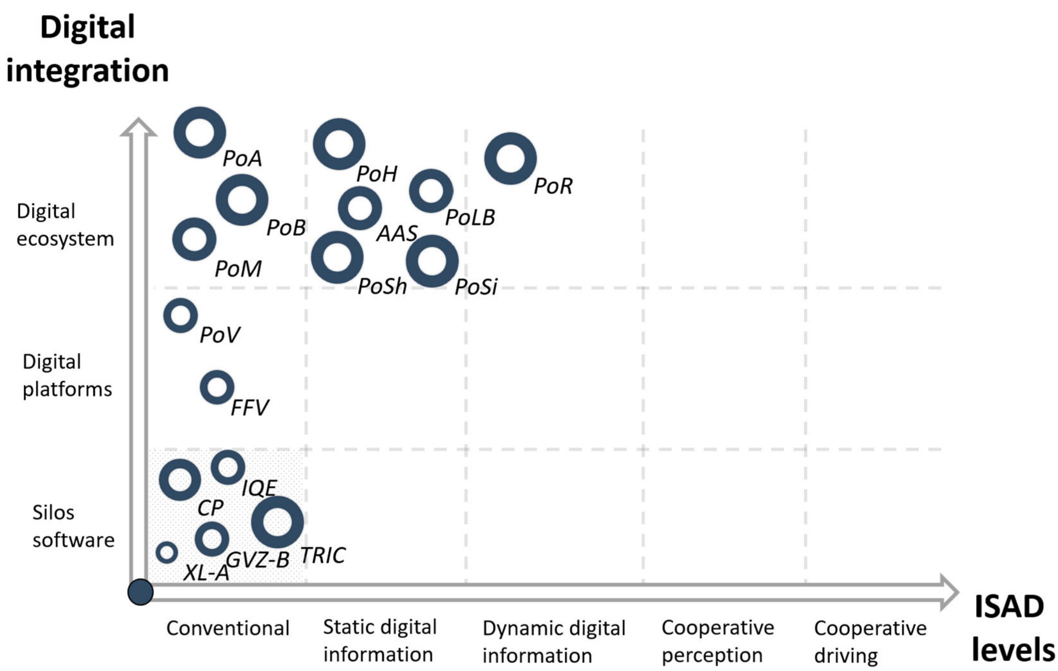

Figure 6. Current digital and automation support capabilities of the logistics nodes.

freight distribution clusters due to the appearance, popularity, and development of Port Community Systems (see Caldeirinha et al. 2020; Moros-Daza, Amaya-Mier, and Paternina-Arboleda 2020), as explained in Section 2.1. Third, most logistics nodes, except for the largest ports, do not provide infrastructure support for automated driving (ISAD). Only XL and XXL ports focusing on rapid freight transit support automated driving in confined areas, with static information provided to CAVs. The PoR is the most advanced in this aspect due to its use of CAVs for hub-to-hub transport of containers, although on dedicated lanes in the Maasvlakte area. We conclude that ISAD and CAVs appeal to logistics nodes, especially larger ones, but their adoption is challenging in hub-to-hub transport. This empirical finding aligns with the need for large-scale, quantitative studies on shared CAV fleets at nodes, as highlighted in Section 2.2. One of the key issues in adopting CAVs in hub-to-hub transport is the legal acceptance of CAVs on public roads, as these are not yet considered safe enough for mixed-traffic environments. For example, at the PoR, CAVs are utilised on dedicated areas and lanes, thus avoiding a mixed-traffic situation. Contrarily, the XL-A wants to evaluate CAVs on public roads but experiences difficulties receiving permission from the governmental authority.

We conclude this general classification by commenting on the SLN status of the logistics nodes. All the ports and the FFV are SLNs, due to their use of digital platforms or ecosystems. However, based on our definition, we do not consider nodes with silos software as SLNs. Therefore, the IQE, CP, TRIC, GVZ-B, and XL-A are currently not classified as SLNs, although they can be assigned an SLN class, as shown in Figure 5. A digital platform or ecosystem is present among the fundamental elements of the SLN listed in Section 3.1. This follows from the definition of SLN: a logistics node that collects, processes, interprets, and shares data among its stakeholders to improve and automate operations. The IQE is peculiar because of its wired network connecting silos software. Still, this wired network does not allow external, shared, and digital services to improve and automate operations seamlessly. Each LC at the node would have to independently extend the capabilities of its software, impairing scalability and coordination.

4.2. In-depth classification of the selected logistics nodes

We now focus on the four selected logistics nodes: PoM, PoV, AAS, and XL-A. First, we exemplify current challenges at these logistics nodes, the development and implementation of SLN's elements, and future goals. Then, we perform an in-depth classification of their SLN elements: physical, digital, and CAT-related. Last, we show the desired extension of the nodes' digital and automation support capabilities. The SLN applications and goals of PoM, PoV, and AAS were first described to some extent by Brunetti, Mes, and Van Heuveln (2020), together with a general simulation framework to model freight and traffic flows at SLNs.

Figure 7 shows PoM and its SLN adaptation. This port presents a compact and confinable layout, with barriers and gates circumscribing the main port area. The possibility of closing off the port area could facilitate the decoupling between automated and manned traffic, e.g. forcing trucks to stop at a pre-gate parking area. The port has several container terminals for (un-)loading transport modalities, a large pipeline and rail network, and numerous LCs. Specifically, PoM is an important industrial hub with several chemical companies and services. Regarding digital integration and automated driving support, the PoM already employs a digital ecosystem (Portbase) to a limited extent, e.g. with notification services for freight transport but no support for automated driving. The main problem of PoM is its lack of maneuvering space at certain roads and intersections in the middle area, which leads to congestion during peak hours. The port authority aims to evaluate using a DP and CAVs, together with a GAS, to reduce congestion and improve hub-to-hub transport.

Figure 8 shows PoV, a North Sea Port coalition port. From an SLN perspective, this is a medium-sized port in a larger decentralised coalition focusing on rapid freight transport with specific value-adding services. Regarding digital integration and ISAD, it features digital platforms for freight and

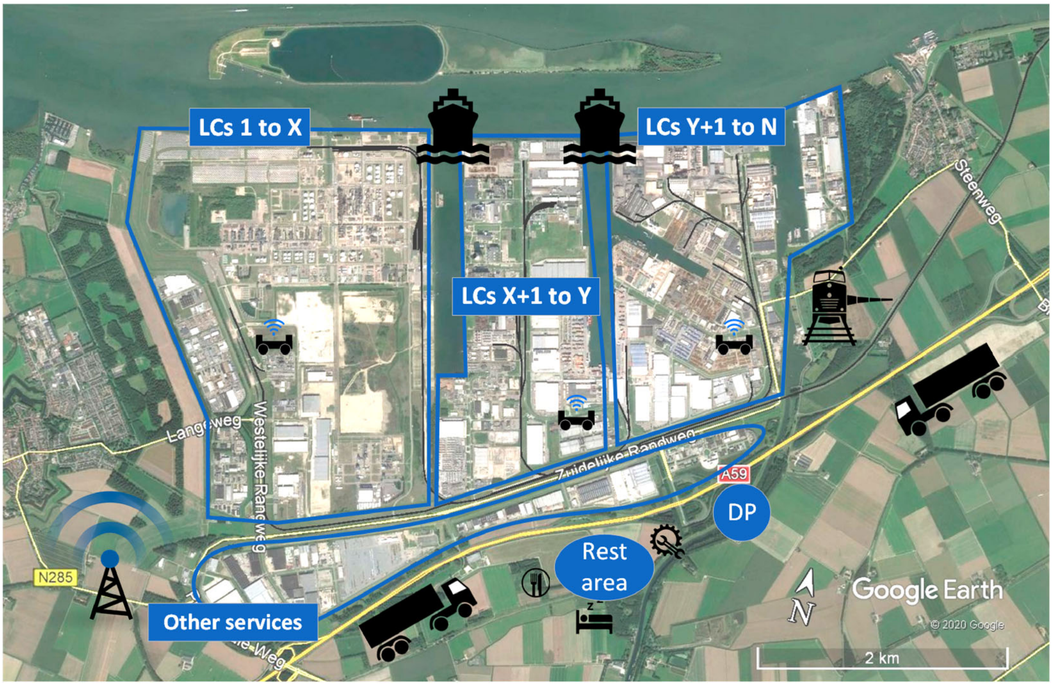

Figure 7. SLN at the Port of Moerdijk (PoM) with a decoupling point (DP) and separately a rest area (Brunetti, Mes, and Van Heuveln 2020).

no automated driving support. Its layout is dispersed and not easily confinable due to its geographical location and lack of port-wide barriers and gates. On the one hand, this results in less congestion because the road infrastructure is simpler, with fewer turns and small roads. On the other hand, this openness brings more safety concerns for truck drivers near the port area. If CAVs were to be employed, PoV would face mixed traffic of manned and automated vehicles. The main goal of PoV is to increase safety and make the port a preferred destination for truck drivers, with indirect benefits for the entire supply chain. Therefore, the rest area for drivers is merged with the DP to achieve a complete Central Gate facility. At this Central Gate, all inbound trucks would stop, detach their trailer, and benefit from the extra services at the rest area. CAVs would take care of hub-to-hub transport inside the SLN, and matchmaking platforms would support freight transport from the SLN to other destinations, e.g. by truck platooning and freight consolidation.

Figure 9 shows AAS. AAS is the third busiest airport in the world, where passenger transport happens together with several types of freight transport. LCs are located internally and all around the main area, i.e. around the landing strips. The freight export at the airport is performed by freight forwarders (external area) that consolidate goods and send them to cargo handlers (internal area). Then, these cargo handlers load freight on assigned planes within tight time windows. The import freight follows the same pattern but in the opposite direction. Following our classification, the primary function of AAS is the rapid flow of goods and passengers. Information sharing is coordinated through a digital ecosystem with multiple sub-platforms, and automated driving support is limited. The two main problems for cargo logistics at AAS are traffic congestion in and outside the airport area and planning disruptions due to inbound trucks with operational priority arriving without prior notice. Automation of freight transport between forwarders and cargo handlers is under study. Moreover, AAS has already pledged to be an autonomous airport by 2050 (Schiphol 2021). Therefore, based on the division between the internal and external areas, we envision an internal automated area for freight transport, i.e. CAVs at SAE levels 4 and 5, within a wider

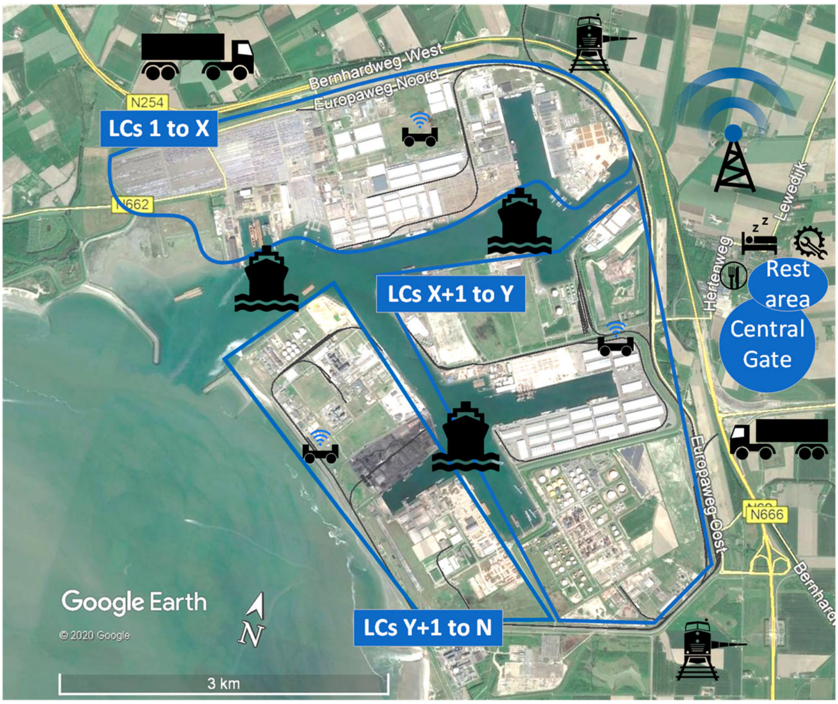

Figure 8. SLN at the Port of Vlissingen East (PoV) with a Central Gate, i.e. a decoupling point (DP) incorporating a rest area and trailer services (Brunetti, Mes, and Van Heuveln 2020).

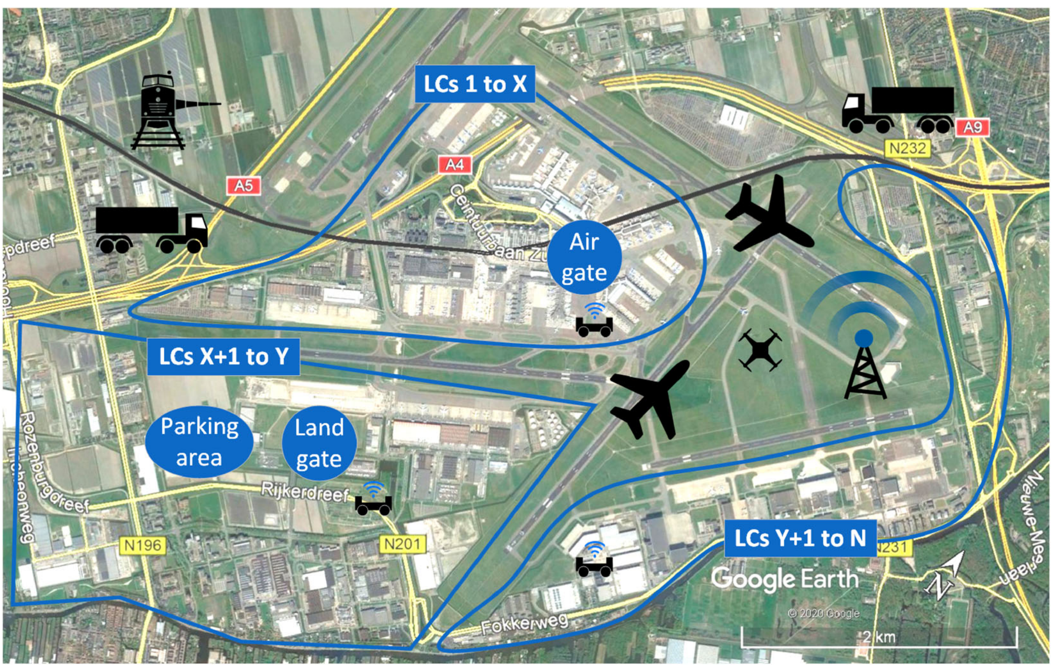

Figure 9. SLN at Amsterdam Airport Schiphol (AAS) with two freight control areas, namely the air and land gates, and a parking area (Brunetti, Mes, and Van Heuveln 2020).

complete mixed traffic SLN. Due to the high strategic value of its land, the airport authority wants first to evaluate a GAS. Then, by using CAVs, improved data sharing, and a DP, the airport authority aims to avoid planning disruptions (i.e. the unannounced trucks with operational priority), reduce congestion (e.g. using real-time analysis of traffic and route selection for CAVs), and benefit from the peak-shaving effect of round-the-clock automated transport.

The last selected logistics node is XL-A, shown in Figure 10. XL-A is a relatively new logistics node undergoing fast development and is part of the Port of Twente association. It features a barge terminal, several LCs using it, and more locations under construction. The road infrastructure is public and utilised by private drivers. The current scope of XL-A is the rapid transit of freight. Regarding information sharing, each LC uses its own IT software and shares only necessary information with the barge terminal. Moreover, the terminal employs a GAS for its inbound trucks. Regarding automation, there is currently no support for CAVs. Nevertheless, XL-A aims to achieve a competitive advantage by being the first Dutch logistics node to employ CAVs for hub-to-hub transport on mixed-traffic roads.

The four logistics nodes in the CATALYST consortium show some of the main challenges that Dutch logistics nodes are currently facing. Also, their goals offer a wide range of foreseen benefits in transitioning to SLNs and adopting CAT.

To provide a detailed snapshot of the SLN status of the four Dutch nodes, as well as plans regarding CAT adoption, we performed an in-depth SLN classification. This was possible because the selected nodes are part of our project consortium, thus we were able to collect more information regarding their SLN elements and CAT implementations. The in-depth classification is shown in Table 4 and Figure 11. Table 4 encompasses all the categories of the SLN's elements shown in Figure 2: stakeholders, freight flows, decoupling points, automation, connectivity, information sharing, data collection, and fleet management services. Moreover, each of the four logistics nodes hosts all three types of freight flows: confined area, hub-to-hub, and first- and last-mile freight flows. Therefore, we merge freight flows and automation technologies as 'automated freight flows' in one column, since each type of freight flow can happen at each node. This also draws further attention to the implementation of CAT technologies.

In Figure 11, a variant of Figure 6, we illustrate the planned evolution of the nodes' digital integration and levels of automated driving support. Hence, we first exemplify the detailed status of

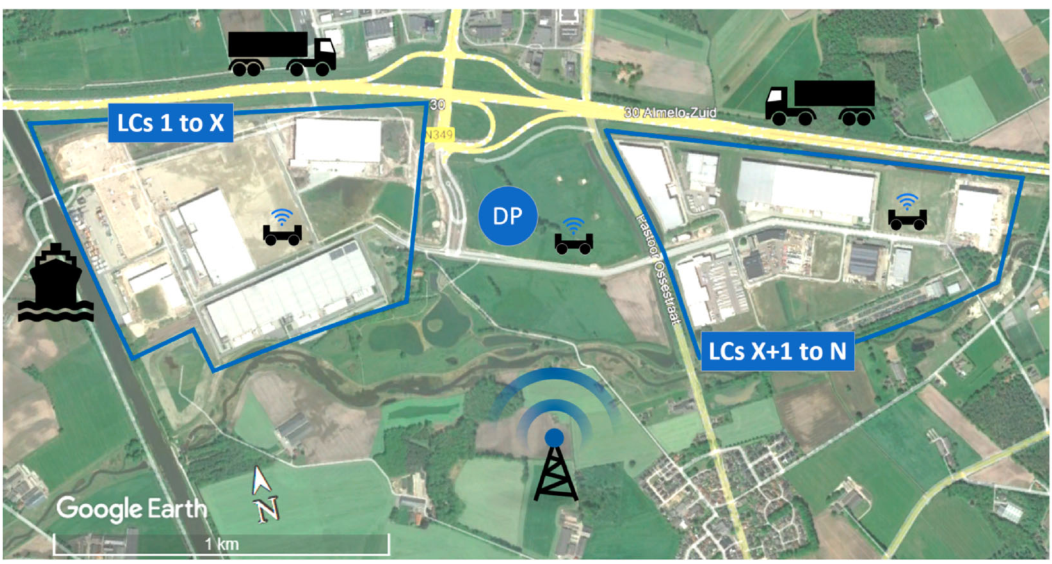

Figure 10. SLN at the XL Business Park Almelo (XL-A) with a decoupling point (DP).

three SLNs in the Netherlands (remember that XL-A is not an SLN yet). Next, we analyse the four selected logistics nodes' current and future ISAD levels and CAT technologies. In doing so, we highlight extended functionalities that future digital ecosystems should target, as Moros-Daza, Amaya-Mier, and Paternina-Arboleda (2020) encouraged.

Table 4 shows that larger port areas, i.e. PoM and AAS, include a more heterogeneous pool of stakeholders and multiple parking areas. Also, we see that only AAS plans to have a Cross-Chain Collaboration Center (4C) soon, probably due to the higher benefits of horizontal collaboration in a more complex, interconnected setting. Next, AAS has a clear edge over the other nodes concerning automation. Specifically, it features smart infrastructure (e.g. smart traffic lights), static ISAD, and aims to employ drones in the short term. Similarly, XL-A plans to quickly adopt automation by separating automated and manned traffic flows in two ways: (i) having dedicated road lanes for CAVs or (ii) forbidding the passage of CAVs and manned vehicles, e.g. by dynamically opening the road for CAVs or manned vehicles only. However, this approach is a temporary solution to speed up CAVs' adoption since it would be difficult to implement at a larger node like AAS, e.g. due to heavy manned traffic at any hour of the day and the need to keep waiting times to a minimum. Following a different approach, PoV is testing remote control of CAVs through 5G networks, considering both road vehicles and surface vessels. These remote operations can serve as a bridge to reach full CAV automation, as explained in Section 2.2.1.

From Figure 11, we gain insights into the potential evolution of the four SLNs, considering their type, size, and goals. The goals of the four SLNs can be easily visualised through the direction of the white arrows in Figure 11. A vertical direction indicates a desire to improve their digital integration capabilities, while a horizontal direction indicates a desire to enhance their ISAD level. First, we see that larger nodes have already achieved the scale of IT system that corresponds to their goals. Contrarily, the smaller and newer XL-A node aims at digital platforms to support information sharing and exploit specific services, e.g. freight transport matchmaking. Moreover, a digital platform

Table 4. In-depth SLN elements of the four selected logistics nodes.

Node	Stakeholders	Decoupling point	Automated freight flows	Connectivity	Information sharing	Data collection	Fleet management
PoM	All except 4C	Two external parking areas. Aim: decoupling	None. Aim: hub-to-hub CAVs	All except 5-6G. Aim: 5G	Track & Trace, digital ecosystem. Aim: node GAS	Cameras, road sensors, weather sensors, RFID	Limited transport planning
PoV	LCs, node authority, manufacturing and chemical companies	In construction: rest area, parking area, and services. Aim: decoupling	None. Testing: 5G teleoperation of vehicles and vessels. Aim: hub-to-hub CAVs	All except 6G. Testing: 5G	Track & Trace, digital ecosystem. Aim: node GAS	Cameras, road sensors, weather sensors, RFID	Limited transport planning. Aim: digital notification of arrivals and registration
AAS	All except 4C. Aim: 4C	Multiple external parking areas with services	Static ISAD, smart traffic lights. Aim: hub-to-hub CAVs and drones	All except 6G	Track & Trace, digital ecosystem. Aim: node GAS	Cameras, road sensors, weather sensors, RFID	Transport planning, digital notification of arrivals and registration
XL-A	LCs, node authority, manufacturing and chemical companies	Internal parking area. Aim: decoupling	None. Aim: hub-to-hub CAVs with dedicated lanes or time slots	All except 5-6G	Terminal GAS, Track & Trace, silos software. Aim: digital platforms	Cameras, RFID	No shared fleet management services

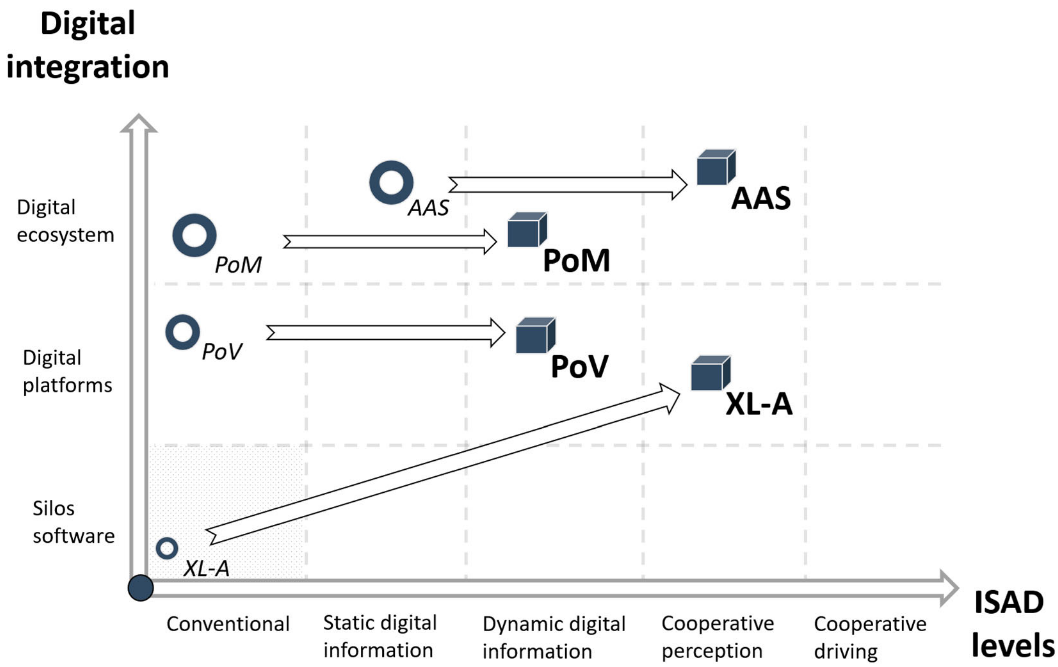

Figure 11. Digital and ISAD capabilities of the selected logistics nodes.

would enable shared fleet management services and the transition to an SLN. Second, due to reduced organisational inertia and complexity, the size difference allows XL-A to test and adopt new automation technologies quickly. In this sense, although the four logistics nodes have little to no support for automated vehicles, the smaller nodes (XL-A, PoV) plan to achieve as much automation as larger nodes, if not more.

Overall, the four logistics nodes see digital integration and automation support as crucial technologies. The first is perceived as a necessary tool to deal with organisational complexity at the node and as a technology enabler. The second is perceived to provide a significant competitive advantage for freight transport. Specifically, by linking the insights from Figure 5, i.e. the SLN function and organisation, and Figure 11, we notice that both types of logistics nodes, i.e. those whose main function is the rapid flow of freight (AAS, PoM, PoV) or those whose main function is value-adding operations (XL-A), are aiming for higher automation levels. The nodes could increase transport efficiency and resilience through higher automation at the cost of increased complexity, investments, and a more decentralised architecture. Optimistically, the widespread adoption of automation technology might lower the required investments and the additional organisational complexity. If not, these factors and the required shift towards a decentralised architecture might be counterproductive for smaller nodes such as XL-A and PoM.

Through our classification, we assessed the current CAT capabilities of logistics nodes in the Netherlands. As a result, we pinpointed critical areas on which to focus implementation efforts, such as improved support for automated driving that fits the business models of each port. In addition, our concept and classification of SLNs allowed for a structured comparison of the four Dutch logistics nodes as well as to plot potential pathways to extend their CAT capabilities.

5. Conclusions

Freight transport is a fundamental part of modern society that faces multiple challenges. Examples are shorter delivery times, driver shortages, traffic congestion, epidemic-related disruptions, and safety and sustainability concerns. Moreover, emerging technologies such as Connected Automated Vehicles (CAVs), Internet of Things, Physical Internet, cloud platforms, and self-configuring systems are transforming the logistics sector, potentially improving its efficiency and resilience. These emerging technologies are part of, or enabling, Connected and Automated Transport (CAT): a set of transportation technologies and concepts that could bring significant benefits for logistics nodes regarding productivity, automation of processes, and information sharing. Logistics nodes are now looking into CAT and other digital technologies for logistics to improve their operational efficiency, environmental footprint, handling of disruptions, and competitive advantage in the market.

We first reviewed the literature on logistics nodes and CAT in this paper. From our findings, we constructed a definition and scope for logistics nodes, after which we identified future challenges regarding collaboration, technology, and business models. In fact, collaboration among stakeholders and process integration are critical points to steer an implementation project from failure to success, and more research on these topics is necessary. Furthermore, quantitative evaluation of CAT's positive and transformative effects on operations is crucial for stakeholder involvement and effective adoption strategies. Also, we delved into connectivity, automation, and information-sharing technologies for logistics. For these aspects, we also identified avenues for future research, such as the need for detailed, large-scale studies on shared fleets of CAVs at logistics nodes.

Based on the applications of CAT and IT at logistics nodes, we introduced the concept of Smart Logistics Nodes (SLN) and developed a classification of SLNs. The classification considers the node's main function, organisation and coordination approaches, and levels of digitalisation and automation. We defined the SLN as any logistics node that collects, processes, interprets, and shares data among its stakeholders to improve and automate operations. Preferably, an SLN would feature predictive, learning, and self-configuring capabilities concerning operations planning and handling disruptions. However, this is not a requirement. Based on our classification, we analysed sixteen logistics nodes from practice. With this, we provided insights into their current state, SLN class, and goals regarding digitalisation and automation.

Our concept and classification of SLNs have both a managerial and a theoretical contribution. Regarding the managerial contribution, we provided an overview of the business function, organisational approach, and technological capabilities of sixteen major logistics nodes worldwide. Next, we analysed four of these nodes in greater detail, exemplifying business goals and case studies for CAT implementation. Furthermore, we developed a state-of-the-art tool for logistics nodes' authorities to assess their nodes regarding CAT and define a roadmap to develop technological capabilities aligned with their business function and organisational structure. Regarding the theoretical contribution, we provided a solid basis for theoretical discussion across emerging research streams in smart logistics, increasing the comparability of studies on technology adoption at logistics nodes. Therefore, we urge fellow researchers to adopt our classification when studying logistics nodes and degrees of smart technology applications.

Combining the managerial and theoretical insights, we found that many logistics nodes already implement digital integration technologies, i.e. digital platforms or ecosystems, and aim to achieve (cooperative) automation via various strategies. In fact, out of our sample of sixteen nodes, eleven featured digital platforms or ecosystems but only one featured the dynamic sharing of traffic information to inter-terminal transport CAVs, i.e. provide support for automated driving (ISAD) of level three. None of the nodes in our study have achieved an ISAD beyond that point. However, their desired automation levels may imply additional complexity and an architectural shift towards decentralised systems. Moreover, such decentralised systems are not necessarily aligned with their current organisational approach and business functions. Therefore, realistic, quantitative studies are necessary to evaluate the best course of action in implementing automation as well as other CAT technologies, such as the simulation of automated transport on dedicated lanes to be managed via a (de-)centralised IT architecture. Furthermore, to reliably assess their full benefits, multiple technologies and concepts must be evaluated in combination, e.g. a truck decoupling point, a gate appointment system, and CAVs. Finally, we noticed how smaller nodes may be quicker in rolling out emerging technologies due to reduced complexity and organisational inertia. Focusing on the rollout of CAVs, their legal acceptance on public roads is still a difficult prerequisite to be obtained from governmental authorities. Nevertheless, interim solutions exist, such as dedicated lanes for CAVs, alternating time windows for automated or manned vehicles, and the remote control of CAVs on public roads.

Our research is subject to two main limitations: the sample used to illustrate our classification and the quick evolution of CAT technology. First, we studied a sample of sixteen logistics nodes. The sample could have been larger as well as more heterogeneous with regards to the business function. On the one hand, we were restricted in our choice of logistics areas by our definition of logistics nodes. On the other hand, the nodes' sample was highly skewed towards the business function of rapid freight transit, in contrast to value-adding services and manufacturing. This could be an insight into the current role of nodes in the global logistics network, but we cannot rule out a biased sample. Second, our research focuses on state-of-the-art CAT applications at logistics nodes, which are bound to become obsolete. As mentioned in Section 3.1, CAT elements such as CAVs, ISAD technologies, and connectivity options are evolving rapidly and will need continuous research. However, the physical and digital elements of an SLN will essentially stay the same, e.g. the stakeholders, the type of freight flows, and data sharing platforms. Moreover, the SLN concept and its classification are higher level concepts that will remain relevant, while evolving along future CAT applications in the field. Similarly, the CAT-related challenges in Table 1 will mature from technology adoption and collaboration schemes to their long-term management.

Possible directions for further research were highlighted at the end of Section 2.2. In particular, further research should focus on (i) studying the transition from logistics nodes to SLNs, both by quantifying the benefits of CAT technologies and a decoupling point and by providing adoption strategies, (ii) evaluating business models for the ownership and use of CAV fleets at (smart) logistics nodes, and (iii) developing decision support for the management of shared CAV fleets at SLNs, extending the inter-terminal transport problem to a generalised hub-to-hub transport problem with real-time information, technical interoperability, and cooperation mechanisms.

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Data availability

Data sharing does not apply to this article as no new data were created or analyzed in this study.

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