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Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues

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ABSTRACT

As supply chain management is becoming demand driven, logistics service providers need to use real-time information efficiently and integrate new technologies into their business. Synchromodal logistics has emerged recently to improve flexibility in supply chains, cooperation among stakeholders, and utilization of resources. We survey the existing scientific literature and real-life developments on synchromodality. We focus on the critical success factors of synchromodality and six categories of enabling technologies. We identify open research issues and propose the introduction of a new stakeholder, which takes on the role of orchestrator to coordinate and provide services through a technology-based platform.

1. Introduction

Synchromodality is an emerging and attractive concept in logistics, developed and established in the Benelux region during the last decade. The main purpose of synchromodality is reducing costs, emissions, and delivery times while maintaining the quality of supply chain service through smart utilization of available resources and synchronization of transport flows. Implementation of the synchromodality concept and some research projects based on this practice have already shown how different kinds of logistics objectives can be achieved or significantly improved, including avoiding empty capacity, reacting to disruptions, and reducing transportation by trucks in favor of railroads, ships, and barges.

However, the current literature lacks a clear, complete, and commonly accepted definition of synchromodal logistics and its features. In our definition, synchromodality is *the provision of efficient, reliable, flexible, and sustainable services through the coordination and cooperation of stakeholders and the synchronization of operations within one or more supply chains driven by information and communication technologies (ICT) and intelligent transportation system (ITS) technologies*. The characteristics considered in our definition have not been described jointly up to now and a shared vision on how to exploit them to support the new trends in supply chain management is not yet available. The present study aims to provide details of this definition, starting from a critical survey of the existing scientific literature and real developments in the field of synchromodal logistics. In fact, our analysis goes beyond a simple review of the state of this transportation system. Instead, this study highlights the clear relationships between critical success factors (CSFs) of synchromodal logistics and enabling technologies, such as ICT and ITS. After considering CSFs for synchromodality at different decision levels, we identify the relevant stakeholders and the enabling technologies required to implement synchromodality in practice. Finally, we make recommendations to address the CSFs for each group of enabling technologies (outlining open research

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issues) and the possible synergies achievable on a common platform. As stakeholders need coordination, we also identify an orchestrator (fifth-party logistics, 5PL) that can acquire this role by providing and managing the common platform.

Despite its importance, synchromodality is at an early stage both from research and practice perspectives. The existing contributions are sparse and treat only one or a few aspects of the matter. A lot of material can be found online, but it is quite disordered. Instead, in our study, we consider the synchromodal logistics phenomenon through a comprehensive and systematic analysis, from social and business consequences up to operation management and enabling technologies. Owing to the characteristics of our analysis, our work provides insights for both executives involved in logistics operations and management, and companies developing technology solutions or services. Moreover, the study is a helpful source of information to researchers and practitioners in diverse fields who are interested in this recent logistics paradigm.

For the sake of completeness, we explain the method adopted in this study. Our aim is to collect, survey, and classify the existing literature related to synchromodality, clarifying the current state and creating a sound reference for future research on the topic. We do not compare specific analytical models, but we discuss the existing approaches at different levels. In fact, we analyze the synchromodal logistics paradigm from a broad perspective, while analytical models usually cope with peculiar aspects (e.g., operational optimization problems). Primary sources for this work have been searched through the main academic databases and available web resources (e.g., Scopus, Google Scholar, and Research Gate) by using selected logistics keywords (e.g., synchromodality, synchromodal, synchro-modality, synchro-modal, intermodality, multimodality, 5PL, fifth-party logistics, 4PL, fourth-party logistics, 3PL, third-party logistics, data analysis logistics, data analysis supply chain, and Industry 4.0). Moreover, we include online reports on practical case studies or research projects, so as to present real-life applications of synchromodality and advances in enabling technologies.

The rest of the paper is organized as follows. In Section 2, we identify and describe the main stakeholders in logistics, their interactions, and a new trend in supply chain management. In Section 3, we collate and describe all the features of synchromodality and its CSFs discussed in the literature. In Section 4, we propose six different categories of ICT/ITS technologies that enable synchromodality, namely traceability, intelligent systems, data analytics, optimization, simulation, and integration platforms, and analyze them in depth. Moreover, in Section 5, we present some case studies and research projects dedicated to the application of synchromodality and advancements in enabling technologies. In Section 6, we suggest the introduction of a 5PL service and technology solutions provider as an orchestrator for synchromodal logistics. Moreover, we present some open research issues for each enabling technology. Finally, Section 7 concludes.

2. Logistics context

According to Jain et al. (2010), a supply chain is “the stream of processes of moving goods from the customer order through the raw materials stage, supply, production, and distribution of products to the customer” and supply chain management consists in “managing the chain of events in this process”. Synchromodality often seems to be related only to the synchronization of transportation modes, and thus, covers only the corresponding activities of supply chain management. However, Dong et al. (2018) recently pointed out that synchromodality has the potential to address several activities of supply chains in addition to transportation. Hence, in our vision, synchromodal logistics should be considered in a broader sense, possibly involving the coordination of all relevant operations in supply chain management.

The context in which synchromodality operates is presented in the following sub-sections. Specifically, we introduce the stakeholders involved in synchromodal logistics, highlighting their current interactions (Section 2.1). Moreover, we show how such interactions are not well suited to cope efficiently with new trends in supply chain management (Section 2.2).

2.1. Stakeholders and their interrelationships

The evolution of supply chain management has occurred in phases, moving from relationships based on simple dyadic linkages to complex multi-actor networks (Braziotis et al., 2013). Currently, supply chain stakeholders are connected to each other either directly or indirectly, and their interrelationships are linked not only to the physical movement of goods but also to the exchange of information. When stakeholders build supply chains based on such complex networks, it becomes necessary to have a coordinating intermediary to achieve a balance between cooperation and competition. Moreover, stakeholders are becoming increasingly aware that their own success is strictly related to the performance of the whole supply chain (Pavlić Skender et al., 2017). For these reasons, modern businesses rely strongly on so-called logistics service providers (LSPs), which offer a range of different services to their clients, from simple transportation operations to complete supply chain management. In fact, depending on their needs and convenience, companies decide to outsource some activities or the complete logistics of their supply chain to LSPs.

In Fig. 1, we depict a proposed interrelationship of supply chain stakeholders with a potential role in synchromodal logistics, including different types of LSPs, and we highlight the flow of goods and information between them. The identified stakeholders are as follows.

- **Customers**: manufacturers, suppliers, or general firms that need to ship raw materials or goods through a supply chain network. Depending on the services required, they may initiate direct relationships with carriers for simple transportation operations or with other partners for more complex logistics operations and long-term supply chain management.
- **Carriers**: companies mainly based on physical assets (e.g., trucks, rails, barges, feeder vessels, oceanic lines, and aircraft) and that provide transportation services by transporting goods. They work directly with their own clients or offer their transportation

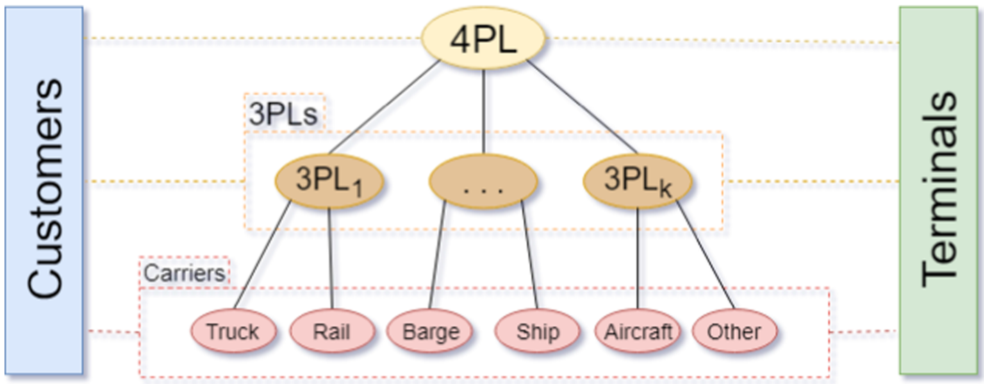

Fig. 1. Logistics stakeholders and their interrelationships.

services to LSPs.

- **Third-party logistics service providers**: LSPs that are usually involved in their customers' businesses, 3PL service providers play an important role in developing the supply chain. These LSPs offer services related to basic logistics activities, such as transport, consolidation, cross-docking, inventory management, packaging, warehousing, and freight forwarding. The 3PL service providers work as an intermediary between buyers and sellers, coordinating between carriers and other suppliers of services, to improve the performance of the whole supply chain. They may own physical assets, but their main resource is knowledge about managing simple technology solutions (e.g., shipment tracking).
- **Fourth-party logistics service providers**: asset-free LSPs that are usually involved in long-term relationships with their customers for which, besides managing their supply chains, they also develop strategies to improve these supply chains. The 4PL service providers work like a single interface between the client and multiple stakeholders, including 3PL service providers. This strong relationship makes 4PL service providers more than simple intermediaries, ideally having total control over their customers' supply chains. Some examples of services offered by 4PL service providers are network analysis and design, business planning, project management, control tower and network management services, inventory planning, and management.
- **Terminals**: port authorities, intermodal hub managers, or any party that needs to handle transshipment operations. They have different types of direct interactions with carriers, 3PL service providers, and 4PL service providers.

We note that Pavlić Skender et al. (2016) also considered freight forwarders among the above stakeholders. Basically, FFs offer services related to transport and storage of goods with the purpose of relieving their customers of the effort and problems of shipping. FFs also consolidate shipments and take care of such aspects as international shipping requirements or insurance of goods. However, FFs' services can be considered as integrated into 3PL service providers' activities, which in fact also consists of freight forwarding services through their physical assets or collaboration with carriers. Therefore, we do not explicitly consider them in the rest of the analysis.

It is important to note that the most commonly outsourced activities are 3PL services, such as transport, warehousing, and freight forwarding. By contrast, 4PL services are relatively new in the real market and their advantages are still not recognized by many companies, which are often reluctant to give total control of their supply chain to outsiders (Pavlić Skender et al., 2017). However, since LSPs often offer different types of services, it is not always possible to exactly classify real companies into one of the categories previously analyzed.

The previous description represents the current situation, but new emerging trends in supply chain management are creating the need for rethinking and redesigning stakeholders' organization and interactions.

2.2. Demand-driven supply chain

One new trend that is becoming a crucial paradigm in supply chain management is the so-called demand-driven supply chain (DDSC). It is "a system of coordinated technologies and processes that senses and reacts to real-time demand signals across a network of customers, suppliers, and employees" (Boston Consulting Group, 2012). To make DDSC more responsive to changes in demand, four enablers have been identified (Boston Consulting Group, 2012): visibility of information across the supply chain, infrastructure that is robust enough to adapt quickly to short-time changes in supply and demand, coordination of stakeholders to operate efficiently and cost-effectively, and optimization of the overall performance of the supply chain to offer the best services to clients while keeping financial benefits. Moreover, it is recognized that to realize an efficient DDSC, it is necessary to deal with the current lack of transparency among stakeholders, which is a major cause of delays in reacting to disruptions (KPMG, 2016). In fact, information tends to flow from one stakeholder to another, implying lateness when it needs to pass through multiple intermediaries. In the DDSC instead, it is necessary to update the flow of information in real time among all stakeholders. This means that the current logistics paradigms need to be adapted or upgraded to cope with DDSC, and synchromodality seems to be promising for enhancing service quality while meeting customers' needs (Tavasszy et al., 2017).

Section 3.2 will discuss in great detail the major features of synchromodality, i.e. real-time information, flexibility, cooperation and coordination, and synchronization. One of the objectives of this paper is to show how these features perfectly fit the abovementioned DDSC enablers (namely, visibility, robust infrastructure, coordination, and optimization) as now briefly described. In fact, the sharing of real-time information among all the stakeholders can improve visibility, while flexibility, which is the ability to develop services capable of adapting and reacting to disruptions, can contribute to the development of a robust infrastructure. The third feature (cooperation and coordination) has the same focus as the corresponding enabler (cooperation), while synchronization is a key factor in several optimization issues.

3. Synchromodal logistics

In this section, we focus on the characteristics of synchromodal logistics. First, we compare synchromodality to previous well-known transportation paradigms (Section 3.1). Then, we describe the features of synchromodal logistics, considering DDSC drivers (Section 3.2). Finally, we discuss the CFSs needed to implement synchromodality in the real world (Section 3.3).

3.1. Legacy with other supply chain paradigms

Before describing the characteristics of synchromodality, it is important to review its relationships with transportation paradigms that shaped the supply chain since the 1980s: multimodality, intermodality, combined transport, and co-modality. Reis (2015) found overlapping features and ambiguity among the definitions of these paradigms and instead highlighted the importance of having a common vision on synchromodality, working in the same direction with equal perspectives and approaches. In the following part, we discuss the characteristics that synchromodality has inherited from the abovementioned practices to become the new leading transportation paradigm able to deal with new trends in the supply chain.

Multimodality simply comprises the utilization of different transportation modes (ship, rail, truck, barge, and aircraft) for a single shipment. Intermodality is an evolution, which implies the integration of different modes in a door-to-door supply chain, in which customers specify an origin and a destination but the paths and transportation modes are disregarded if the demand is eventually met. In this context, the concept of load unit, that is, a physical object in which items are packed, like a pallet or a container, becomes central to facilitate the mode change and to manage the relative operations efficiently. Combined transport is an evolution of intermodality that aims to reduce the environmental impact of transport, especially relying on more sustainable modes (e.g., ship and rail) and fostering less utilization of trucks. Finally, co-modality aims to have optimal and sustainable utilization of different modes, both combined and individually.

Synchromodality can be regarded definitively as a further evolution of these transportation paradigms. In fact, synchromodal logistics should involve different and strongly integrated transportation modes. The aim is to provide a sustainable and, at the same time, efficient supply chain that reduces its environmental impact while optimizing resource utilization. Synchromodality inherits from intermodality the vision of high-level flexible management of corridors to meet the wider interests of the whole supply chain, not only a specific shipment or company.

3.2. Features

The characteristics of synchromodal logistics that allow smarter utilization of available resources are real-time information, flexibility, cooperation and coordination, and synchronization.

Real-time information is essential for synchromodal logistics. In fact, the other features rely strongly on real-time information. Ideally, in a synchromodal supply chain, stakeholders should be able to have a global view of their activity status and events affecting them. With this knowledge, it is possible to adopt effective replanning procedures and react immediately to unexpected events. For instance, real-time information can be used to control and reschedule railway traffic (Corman et al., 2017) or to update the routing and scheduling plans of fuel supply vessels that serve customer ships outside ports (Christiansen et al., 2017).

Flexibility is often related to customers that relax certain constraints for their shipments, while giving more freedom to LSPs. For instance, amodal booking implies that customers do not select modes and routes for their shipments. This allows LSPs to optimize the available capacities and to react effectively when disruptions occur by automatically switching modes or prioritizing shipments. For instance, freight of delayed shipments and that close to missing the due date (Nabais et al., 2015) or perishable goods at the risk of losing their freshness (Lin et al., 2016) could be assigned to different modes instead of the planned ones to meet demand. The more freedom given to LSPs, the more efficiently they can react to disruptions, thereby increasing the possibility of fulfilling requirements by adopting synchromodal operations (e.g., rescheduling, rerouting, and modal shift). For instance, flexible synchromodal solutions and their cost-saving and environmental impact benefits have been studied in network affected by disruptions (Ambra et al., 2019).

Cooperation and coordination among stakeholders are fundamental for building a resilient network and better visibility of information. On the one hand, cooperation requires the integration of stakeholders' networks, to improve consolidation of flows and increase the overall capacity. For instance, this allows every stakeholder to benefit from enhanced flexibility in case of disturbances (van Riessen et al., 2015). However, as highlighted in Tavasszy et al. (2017), while only vertical integration is considered in intermodality (i.e., among stakeholders operating at different levels of the supply chain), horizontal integration is important in synchromodality (i.e., among stakeholders doing similar activities, e.g., transportation services in different modes). On the other hand, cooperation also means sharing real-time information among stakeholders. This benefits everyone, especially those concerned with planning, forecasting, and risk management, leading to improvement in the overall quality and visibility of the supply chain. For instance, to avoid empty truck trips and to reduce emissions, truck appointment systems can be used to coordinate and create collaboration among truck drivers (Schulte et al., 2017). For this reason, it is necessary to organize integration and data sharing to maximize advantages for all stakeholders without harming others' interests.

The aspects just analyzed are essential to achieve the main feature of this paradigm, that is, synchronization of operations, as the name suggests. This must always be considered throughout the supply chain to use the available resources optimally. One example that could help us to understand the importance of synchronized activities is related to the practice of slow steaming, that is, operating ships at significantly less than their maximum travel speed to decrease emissions (Cariou, 2011; Lee et al., 2015). In synchromodal transportation networks, slow steaming can be enhanced to become smart steaming (The Motorways of the Sea Digital Multichannel Platform, 2017; MJC2, 2017), exploiting the dynamic changes of vessel speed according to real-time information about port congestion and weather conditions. For instance, planning services that operate at medium speed help to accelerate speed in the case a ship is late owing to poor sea conditions or to decelerate speed to avoid arriving at a congested port with a waiting time of many hours. In fact, synchronization is a concept that should also be extended to the whole supply chain besides transport, such as inventory management and production scheduling (Dong et al., 2018). Moreover, collaboration among stakeholders and synchronization of their resources must be considered to achieve win–win solutions. For instance, Guo et al. (2017) analyzed the introduction of synchromodality in the global cold chain to understand its impact with respect to specific requirements (e.g., strict time constraints and temperature-controlled logistics operations).

In summary, it is important to build a supply chain in which stakeholders cooperate and share information at different levels, enabling more flexibility to meet demand when disruptions occur. Synchronizing operations across the entire supply chain is the optimal utilization of available resources. Obviously, managing a synchromodal network, instead of single entities operating on their own, requires great effort and coordination between stakeholders and synchronization of resources, even as it provides benefits, such as improvement in efficiency, reliability, sustainability, and revenue. In fact, such characteristics as coordination and data exchange are considered crucial factors to improve efficiency and take logistics to a higher level, helping to make synchromodality an essential pre-condition for optimal and sustainable transportation in the future (Pleszko, 2012).

3.3. Critical success factors

Based on literature reviews and interviews with experts in the transportation sector, Pfoser et al. (2016) defined the main CFSs concerning synchromodal logistics. They are as follows:

- **Network, collaboration, and trust**: since cooperation is essential in synchromodality, stakeholders should better integrate their networks to maximize benefits. Building trust among players and coordinating their operations seems to be a challenge, especially when the full supply chain management relies on a third party (e.g., 4PL service provider). In that case, the main goal is to find the right balance between competition and cooperation of stakeholders involved in the same business.
- **Sophisticated planning**: increased network complexity and real-time data require dynamic planning that is based on the network structure. From strategic to operational levels, optimizing decision making must consider such aspects as user preferences, dynamic allocation of available resources, forecasting, and recalculation when new information is available. Moreover, the design of infrastructure and services, as well as allocation of resources and replanning, should consider the characteristics of synchromodality to build a robust network with a high level of flexibility and synchronization.
- **ICT/ITS technologies**: information flow has a key role in synchromodal logistics, requiring complex ICT/ITS systems to collect and share data originating from different parties that follow common standards. Information must be secured, and for each stakeholder, accessibility rights for all data must be defined. In a context strongly driven by data, information should be collected automatically, when possible, and other technologies should provide the best data utilization.
- **Physical infrastructure**: configuration of the infrastructure network must be reorganized to create smart hubs and corridors. The location of terminals and production sites alongside infrastructure design are important to achieve synchromodality goals.
- **Legal and political framework**: regulation of the new dynamics created by synchromodal logistics is a key issue that can also affect other CSFs. For instance, since an unforeseen modal shift can occur in synchromodal networks, there should be a clear understanding of who is liable in the case of any loss, damage, or delay. Moreover, data sharing should be regulated to secure sensitive information.
- **Awareness and mental shift**: in synchromodal logistics, customers should only focus on basic decisions, such as where to ship, expected arrival time, and costs, while giving more freedom to LSPs, which should provide more reliable services in exchange. Therefore, all supply chain stakeholders are required to make a mental shift to understand the importance of sustainability and efficiency of the entire network in order to be able to react when disruptions occur.
- **Pricing/cost/service**: due to the flexibility required in a synchromodal network, which often provides advance information on which modes will be used, pricing services are more complex because costs are relative to the chosen modes. Moreover, synchromodality pursues a higher quality of the services while decreasing, or at least maintaining similar, costs.

From our perspective, despite of the importance of all the described CSFs, ICT/ITS technologies take the role of a meta-CSF, enabling any other one. These technologies have also been described as a prerequisite for other CFSs in other studies (see, e.g., Singh et al., 2016). For this reason, in the next section, we analyze in depth the main enabling technologies for achieving synchromodal logistics.

Enabling technologies \ Critical success factors	Network, collaboration and trust	Sophisticated planning	Physical infrastructure	Legal and political framework	Awareness and mental shift	Pricing, cost, service
Traceability	✓			✓		
Intelligent systems		✓	✓			
Data analytics		✓			✓	✓
Optimization		✓	✓			✓
Simulation	✓	✓	✓		✓	
Integration platforms	✓			✓	✓	✓

Fig. 2. Critical success factors and enabling technologies.

4. Enabling technologies

We selected six groups of technologies that have a relevant impact on CSFs. They are as follows:

- **Traceability**: it is the identification and data capture of trade items and a record of the transit and operations performed.
- **Intelligent systems**: they are intended to integrate the physical and digital worlds. They can help humans take informed decisions by providing functionalities, like data analytics, optimization, and simulation.
- **Data analytics**: it is an essential aid to take informed decisions. In the realm of supply chains, predictive analytics can be used to forecast trends in the flow of goods as well as in terms of costs and service levels.
- **Optimization**: it mainly addresses the optimal use of resources at different levels, that is, strategic, tactical and operational, and real-time.
- **Simulation**: it has the purpose of defining and simulating scenarios as a support for decision making.
- **Integration platforms**: they are intended to allow stakeholders to communicate, share data, and exchange business interactions, also embedding the previous technologies as services.

In Fig. 2, the rows correspond to enabling technologies and the columns to CSFs. The marked cells indicate which enabling technologies affect specific CSFs. In the following, we illustrate the major features of the enabling technologies and explain, at the end of each relevant subsection, how CFSs can leverage them.

However, before analyzing the benefits of the enabling technologies, we believe that a brief discussion about possible barriers to their adoption by companies is needed. Analyzing the technological trends in multimodal transportation Harris et al. (2015) have found three categories of barriers to ICT implementation: user-related, technology-related, and policy-related. The first category includes economic, operational, and managerial barriers, such as the cost of implementing and maintaining technology solutions, the lack of ICT specialists, and the uncertainty about the return on investment. The second category encompasses incompatibility issues between ICT applications, the lack of ICT standards, security and data protection. The last category concerns the lack of policies meant to facilitate new ICT adoptions, to coordinate and harmonize regulations on a national and continental level, and to define standards.

4.1. Traceability

Traceability provides transparency to the flow of goods in supply chains. Items can be tracked during transport to provide stakeholders with accurate and up-to-date information on the route taken and the transit times at the reference points. Synchromodality can take advantage of such information to take real-time decisions, such as switching to a different transportation mode. Traceability is based on the identification and data capture of trade items, their transits, and the operations performed.

Standardization efforts have been made to provide a common way to identify logistic units, such as box, pallets, or containers. GS1 (https://www.gs1.org/transport-and-logistics, accessed: 2019-01-24) has developed the serial shipping container code and the electronic product code, which can be associated with logistic units through devices, such as bar codes and RFID (radio-frequency identification) tags, to facilitate their reading. Moreover, the electronic product code information services, which is the standard that GS1 uses to record critical data exchanges and make them available to trading partners.

In addition to the flow of goods, there are other factors that need to be tracked, such as weather, water levels, traffic, and accidents. Usually, information comes from different sources and this entails standardization work to make the data collected homogeneous. To this end, Singh and Van Sinderen (2015) proposed a common message format in XML to make critical information available to 4PL service providers as the basis for their decisions and actions.

Traceability implies the collection and recording of several (digital) data related to physical entities, such as trade items and logistics units. However, digital representation of the physical entities is missing; to this end, the notion of digital twin comes into play. A digital twin is an information entity that collects the features of a physical entity. These features concern the properties, state, evolution, and operations carried out by the physical entity. A review of digital twins is provided by Tao et al. (2018). This notion can be applied to the supply chain as well. For example, shipments can be represented by digital twins that provide up-to-date information on the state of shipments by leveraging the operations carried on the shipments. Moreover, digital twins can be used for simulation purposes to test critical decisions, such as modal shifts.

The visibility provided by traceability has a positive impact on two CSFs, (i.e., network, and collaboration and trust) as well as the legal and political framework. First, it helps to strengthen trust among stakeholders, and second, it simplifies the determination of liabilities based on the facts recorded.

4.2. Intelligent systems

Intelligent systems can take many forms. In this study, we are interested in two aspects, namely, intelligent assistants (IAs) and cyber physical systems, since they have a critical impact on logistics.

An IA is a virtual entity that can help humans to take decisions by providing functionalities, like data analytics, optimization, and simulation. Dobrkovic et al. (2016) provided a case study on scheduling of shipments in synchromodal logistics. They developed various IAs to handle specific tasks, some of them operating continuously and others on demand. During the testing phase, they used a simulation game called Synchro Mania (Buiel et al., 2015) to compare the performance of two groups of participants: one supported by an IA and the other depending only on members' abilities. The first group outperformed the second one. The winners could focus on high-level decisions taking advantage of the capabilities provided by the IAs, that is, they could analyze a large amount of data, identify alternatives, and simulate outcomes. They combined the information originating from the IAs with their experience in different fields.

Cyber physical systems (CPSs) integrate the physical and digital (cyber) worlds. They encompass consumer goods, industrial tools, and large-scale systems (Broy and Schmidt, 2014) and take advantage of computation, communication, and control technologies (Müller, 2017). Moreover, they are a key component of the Industry 4.0 initiative. The CPSs can also be considered the technical foundation of logistics and supply chain management (Klötzer and Pflaum, 2015). The major design principles pointed out by Hermann et al. (2016) for Industry 4.0 scenarios can be equally applied to the realm of logistics and supply chains. These four principles are: interconnection, information transparency, decentralized decisions, and technical assistance. One example of CPSs is waterborne autonomous guided vessels controlled in a cooperative distributed way to transport containers between terminals (Zheng et al., 2017). Automatic cranes and collaborative robots operating in terminals are other examples of technical assistance that benefit dock workers, while self-driving vehicles are examples of technologies that are entrusted with decentralized decisions. Some related case studies are presented in Section 5.1.

Intelligent systems deal with two CSFs. As for physical infrastructure, intelligent systems comprise CPSs capable of performing precise mechanical operations instead of humans, thus improving the efficiency of operations in hubs and corridors. Sophisticated planning can take advantage of IAs, which support human decisions by leveraging the analysis of data and the coordination of CPSs.

4.3. Data analytics

In this subsection a short overview of data analytics and business intelligence is given, and some examples related to supply chains are illustrated.

Data analytics is widely considered an essential aid for taking better decisions. In the realm of supply chains, predictive analytics can be used to forecast trends in the flow of goods as well as in costs and service levels (Waller and Fawcett, 2013). Moreover, the importance of big data analytics techniques and strategies has been highlighted for such fields as risk analysis, supply chain management, transport, revenue management and marketing, inventory management, and forecasting (Choi et al., 2017). In practice, data analytics is a technique for analyzing a large amount of data with the purpose of uncovering information, such as market trends and customer preferences, which can help companies improve their business. It can also be used to forecast future events and situations, and this may help managers to decide whether to change their business strategies. There may be several data sources, that is, social media content, emails, and Internet of things. The aim of relying on data analytics and business intelligence is to produce results in various forms (e.g., reports and visual representations) to help managers take more informed decisions. A few examples of the use of such techniques in supply chains are as follows.

Singh et al. (2018) proposed a technique for identifying supply chain issues in the food industry, based on the analysis of data from the Twitter social network. The study reported a case study and explained how data analytics yielded the reasons for positive and negative sentiments. Then, the authors proposed a set of recommendations for the development of a customer-centric supply chain. Silva et al. (2017) developed an artificial neural network (ANN) to forecast the ability of a simulated supply chain to fulfill incoming orders. The authors modeled and simulated a supply chain with different stakeholders, and used it to train the ANN. Subsequently, they conducted two experiments. In the first, the objective was to forecast, over a given time horizon, whether the upcoming orders would be fulfilled instantaneously. In the second experiment, the forecasting concerned the time when a reordering point would be reached, and a new replenishment order would have to be placed. In another study involving ANN, Du et al. (2019) developed two ANN models to analyze the efficiency of shipping fuel, and that are capable of using historical data to quantify the impact of sailing speed, displacement, trim, weather, and sea conditions. Based on this analysis, the authors used the ANNs to optimize fuel consumption while meeting the estimated arrival time, and developed solutions to optimize speed and trim during the journey. More examples of application of big data analytics in logistics and supply chain management are found in Govindan et al. (2018). In particular, the authors analyzed projects whose impact based on real-time analysis of supply chain design and management was to reduce costs, mitigate risks, and take better and faster decisions to meet customers' demand.

Data analytics is critical for logistics and therefore, techniques are required to extract valuable information within a reasonable computation time. Data analytics has a positive influence on three CSFs. Sophisticated planning can benefit from the forecasting of future events that may have disruptive effects. Information on market trends and customer preferences may help stakeholders re-organize their business and this affects awareness and mental shift, as well as pricing, cost, and service.

4.4. Optimization

Optimization is a crucial technology in synchromodal logistics, whereby scarce resources must be smartly allocated, and operations synchronized to limit waste. The large amount of data collected and analyzed with previous approaches should be well structured to be used as an input for optimization methods. However, even if information is filtered and organized through data analytics procedures, the complexity of synchromodal networks leads to the need for evolving existing optimization approaches and developing new ones capable of computing good solutions within a reasonable time. In particular, in short-time and real-time planning, some decisions need to be made within a few minutes or seconds. Optimization methods should be efficient enough to provide both human decision makers and IAs with a list of solutions as fast as possible. In the existing literature, the related studies can be classified into strategic/tactical planning, operational planning, and real-time optimization. These three categories deal with sophisticated planning CSFs in different time horizons. Strategic and tactical planning consists mainly of network and service design in long and medium time horizons. Operational planning focuses on the allocation of resources that required optimization in short time horizons. Finally, real-time optimization deals with disruptions by adapting existing plans through a quick replanning.

4.4.1. Strategic and tactical planning

Only a few studies are available on strategic/tactical planning in relation to synchromodal logistics.

Behdani et al. (2014) presented a model to design integrated service schedules with the objective of minimizing the total cost of operations, including transportation cost and waiting penalties. To test its applicability, the authors tested the model to design service schedules for container transport between a port and an inland terminal. With respect to intermodality, the authors showed that including synchronization in the design process could improve transportation performance. van Riessen et al. (2017) used a Markov decision process to maximize the revenue of a transportation provider by considering the available capacity (at operational level) as a fixed limit for each possible fare class (at tactical level). Since contracts have different time and flexibility constraints, the authors proposed a method to balance the availability of each fare class to avoid issues of insufficient capacity, which erode profits. Li et al. (2017) instead proposed three distributed model predictive flow control approaches in service networks under dynamic demand and traffic conditions. In this study, the authors aimed to enhance cooperation among stakeholders (crucial in synchromodality) by using multiple interconnected sub-networks that attempted to use the least number of interactions and information exchange among stakeholders.

Zhao et al. (2018) exploited the location of consolidation centers in China to improve the efficiency of the internal and China-Europe rail transport. They established criteria to pre-select some candidates and used the information about railways, highways, and national roads to build a graph. Then, they used a K-shell method to evaluate the importance of each node and a mixed-integer programming model to find the best location.

Finally, Dong et al. (2018) proposed parallel optimization between transport and storage, highlighting the importance of considering the synchronization of operations at different levels and for different aspects of the supply chain. They used a case study to show how this approach could increase the utilization of rail transport, resulting in reduction of emissions and total logistics cost saving. This study can be extended to other aspects to optimize the supply chain as a complete entity.

Interestingly, we found no work related to network design considering all the aspects of synchromodal logistics but only real-time coordination. Karsten et al. (2017) presented a model to maximize the profits of container carriers, and designed a set of cyclic routes and services considering coordination between vessels and transit time restrictions. Possible solutions to improve the network are provided with a metaheuristic based on a greedy, knapsack-based construction heuristic.

Besides sophisticated planning, strategic and tactical planning are important for two other CSFs. First, it plays a fundamental role in the design of physical infrastructure. Second, it can facilitate the design of services and related pricing, as proposed by van Riessen et al. (2017) for the Cargo Fare Class Mix problem.

4.4.2. Operational planning

Operational planning deals with the optimal allocation of resources, sometimes in stochastic, dynamic, and multi-periodic environments.

Mes and Iacob (2016) developed a multi-objective k-shortest path algorithm that works on a full connected graph (with hubs, e.g., nodes, and routes, e.g., links) to support transportation planning by minimizing costs, delays, and emissions. The approach has a pre-processing phase in which the network is reduced by eliminating unfeasible nodes (e.g., too far), generating different sub-networks for all pairs of origins/destinations. Then, when an order arrives, it is assigned to the sub-network corresponding to its origin/destination. Finally, after having eliminated unfeasible routes (e.g., due to insufficient capacity), the best route is selected.

Xu et al. (2015) developed a stochastic integer programming model to maximize the total transportation profit for a container capacity allocation problem. The author considered different modes and random demand in the model, and genetics algorithms are used to achieve optimal solutions.

van Riessen et al. (2016) proposed a procedure using data of optimal historical plans to build a decision tree for immediate allocation of an incoming order considering the entire network. The great advantage of this approach is that the optimization method is based on offline historical data and, hence, a centralized platform is not needed. Moreover, the procedure totally outperforms usual real-world practices in which orders are managed through greedy approaches (i.e., cheapest service first) or through a first-come/first-serve policy.

Pérez Rivera and Mes (2016) proposed a forward dynamic programming approach to solve the problem of the LSP that needs to minimize freight selection costs in intermodal long-haul round-trips, in which freight becomes known gradually over time and has different pick-up and delivery locations. Compared to the impact of decisions made with and without the use of probabilistic knowledge about future freight, this approach could lead to significant savings. The same authors also used a dynamic programming approach to study the flexibility in contracts to minimize costs over a multi-period horizon through the application of mode-free policies (Pérez Rivera and Mes, 2017). The authors simulated a network that evolves with respect to the decisions previously taken, schedule of services, and status of freight. In each time horizon, some shipments have already arrived while others are still traveling, and thus, the system has probabilistic knowledge about future arrivals. They used a model and solved it through a heuristic based on approximate dynamic programming.

Finally, we found a study that considers the possibility of replanning (usually done in real-time optimization). Pérez Rivera and Mes (2017) studied the optimal allocation of resources of drayage operations, that is, transport of goods over a short distance, in which the objective is to minimize routing and terminal assignment costs by coordinating three simultaneous decisions, namely, timing shipments, routing vehicles, and assigning long-haul terminals. The authors formulated a mixed integer linear programming model and designed a matheuristics solution considering such information as available trucks, containers, and terminals, as well as shipment characteristics. A trigger to activate rescheduling processes was tested and, theoretically, others could be implemented.

4.4.3. Real-time optimization

In real-time optimization, efficient replanning is needed to deal with new data collected in real time.

Nabais et al. (2015) proposed a model predictive control (MPC) approach to find faster connections for shipment at risk of not reaching their destinations on time. The model is based on cooperation through information exchange among transportation providers and intermodal hubs that categorized cargo based on three main properties: destination, type, and remaining time until the delivery date. Knowledge about cargo transiting in the hub and available transportation connections are used to optimize operations across different time windows. At each stage, the system is updated with new information about the current state, available prediction, and goals. The MPC identifies the over-due cargo, prioritizes it, and expects a connection to allocate it.

In another study, Lin et al. (2016) designed a controller that measures and predicts the quality of perishable goods inside containers, then decides where and when all shipments should be moved. In this context, delays could easily lead to large losses. A direct graph is used to represent stages, handling, and transportation operations with maximum number of container slots. An integer programming approach is used to decide which containers move from one stage to another, prioritizing orders that have greater lost freshness. Other aspects, like poor performance of cooling systems, are considered to speed up the loss of freshness from some cargo.

Resat and Turkay (2019) used historical data on traffic, fleets, customers' locations and demand, and logistics nodes to design a transportation network in the Turkish region of Marmara. Then, they adopted a multi-objective approach based on the total transportation costs, the total time spent on the system, and the total amount of emissions to assign fleets and optimize cargo distribution. The authors considered a planning horizon of 24 h and assumed that the demand is known at the beginning of each day. Moreover, a replanning procedure is activated every time the orders change or a disruption occurs on a link.

As the literature review shows, there are still too few studies concerning real-time optimization problems and, therefore, we hope that future research will increase their number.

4.5. Simulation

Simulation is a technology that uses off-line systems to show the potential benefits of synchromodal logistics. In the literature, two different categories of approaches are found, namely, gaming and evaluation/forecasting. From the following analysis, it is clear that simulation can be used to digitalize the real world and to add or modify some characteristics, to experience new dynamics in a safe environment. Both gaming and evaluation/forecasting simulations are useful tools to better understand the benefits of applying new concepts or to take more conscious operational decisions in the real world. In particular, gaming is able to show win–win solutions. It can help build awareness of the benefits of collaboration and facilitate mental shifts while building trust and collaboration among stakeholders. Evaluation/forecasting, instead, can simulate possible scenarios and support sophisticated planning methods. Finally, we briefly discuss how digital twins can be useful for assessing physical infrastructure.

4.5.1. Gaming

In the gaming category, the real supply chain is virtualized and simplified as if it were a game. Such type of applications enable stakeholders to engage in different dynamics of synchromodality and to emerge as real actors.

A simulation game, called *Modal Manager*, was developed by Kurapati et al. (2017, 2018) to highlight the importance of information exchange as a critical enabler of stakeholder collaboration. In this game, the participants take over the role of infrastructure managers, who must use shared data to control flows and solve problems related to disruptions and accidents. The authors considered gaming a good approach, since it is easier and cheaper to experiment in a simulation than in the real world. Studying a specific phenomenon in this safe environment can control constraints and simulate different events that are too complex and chaotic in real life. Game sessions were organized to allow Dutch experts in transport and logistics to test the game and discuss their experience with greater focus on the benefits and criticalities.

Instead, Buiel et al. (2015) developed a digital game called *Synchro Mania*, in which players must act like a planner at the planning desk of an imaginary synchromodal company. The mission is to organize transport of containers by balancing three key performance indicators (transportation costs, customer satisfaction, and emissions). The game is divided into rounds, and during each round, different shipments must be allocated in a weekly calendar. Between the rounds, synchromodal strategies can be applied to enhance the network for the whole game, evolving from the current logistics situation to a synchromodal environment. The game was tested during workshops with employees from logistics companies, and the players' strategies were discussed and analyzed. *Synchro Mania* also shows the importance of simulation for other enabling technologies; in fact, Dobrkovic et al. (2016) developed and tested an intelligent amplification framework inside the game, where IAs are used as a support for human decision making.

Another simulation game called *You've Got Freight!* is found online (http://www.youvegotfreight.nl/en/youve-got-freight/, accessed: 2019-02-04). Players enact the role of an freight forwarder that has to transport goods from a harbor to the hinterland. During the game, players have personal experience of managing the complex challenges embedded in synchromodal logistics. In particular, the dynamics of flexible planning and coupling of different modalities of expeditors are central elements in the game. Players become aware of the essence of collaboration, which is needed to implement synchromodality successfully.

Finally, a serious game (https://www.dinalog.nl/project/serious-gaming-spoor-en-synchromodaalvervoer/, accessed: 2019-02-04) was developed by the Dutch Institute for Advanced Logistics to help stakeholders to understand the importance of synchromodality while working in a safe environment that simulates real scenarios. The players can themselves experience the effectiveness of synchromodal transport through action learning. Playing the game helps operational staff to develop improved internal and external procedures. In addition, when playing the game with sellers and customers, a mind shift is expected, which leads to an increased percentage of amodal booking. In addition to the development of the game and gaming workshops, the project also demonstrates the lessons learned in real life. Daily activities of a network of partners improves in a living lab environment based on the outcomes of gaming. The result of the project is the development of new operational procedures and an increased number of amodal bookings.

The main contribution of gaming is that it provides interactive and collaborative environments to test and understand the characteristics and advantages of synchromodality. Hence, gaming deals with two CSFs (awareness and mental shift) as well as network, collaboration, and trust.

4.5.2. Evaluation and forecasting

Other simulation software is more focused on evaluation and forecasting, namely, virtualization of the real world is used to predict the outcome of future scenarios and evaluate specific operations. The impact of these operations remains at a simulation level, without the risk of acting on real processes.

Farahani et al. (2018) developed a tool called SySCEA (synchromodal supply chain energy analysis) that simulates the overall supply chain environmental impact and costs derived from the total amount of fuel consumption. The information elaborated in the simulation can be used both to understand the benefits of operating in a synchromodal transportation network or taking decisions at different planning levels with more consciousness of the impact of transportation operations on the environment. Distance, time-related, packaging-related, and fuel related parameters are used in the simulation. Again, Zhang and Pel (2016) developed a model called SynchroMO to evaluate the performance of a synchromodal networks. The authors used historical data to generate the daily demand by using historical data and Monte Carlo simulation, followed by assigning each shipment to a route with a capacitated schedule-based flow assignment algorithm. This procedure enables calculation of the performance indicators that were tested for the case of the transport of containers between the Port of Rotterdam and its hinterland. From this analysis, the authors found out that synchromodality brings greater benefits than intermodality, especially in reducing delivery time, less road transport, and consequently, less emissions.

Other studies present simulation applications, which, besides their role in evaluating possible situations, can be connected directly to a more general decision support system. For instance, Kapetanis et al. (2016) proposed a tool to calculate the costs, emissions, and delivery time of different possible transportation routes for the same shipment, comparing the alternatives of these factors. The tool works as a decision support system for the planning phase, but it could also work continuously and refine the simulation if real-time data could be provided, allowing consciousness of unexpected issues and replanning. The authors presented a case study related to the port of Piraeus, in which the tool simulates an itinerary starting from Shanghai, passing through Piraeus, and arriving at Prague. However, it can be adapted to work for other ports and routes.

Another application of this kind of simulation is related to urban traffic. Sirmatel and Geroliminis (2018) proposed an economic MPC approach to better manage traffic in highly congested urban areas. In their model, they integrated perimeter control and route guidance, two features that were important during simulations to show the potential impact of this approach on urban mobility.

Finally, Giusti et al. (2018) developed an optimization and simulation toolset to support decision making at the strategic planning level, in the context of the SYNCHRO-NET project (see Section 5.2). In this interactive and map-based simulator, the user can simulate a shipment from an origin to a destination in a given time horizon. To customize the simulation experience, the user can specify advanced searching options (e.g., mandatory and forbidden routes/stops, multiple destinations, number of containers) and configurations (e.g., customized values for different parameters). Moreover, data regarding nodes, routes, and services can be added or modified to allow the user to include the current or hypothetical future developments of the logistics network. The response of the tool is a list of feasible itineraries using combinations of different synchromodal routes, transportation modes, agencies, and schedules. The user can compare different itineraries based on time duration, distance, costs, CO_2 emissions, number of stops, and key risk indicators calculated through a Monte Carlo roll-out approach (Holfeld et al., 2018b).

Evaluation and forecasting mainly contribute to sophisticated planning by providing tools to estimate the impact of immediate decisions on future scenarios.

4.5.3. Digital twins

Potential future developments of the physical infrastructure can be addressed through simulation. In fact, the concept of digital twins, which aims to digitalize both physical infrastructure and activities, can be useful for simulating network performance at different decision levels. For example, in strategic planning (long-term decisions involving great investments that shape the general development policies and the operating strategies of the system), simulations can aid design of a more reliable physical network by testing the impact on the virtual network of resources and infrastructure not yet acquired. Other aspects, like physical network configuration and evolution, location of facilities, resource acquisition, services, and tariff policies, can be addressed. At the tactical level, at which decisions over a medium-term horizon need to be taken and utilization of resources must be optimized to improve network performance (Crainic and Laporte, 1997), the digital twins of infrastructure and resources can be used to plan services and transportation flows on the physical network by simulating different activities and disruption scenarios. The addressed tactical problems are mainly of two types: network flow planning problems (i.e., movement of orders throughout the physical infrastructure), and service network design problems (i.e., selection of transportation services and modes to move goods (Steadieseifi et al., 2014). At the operational level, demand must be satisfied by planning the allocation of resources over a short time horizon and finding the best itineraries and services for customers' orders, considering also the limited capacity of vehicles and resource repositioning, for example, empty load units (Steadieseifi et al., 2014). At this level, a detailed representation of resources and accurate planning of the activities is essential, since the high dynamicity of the supply chain gives time factor an important role (Crainic and Laporte, 1997). Finally, in real time, unexpected events play an important role that lead to replanning procedures. At this level, simulation is important to test the ability of the network to react to disruptions.

Simulation based on digitalized infrastructure, services, and activities enables a more conscious understanding of future scenarios and the synchronization of activities and resources; for these reasons, it benefits sophisticated planning. Moreover, simulation based on digital twins can contribute to evaluate possible future investments on the physical infrastructure.

4.6. Integration platforms

The definition of a suitable common platform has been addressed by various research studies and an overview of several of them is presented in this subsection.

Tsertou et al. (2016) outlined the lack of real-time information exchange among stakeholders as a critical barrier to an effective consolidation of containers (different shipments sent as a single unit to the same destination). To overcome that barrier for the Port of Piraeus, the authors proposed a cloud-based information portal, to collect data from various sources and make them available to all stakeholders through a single platform.

If the adoption of a single platform is not feasible (e.g., in many cases companies feel safer operating their own systems), federated infrastructure (private interconnected systems to allow interoperability and information sharing) could be a valid alternative, as pointed out by Hofman (2015). Based on his work, federated infrastructure relies on data classification, definition of roles, and communication protocols. Specifically, data need to be supplemented with information on ownership, accessibility, cost, lifetime, and policies on change management. Regarding accessibility level, data can be classified as follows: open data (for every user of the infrastructure), community data (for a restricted number of stakeholders), partner data (for stakeholders in a partnership), and internal data (for a single company). A clear definition of roles is the basis for defining each stakeholder's information accessibility. Moreover, a common protocol is needed to regulate data sharing and allow the development of services.

Raap et al. (2016) proposed a new architecture based on a common data model for an integration platform for 4PL service providers, which ideally manage the whole supply chain for their customers by interfacing with different 3PL service providers. The common data model facilitates the integration of different data types, mainly collected from web pages and through the platform, and this information is made available to stakeholders. The reported benefits include tracking of shipments in real time, and increasing the efficiency of the use of the physical infrastructure.

Singh (2014) proposed a service-oriented IT platform to enhance the cooperation of LSPs. The platform is meant to operate ahead of the internal systems of companies and focuses on synchromodal operations (e.g., switching mode). Moreover, it considers cooperation among competitors. Hofman (2014) presented architecture aimed at sharing business information. It consists of IT components that share information in a cloud-based data store, which is provided with a data management layer for keeping track of data changes. The main functionalities of the IT components are: creating and coordinating value chains (set of activities to deliver a valuable product or service), managing business transactions between customers and service providers, planning resources, and evaluating the impact on business transactions of data provided by sensors (e.g., change of estimated arrival time of a truck in a terminal).

Given that security issues are of paramount importance, there is increasing interest in new technologies related to blockchains and

Table 1
Existing implementation (I) and research projects (R) involving synchromodality.

Name	Type	Main topic	Enabling technologies
TKI-Dinalog	R	Synchromodal tools for real industry problems	Traceability, optimization, integration platforms
Embark	I	Self-driving trucks for long haul journeys	Intelligent systems
EGS	I	European synchromodal service provider	Not publicly available
Merck Group	I	Demand forecast and automation of purchasing, production, and distribution operations	Data analytics, intelligent systems
ITeLS tools	R	Diagnostic tools for supply chain managers	Data analytics, simulation
Port of Rotterdam	I	Some tools specifically developed for the largest European sea port	Traceability, intelligent systems, data analytics, integration platforms
Rolls-Royce	I	Self-driving ships capable of navigating and berthing	Intelligent systems
SYNCHRO-NET	R	Cloud-based integrated tools for logistics management at strategic, tactical, operational, and real-time levels	All
T-Mining	I	Blockchain system in container collection for the Port of Antwerp	Integration platforms
Volvo	I	Self-driving vehicles for transport in open pit mines, terminals, and garbage collection	Intelligent systems

smart contracts. In the real world, cases in the supply chain can be found in Perboli et al. (2018). Blockchains are distributed ledgers that can record transactions between parties in a verifiable and permanent manner. In addition, a blockchain may be equipped with programs called smart contracts, which can be used to define a set of rules to regulate stakeholders' business interactions. Event-driven operations may be predefined as well. An example based on Bartoletti and Pompianu (2017) is as follows: payment made by a customer to an LSP can automatically bring about the payment of the carriers involved in the shipment.

Integration platforms may have a positive impact on several CSFs. Network, collaboration, and trust can take advantage of trustworthy foundations, such as blockchains, which can enhance collaboration by making stakeholders feel safe doing business on an IT platform. Smart contracts can contribute to a legal and political framework, by encouraging the definition of stakeholders' liabilities in a clear and transparent manner. Awareness and mental shift can benefit from the variety of services the platform offers and, therefore, stakeholders can be driven to experiment with new approaches. Lastly, smart contracts can help improve flexibility and transparency, which are essential issues for pricing, cost, and service.

5. Case studies

In the next two sections, we present some real experiences and implementation of synchromodality logistics and successful research projects involving synchromodal logistics concepts and the relative enabling technologies. A summary of the implementation (I) and research projects (R) is presented in Table 1.

5.1. Real experiences and implementation

The Port of Rotterdam is the largest European sea port; its leading position is due to its outstanding accessibility for sea-going vessels, intermodal connections, and a workforce of about 180,000 people inside the port and related industrial area. The city and port of Rotterdam form an innovative ecosystem in which institutes, government organizations, logistics stakeholders, test and prototype facilities, start-up accelerators, network organizations, and investment funds cohabit and cooperate under the vision of a global hub. For this reason, in its *Port Vision for 2030* program, (https://www.portofrotterdam.com/sites/default/files/upload/Port-Vision/Port-Vision-2030/files/assets/basic-html/index.html, accessed: 2019-02-04), the Port of Rotterdam outlined a plan to become the most important synchromodal hub in northwest Europe and to achieve a leading position in the transition to cleaner energy.

A big focus of the abovementioned program is on the efficient use of transport, since substantial expansion of the infrastructure is undesirable owing to its high costs and negative local and environmental impacts. In order to achieve this efficiency, the various elements of international supply chains and networks (e.g., hinterland terminals, sea terminals and hinterland transportation systems) will be further integrated into a single coherent, coordinated system. Moreover, information flows between all the parties involved in the supply chain should be organized in the best possible way for this purpose. For example, *European Gateway Services* (EGS, http://www.europeangatewayservices.com/en/, accessed: 2019-02-04) is a synchromodal LSP connecting the Port of Rotterdam to strategical inland terminals. EGS offers services based on different modes, especially high frequency rail and barge routes to reduce use of trucks, thereby, lowering emissions. Flexibility and contingency solutions (e.g., modal shifts) form the basis of their business, enabling customers to operate at lower costs while maintaining high-quality services.

According to the *Port Vision for 2030* progress report for 2014 (Port of Rotterdam, 2014), information technologies play an essential role in improving the performance of the entire logistics system. Some tools and services, like *Pronto*, *Navigate*, *Shiptracker*, and *Portmaster*, have been developed and are already in use. *Pronto* (https://www.portofrotterdam.com/en/tools-services/pronto, accessed: 2019-02-04) is a real-time application through which shippers, terminals, and service providers can share real-time information about port calls. This, combined with AI-based forecasting, improves the efficient execution of activities, achieving greater benefits in terms of costs and emissions reduction. *Navigate* (https://www.portofrotterdam.com/en/tools-services/navigate, accessed: 2019-02-04) is a tool designed to compare routes and find all terminals and companies working in the Port of Rotterdam, also offering an empty depot planner for repositioning empty containers. *Shiptracker* (https://www.portofrotterdam.com/en/tools-services/shiptracker-beta, accessed: 2019-02-04.) is a tool for collecting information with an automatic system that integrates big data and machine-learning algorithms to identify and track ships, allowing better calculation of the estimated arrival time. Finally, *Portmaster* (https://www.portofrotterdam.com/en/doing-business/services/online-services/portmaster-port-management-system, accessed: 2019-02-04) is a port management system integrating different modules that are based on big data and artificial intelligence (AI) technologies, which combine a large amount of data accessed from different sources and several port customers. The system offers tools to plan, monitor, and administer a port with high consciousness of the overall situation and the ability to focus on specific events.

Another clear output of the *Port Vision for 2030* progress report is the importance of automation to handle increasing container flow. Some terminals are already operating autonomously and remote operators using technologies, like automated guided vehicles and cranes monitored in offices (Port of Rotterdam, 2016). These kinds of robots can significantly help workers by doing dangerous and repetitive tasks more efficiently and reduce their work effort required. In fact, other projects related to automation and self-driving vehicles have been implemented in other places. Rolls-Royce and Finferries collaborate in an archipelago near Turku (Finland) to equip a ferry with intelligent technologies so to achieve autonomous navigation, without human intervention (Rolls-Royce, 2018a,b). During the demonstration, the ferry was able to avoid collisions by using sensor fusion and AI, also performing automatic berthing. Recently, Rolls-Royce started collaborating with Google to improve its AI technologies, with the aim of making autonomous ships a reality in logistics (Rolls-Royce, 2017). Again, Volvo (https://www.volvotrucks.com/en-en/about-us/automation.html, accessed: 2019-01-24) is testing autonomous trucks to transport lime stones from an open pit mine and to collect garbage. They are also developing an autonomous vehicle (called Vera, https://www.volvotrucks.com/en-en/about-us/automation/vera.html, accessed: 2019-01-24) to optimize short transport of large volumes of containers in terminals, which is also connected to a cloud-based service and a management center. Self-driving trucks are also becoming a reality for long distance trips, for instance, the startup Embark (https://embarktrucks.com/, accessed: 2019-01-24) is testing autonomous vehicles for long-haul trips on US highways. Finally, Merck Group (a global manufacturer of chemicals and pharmaceutical products) aims to build what it calls a “self-driving supply chain” (Delivered. The Global Logistics Magazine, 2018). In fact, by using machine-learning algorithms, they are close to obtaining fully automated demand forecasts, whereas by developing AI systems, they aim to automate supply planning, and become smart enough to manage such aspects as purchasing, production, and distribution without human help.

For completeness, we present another interesting project to enhance security for collecting containers developed by the startup *T-Mining* in the Port of Antwerp (Port of Antwerp, 2017). Through a blockchain system, stakeholders obtain digital rights that allow collection only for them. A blockchain helps to prevent fraud and to have continuous flow of goods, thanks to its distributive structure, which works properly even if a node goes down.

5.2. Research projects

The Dutch Institute for Advanced Logistics, TKI-Dinalog, which actively works on research projects to provide solutions to real industry problems, has recently started to focus on synchromodality. Some related projects are Ultimate, SPoT, and TEUbooker. Ultimate (https://www.dinalog.nl/en/project/ultimate/, accessed: 2019-02-04) is based on a control center where available information is optimized to manage flows from seaports to the European hinterland. It aims to avoid congestion and enhance cooperation among operators. SPoT (https://www.dinalog.nl/en/project/spot/, accessed: 2019-02-04) is a decision support tool that monitors shipments, exchanges information about real-time events, and helps to choose synchromodal solutions. SPoT provides services that can reduce costs and delivery times while being more reliable and sustainable. Moreover, it can be integrated into stakeholders’ ICT systems through APIs (Application Programming Interfaces). Finally, TEUbooker (https://www.dinalog.nl/project/teubooker/, accessed: 2019-02-04) is a booking system that offers synchromodal solutions that optimize the unused capacity of all modes to reduce the cost of transport.

Mason and Lalwani (2006) presented a set of diagnostic tools for supply chain managers, enabling better knowledge of operations and performance of their supply chains. The tools are part of a research program of the Cardiff Business School, called Integrating Transport and e-Commerce in Logistics and Supply Chains (ITeLS), which studied how better integration of transport leads to better performance of the supply chain. The ITeLS tools comprise different techniques and a few examples are presented. Quick Scan is a supply chain-oriented business diagnostic used to improve the understanding of capabilities, competencies, and weaknesses of supply chains. Quick Scan was used to study the impact on the overall performance of the supply chain for inventory management between different stakeholders. In another ITeLS case study, researchers used simulation to improve the ordering system of an industrial partner, thereby achieving better product flow in respect of demand oscillation. Other tools comprise measurement of key performance indicators of vehicle effectiveness and sustainability, evolutionary models to assess supply chain integration, and big picture mapping techniques.

Under the Horizon 2020 EU Framework Programme for Research and Innovation, a project called SYNCHRO-NET (Synchromodal supply chain eco-NET) has successfully demonstrated that it is possible to overcome the stress caused by increasing transportation distances, higher complexity, and vulnerability of current international supply chains (Giusti et al., 2019). The SYNCHRO-NET approach exploits the possible benefits from slow/smart-steaming and synchromodality transportation strategies, as well as related business models, to foster sustainability, quality, and reliability of freight logistics. From an ICT perspective (Holfeld et al., 2018a), SYNCHRO-NET is conceived as an integrated and collaborative cloud-based eco-system of optimization and simulation software modules that supports stakeholders’ decisions in freight transport and logistics management at strategic, tactical, operational, and real-time levels. The platform, which embeds AI agents to analyze and extract knowledge from the collected data, has

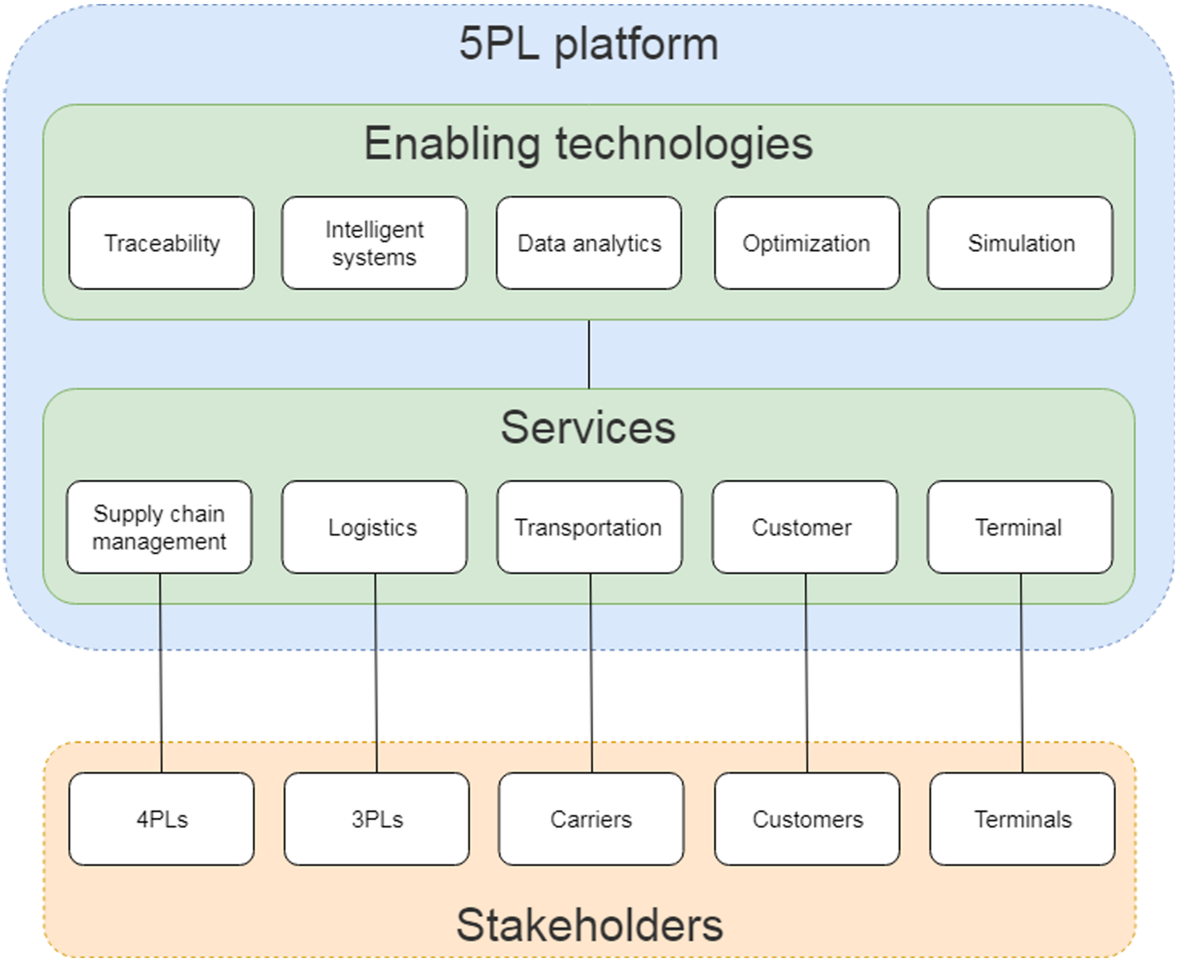

Fig. 3. 5PL platform.

achieved a high grade of automation in several processes to overcome all issues related to human-based operations. Moreover, the cloud provides connectivity and protocols to communicate and share information internally and, potentially, with related external information systems. An added value of this approach is to involve several stakeholders in the process to better understand their vision and needs and to assess the value proposition of the SYNCHRO-NET solutions (Perboli et al., 2017). The SYNCHRO-NET approach has been tested on real-case demonstrators, which vary from trans-oceanic trade lanes (e.g., long-haul commerce between the Far East and main European ports), to intra-European routes (e.g., truck and rail corridors and Mediterranean feeder services), up to very specific regional supply chains (e.g., shipments through the port of Cork, Ireland).

6. Open research issues

In this section, we propose some open issues related to synchromodal logistics, based on our previous analysis. We discuss the emerging concept of 5PL service providers and the need for a holistic platform that enables stakeholders to interact through technological services. We then present, for each enabling technology, some promising future research directions. Finally, we briefly present the physical internet (PI) paradigm and its integration with synchromodality.

6.1. Fifth-party logistics service providers

The concept of 5PL is still at an early stage and information is limited. Pavlić Skender et al. (2016) described 5PL service providers as LSPs that focus their businesses on the strategic management of supply chains through technology solutions that are often related to e-business. In practice, 5PL service providers use technology solutions to solve logistics and strategic management problems in supply chains with complex networks. Since the concept of 5PL is new and still not well defined, we provide our vision on its role, which is strongly related to enabling technologies. In fact, integrated into the 5PL platform (Fig. 3), enabling technologies together form a common system such that all stakeholders can benefit entirely from their synergy. In this vision, the role of 5PL is to develop specific technology solutions for each stakeholder integrated into the 5PL platform. The platform provides an easier way to communicate, to have business interactions, and to share information securely. It allows stakeholders to manage their business interactions easily while having access to technology tools for tracking, using intelligent systems, and performing data analytics, optimization, and simulation. Since each enabling technology is strongly related to others, it is important to organize them under this common platform. In fact, advancements in one technology strengthen and benefit others. Moreover, each stakeholder may have access to different services by interfacing with modules specifically designed for its needs. Through the 5PL platform, 5PL service providers could become important intermediaries providing technology solutions to overcome CSFs and fill the lack of technology that many companies have. In fact, most companies working in the logistics market are small and medium-sized enterprises (around 80%) and often they have very simple or almost no IT solutions at all, usually interfacing manually with the web interfaces of their customers and collaborators (Hofman, 2015).

It is important to note that most of the enabling technologies discussed so far have been considered, implemented, and assessed in the SYNCHRO-NET project described in Section 5.2. In fact, the SYNCHRO-NET project pursued the objective of creating a prototype of such a kind of coordinating platform. Therefore, it could be a starting point to study the real implementation of a 5PL platform, also considering the continuing evolution of enabling technologies. However, the SYNCHRO-NET platform was merely a prototype and its transposition into real-world markets strongly depends on its capability to address all the CSFs presented in this study.

6.2. Promising future research lines

For each enabling technology of the 5PL platform, we discuss a few issues for future research.

Regarding traceability, common standards have not been globally adopted yet, but there has been some effort in that direction (e.g., GS1 standards and Singh and Van Sinderen, 2015). Defining common standards is a key prerequisite for complete visibility of the supply chain and simplification of data management. In the supply chain context, the use of information to build digital twins must be studied and the benefits for visibility and the implications for simulation should be considered. Lastly, the consequences and prospects derived from complete visibility must be addressed. For instance, if all orders and product life cycles were tracked, goods could be easily labeled by the origin of raw materials or transportation modes used in the shipment. This would enable greater consciousness of the product quality and environmental impact. In our view, a more complex and complete tracking system able to provide visibility of the entire supply chain is required.

A promising and interesting field of intelligent systems is that related to IAs. Considering that synchromodality requires quick decision making, building IAs to reduce the human effort can help to accelerate supply chain management. Furthermore, IAs should integrate tools from other categories (e.g., data analytics and optimization). Moreover, CPSs are an interesting topic of study. To find new ideas about how to automate manual operations can make information about their execution more predictable. It is also important to study how to create systems, in which IAs and CPSs are synchronized to reduce the human involvement in routine operations and simple decision making.

With regard to data analytics, there is a need to understand how to use different types of data available from different sources to create value-based information. Considering that data could come from many disparate sources (e.g., Singh et al., 2018 based their research on Twitter posts), we should consider which information could be useful for synchromodality, where to source it from, and how to use it. Moreover, in the case of synchromodality, we found no study that developed methods to transform generic information into complex knowledge (e.g., neural networks and machine learning algorithms). Future efforts in this direction are needed.

For optimization, we identify common and different kinds of approaches for strategic/tactical, operational, and real-time planning. All of them should consider that the high complexity of synchromodal networks requires very efficient approaches, with high performance in computational time. Moreover, each planning level should now consider the features of synchromodality:

- Strategic/tactical planning, which comprises network design, network flow planning, and service network design problems, should also address aspects of the operational and real-time levels (e.g., disruptions and traffic congestion) to build resilient networks. Infrastructure and services should provide flexible solutions for dealing with uncertainty, while maintaining efficiency and reliability. In addition to considering the best combination of infrastructure and services to provide high revenue, it is important to keep in mind that synchromodal networks are based on resilience and revenue is strongly related to how we address uncertainty.
- Operational planning focuses on the allocation of resources needed for prior planning, depending on the category of activities and policies. Operational planning is done a few days or weeks in advance, and in some cases, at the last possible moment (e.g., Crainic et al., 2005 for the day-before planning problem in city logistics). For this reason, operational planning should be split into two phases: early planning and final planning. Allocation of resources to activities must be planned in advance (early planning), but at the last available moment before execution, new knowledge should be used to make adjustments (final planning).
- Real-time planning focuses on re-planning operations. At this planning level, real-time information plays a key role. In fact, complete visibility of all operations is required to reallocate resources during the execution; however, the quantity of data and the need to take quick decisions drastically increase the complexity. To deal with this, new approaches to provide rapid solutions must be studied.

Broadly, each plan at different levels should be made and updated even during its actuation. For this reason, we identify four stages in which each type of plan is involved: planning, validation, execution, and evaluation. The first stage is planning, in which a new plan is made. In the early stage, some information might not be available, and hence, planning is undertaken by combining the deterministic and stochastic variables based on historical data. In this phase, it is also important to prepare risk-solving procedures, that is, how to react when disruptions occur during the execution phase. In the second or validation stage, some stochastic variables considered in the planning phase could become deterministic when new information is available. This new knowledge must be used to validate the plan by making adjustments, and implementing the risk-solving procedures. The third phase is execution, which starts when a plan is activated and continues until it is completed. During execution, how the plan is actuated as well as the workflow and disruptions of the whole supply chain must be tracked. In this phase, risk-solving procedures must be activated. The last or evaluation phase is reached when the plan is completely executed. In this phase, the original plan and historical information about its execution are analyzed, providing insights to make new plans or adjust previous ones.

It is important to consider plans as a complete entity instead of separate ones and to use information about the status of plans in each phase to synchronize them. Even if a disruption does not directly affect a plan, a good option is to adjust it to solve more urgent issues affecting other plans. Moreover, Dong et al. (2018) suggested that synchromodality should consider different aspects of the supply chain, such as inventory management, transportation, and production. Finally, all the new features of synchromodality involve changes to old optimization problems and, as De Juncker et al. (2017) suggested, a common framework to classify synchromodal problems and models could help researchers to find common methods to solve related problems.

A promising field in simulation is related to serious games that can help to accelerate the mental shift. In general, both simulation games and digital twins should increase their complexity and move closer to the ideal synchromodal network. Digital twins of synchromodal networks must be studied to enable tests on future developments, as the testing environment for conducting experiments on other technologies (e.g., like Dobrkovic et al., 2016 did with the serious game of Buiel et al., 2015). Lastly, simulation should be refined for a better comparison of intermodality and synchromodality.

Much research has been undertaken on the realization of integration platforms (Tsertou et al., 2016; Hofman, 2015; Raap et al., 2016; Singh, 2014; Hofman, 2014). They should be tested in the real world to understand which approach fits better (e.g., centralized, distributed, or federated). Moreover, referring to SYNCHRO-NET (Giusti et al., 2018; Giusti et al., 2019; Perboli et al., 2017; Holfeld et al., 2018a,b), platforms should focus on integrating complex technology solutions (as in the theoretical 5PL platform), going beyond the simple collection and sharing of data. Moreover, new concepts, like blockchain and smart contracts, deserve more attention in the context of synchromodal logistics. In addition, other techniques, such as cloud computing, parallel computing, and ubiquitous computing, can be considered while developing platforms capable of offering better computational performance.

6.3. Integration with the physical internet paradigm

The PI "aims to organize the transport of goods similar to the way data packages flow in the digital Internet" (Treiblmaier et al., 2016). In practice, PI leverages the way messages are sent through the internet in standardized data packets to make logistics more efficient and flexible. Items are shipped through smart interfaces following collaboration protocols and during the journey, they are encapsulated into modular units (i.e., pallets and containers). During transport, items can go through encapsulation and decapsulation processes several times to optimize the carrier load. This approach, strongly ruled by modularity, complicates the transport of goods and requires complex tracking and synchronization of flows.

Like synchromodality, PI relies on real-time information, flexible transportation networks, cooperation, coordination, and synchronization. Ambra et al. (2018) studied the evolution in the literature of both PI and synchromodality paradigms to understand how each could enhance each other. In fact, the authors highlighted that these two paradigms are studied in parallel despite the integrated vision of the European Technology Platform—Alliance for Logistics Innovation through collaboration in Europe (http://www.etp-logistics.eu/). Studies on synchromodality tend to focus on the transportation of large containers, whereas those on PI tend to focus on smaller units. Given that in synchromodality, the optimal consolidation of containers is essential, and repositioning of empty containers is still an issue, PI could provide insights to increase the fill rate with such approaches as advanced encapsulation processes and real-time optimization. The PI mostly focuses on truck transport in the local context, whereas synchromodality usually considers long-haul journeys by truck, train, ship, barge, and aircraft. We strongly agree with the authors that synchromodality and PI should be studied together. For instance, other researchers studied policies to reduce emissions that could be applied to both synchromodal and PI networks (Lemmens et al., 2019). Moreover, we consider the enabling technologies presented in this study to be common enablers for both paradigms.

7. Conclusions

In this study, we provided a comprehensive overview of the state on synchromodal logistics. Since an exhaustive definition of synchromodality was not yet available, we presented the main features of this paradigm to help other researchers to understand the characteristics of synchromodality clearly and to use them for future study. Moreover, we attempted to link the identified CSFs of this paradigm to six classes of enabling ICT/ITS technologies. Characteristics, interrelationships, and future research directions were analyzed for each enabling technology. Moreover, we pointed out the importance of leveraging the synergies between enabling technologies by defining a technological common platform that allows synchronization of stakeholders' activities and simplifies their business. We also proposed a new type of LSP (5PL, often debated in the literature but never clearly defined) that could develop this common platform by taking on the role of the synchromodality orchestrator.

Our definition of synchromodality provided in the introduction is based on the main characteristics that emerged during the analysis of this study. We now motivate our choice. With "efficient, reliable, flexible, and sustainable services" we focus on the characteristics that synchromodal services should have, inheriting efficiency and sustainability from the previous concepts and introducing reliability and flexibility to provide services resilient to disruptions. With "coordination and cooperation of stakeholders" we emphasize the importance of cooperation and the need for an orchestrator (5PL) to coordinate the system. The main feature of synchromodality is embedded in the "synchronization of operations". Note that, in using the word *operations*, we move the focus from synchronizing only transportation activities to possibly synchronizing all activities performed in a supply chain. With "one or more supply chains" we point out that the collaboration could be improved by integrating activities and relevant information in a bigger network. Lastly, "driven by ICT/ITS technologies" emphasizes the importance of the described technological enabler to implement synchromodal logistics concepts efficiently.

In conclusion, we argue that synchromodal logistics must be studied in the future by considering all possible enabling technologies associated with CSFs. Specifically, scientists analyzing in each of these technologies should develop research supporting the features of the synchromodal paradigm. Moreover, the integration between technologies under a common 5PL platform is essential for enhancing the benefits of adopting synchromodality and building a stronger, reliable, and flexible system. In addition, it is important to study and define the role of 5PL service providers in the supply chain from different perspectives, like business management or law. The 5PL service providers could be interpreted either as technology solution service providers or as an evolution of the 4PL service providers with their businesses largely driven by technology. There is a strong case to be made to use recent or ongoing research projects and case studies of real-life applications of synchromodal logistics as a starting point to implement synchromodality in the broader context. For instance, Agbo et al. (2017) and Agbo and Zhang (2017) performed a feasibility study about implementing synchromodality in a developing country (Ghana). However, more effort is required to build a global supply chain that is driven by synchromodality.

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Appendix A. List of acronyms

Acronym	Definition
3PL	Third-party logistics service provider
4PL	Fourth-party logistics service provider
5PL	Fifth-party logistics service provider
AI	Artificial intelligence
CPS	Cyber physical system
CSF	Critical success factor
DDSC	Demand-driven supply chain
IA	Intelligent assistant
ICT	Information and communication technologies
ITS	Intelligent transportation systems
LSP	Logistics service provider

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