Environmental impact assessment of intercontinental transport network with digital twin under PI framework

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Abstract: *This paper evaluates the impact of collaborative transport strategies and emerging technologies on an intercontinental transport network with a digital twin. The study assesses the effects of applying Physical Internet (PI) concepts and enabling technologies, such as Internet of Things, blockchain, and artificial intelligence, on the performance of the transport network, including key indicators such as carbon emissions, delivery performance, and logistics costs. Results show that implementing PI concepts and integrating these technologies can lead to improvements in environmental and economic indicators. Despite these benefits, there are several challenges to overcome, including the integration of these technologies into existing logistics systems, coordination among stakeholders, security and confidentiality. Overall, the study demonstrates the potential of these technologies and concepts to contribute to sustainable transportation systems, but further research is needed to evaluate their feasibility and scalability in real-world transportation networks, as well as to develop strategies to address the challenges.*

Keywords: *Digital Twin, Agent-Based Simulation, Intermodal and Synchromodal Transport.*

Conference Topic(s): *PI impacts; PI modelling and simulation.*

Physical Internet Roadmap *(Link): ☒ PI Nodes, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

1 Introduction

Supply chain disruptions could cost European economies around €920 billion of their gross domestic product by 2023, which corresponds to a loss of 7.7 percent of the eurozone's GDP in 2023 (Accenture, 2022). Over the past few years, there have been several significant events that have impacted global supply chains, including the well-known COVID-19 pandemic, the war in Ukraine, and the recent Evergreen vessel blockage in the Suez Canal. These events have highlighted the importance of resilient supply chains and the need for businesses to prioritize supply chain risk management.

Supply chain resilience and sustainability are closely related. Supply chain resilience is an important condition for supply chain sustainability at its three levels: social, economic and environmental (Zhu and Wu, 2022).

Based on the Internet of Things, standard coordination protocol, smart containers and other key foundations, the Physical Internet (PI) provides an interconnected, shared and adaptable logistics system, which has great potential to significantly increase the reliability and resilience of supply chains (Ben Neila and Nemeth, 2021; Peng et al, 2021). The PI concept roots its origins in the unsustainability in the long run from economic, environmental and societal perspectives of the current global logistics and supply chain management practices that constitute the "worldwide global logistics sustainability grand challenge" (Montreuil, 2011). The PI is an integrative concept, which spans the boundaries between companies and therefore also necessitates substantial changes within and between organizations (Treiblmaier, 2019). The realization of the PI requires a fundamental re-organization in logistics that entails truly integrated processes and horizontal collaboration among organizations where collaboration among participating companies in the supply chain, third parties and externalities play a central role in its conception.

Technology can play a significant role in building resilient and yet still competitively cost-efficient supply chains enablers are intended to create an open, interconnected global logistics system (Zhu and Wu, 2022).

The ALICE roadmap to the physical internet explains the development of the PI over the next twenty years. The roadmap dictates the development path of five specific areas (logistics nodes, logistic networks, system of logistics networks, access and adoption, and governance) for the PI realization. The role of technologies is as enablers and facilitators of their development paths. This article explores the role of three specific technologies that enable the PI realization and increase supply chain resilience: Internet of things (IoT), Artificial Intelligence (AI) and Blockchain.

IoT devices are equipped with sensors and other hardware components that allow them to collect data such as temperature, humidity, motion, and location. Thus, the IoT enables the Physical Internet by providing real-time data of logistics goods and assets that can be used to optimize logistics operations. AI can enable the Physical Internet by providing real-time data analysis, predictive analytics, and machine learning algorithms that can optimize the logistics network (Radanliev et al., 2021). Blockchain helps track data transactions taking place between multiple networks owned and administered by various organizations as physical goods pass between points in the supply chain. It enables immutable data records and facilitates a shared data view along the supply chain. The blockchain can be used to alleviate risks inherent to supply chain management such as uncertainty regarding quantities of production, lack of transparency when a manufacturer changes supplier, unethical behavior of middlemen, and complicated inventory management (Treiblmaier, 2019). This technology offers a solution for fundamental barriers of the Physical Internet concerning the exchange of value and physical assets in logistics networks and decentralized leadership structures (Kuhn et al, 2019).

A supply chain digital twin is a detailed simulation (virtual representation) of real-world supply-chain entities and processes. Digital twins use real-time data to forecast supply chain dynamics and understand supply chains' behavior. Digital twins can help to optimize performance, predict outcomes, and test scenarios in a safe and cost-effective way. By simulating different scenarios of the supply chain, companies and governments can evaluate the impact of proposed changes before implementing them.

After a literature review to position this work in the current state of knowledge in the area, this paper evaluates the impact of PI strategies and emerging technologies on an intercontinental transport network with a digital twin based on multi-agent simulation techniques.

2 Literature review

The general interest in the PI concept is growing. Treiblmaier et al. (2016) identified a list of PI-related problems and questions yet to be answered by research. In this sense, the work carried out in this paper contribute to the area related to change in business models and culture trough the evaluation of the benefits and challenges of adopting a new paradigm in business practice.

Indeed, simulation techniques help evaluate the impact of various decisions on indicators of cost and emissions, showing the benefits of adopting more sustainable and efficient practices. Simulation techniques can thus support the transition to a low-carbon economy and society.

Digital twin, referring to the virtual representation of a physical object, is well-perceived as a key driver in the development of PI-based Supply Chain Management. Nguyen et al. (2022) concluded from their comprehensive review of the literature in this field that throughout the years, PI was investigated typically from the logistics and manufacturing perspective. Meanwhile, Digital Twin was mostly adopted as an enabler for smart manufacturing. Only most recently, it was adopted for supply chain resilience development in response to the COVID-19 pandemic and its consequences (Dy et al., 2022; Lv et al., 2022; Klöckner et al., 2023; Ivanov 2021; Burgos 2021).

Wang et al. (2022) highlighted the opportunities to build and improve the smart supply chain by building Digital Twins. In this regard Multi-Agent Simulation of PI supply chain networks is a common methodology to capture the diversity, dynamics, and emergent behaviors of the agents involved in a digital twin (Hakimi et al., 2012; Furtado, 2013; Sun et al., 2018; Chargui et al., 2020).

Recently, authors on the field have started to investigate opportunities of application of new disruptive technologies in the PI vision. Tran-Dang et al. (2019 and 2020) investigated the perspectives of PI under the impact of the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), big data analytics (BDA), cloud computing and blockchain. In the studies, important perspectives were identified. However, it was pinpointed that since the PI is still in the initial stage of development and realization, the co-implementation of PI and the new disruptive facilitating technologies faces many critical challenges and barriers related to system, business, data, and policy issues. They concluded that besides the vital role of technologies, a mind shift in the business culture, policies, competition, and collaboration has a significant impact in the success of PI. Little has been investigated of the impact of combining different technologies in a PI network, as is the problem addressed in this work. This paper tries to close the gap related to the implementation of different disruptive technologies and new modes of transport in an intercontinental transport network applying PI related concepts.

3 Methodology

The maritime transport industry has experienced a surge in demand post-pandemic that exceeds the current supply, leading to a sharp increase in operating costs and a change in the rules of the game. Players are now required to control their economic risks much more rigorously, among other requirements. In 2021, China accounted for 63% of the volume of Spanish imports (1,487 thousands of tonnes) (Spanish Ports, 2022). The China-Spain container transport network was chosen as the case study for this research due to its significant size and complexity, making it an ideal representation of a typical PI. A range of transportation modes, including maritime, rail, and road transport, is involved, allowing the impact of enabling technologies to be evaluated. Additionally, valuable insights into how these technologies can improve the environmental and economic performance of the PI system on a global scale can be gained by analyzing the impact of enabling technologies on this network.

As the first step of the methodology, diagrams of the main processes involved in container shipping, such as port operations and the different modes of transportation were designed. This was undertaken to provide a comprehensive understanding of the different stages of the considered container transport network and to identify key areas where enabling technologies can be applied to improve performance. The process diagrams were also used to guide data collection and integration into the digital twin. Figure 1 shows an example of a process diagram for road transport, including truck operations in the port.

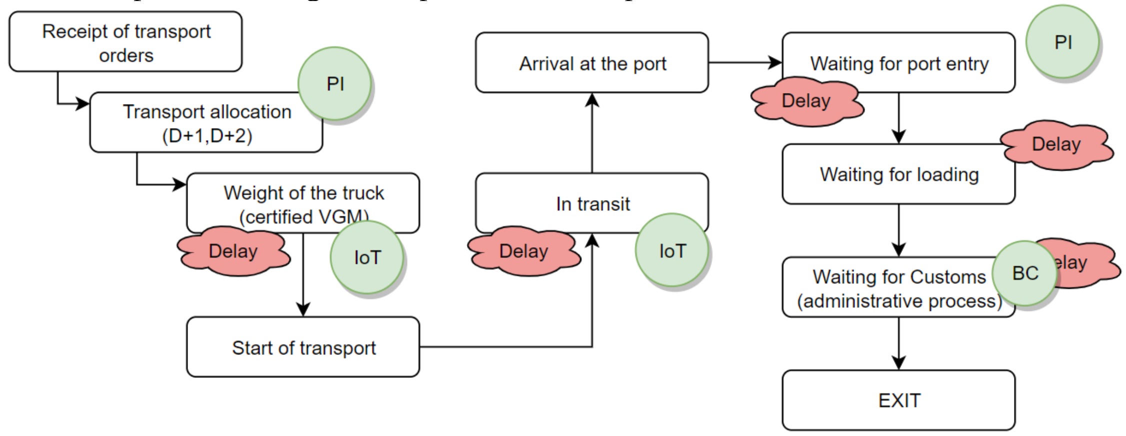

Figure 1: Process diagram for road transport, including potential impacts of enabling technologies

Following the development of the process diagrams, a set of logical rules was devised to represent the potential impact of IoT, blockchain, and artificial intelligence on the network.

Regarding IoT, the implementation of a track and trace service has been considered as a potential solution to reduce delays and the number of incidents in transportation. This service enables real-time monitoring of goods and vehicles, allowing for more accurate predictions of arrival times and better management of transportation resources. By providing greater visibility into transportation operations, the track and trace service can help identify potential issues before they escalate, enabling swift action to be taken to minimize disruption and prevent delays. Furthermore, IoT-based technologies, such as weight sensors, could be used to improve the efficiency of port operations. By verifying the weight of containers (VGM) in advance, these sensors could help to reduce waiting times and avoid additional movements during the entry and exit of the port, as shown in Figure 2.

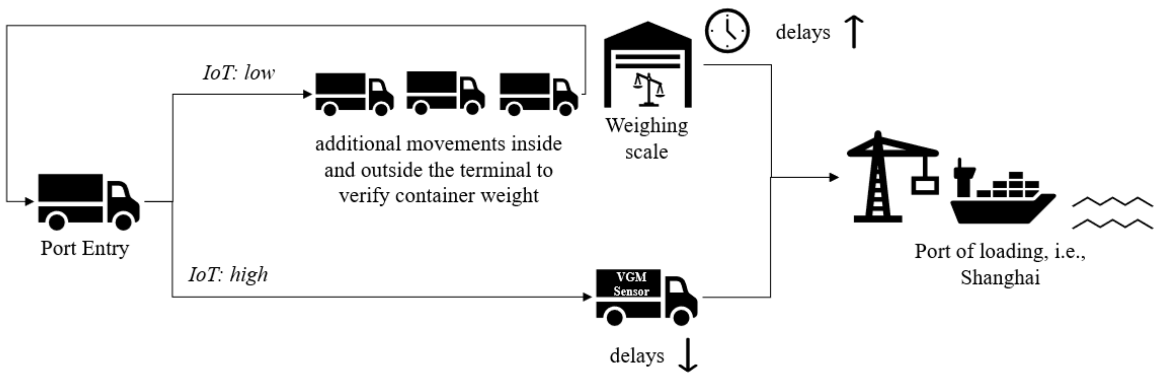

Figure 2: Potential impact of IoT on port operations

In the context of blockchain technology, one of the key applications being considered is the use of smart contracts to automate and streamline the contracting process. Smart contracts ensure that all parties involved in the logistics operation are in agreement and that the terms and conditions are met, which enables the customs clearance of seaborne cargo to take place at a dry port near the receiver/consignee, without any paperwork. This can help reduce queues and delays at customs clearance, as shown in Figure 3.

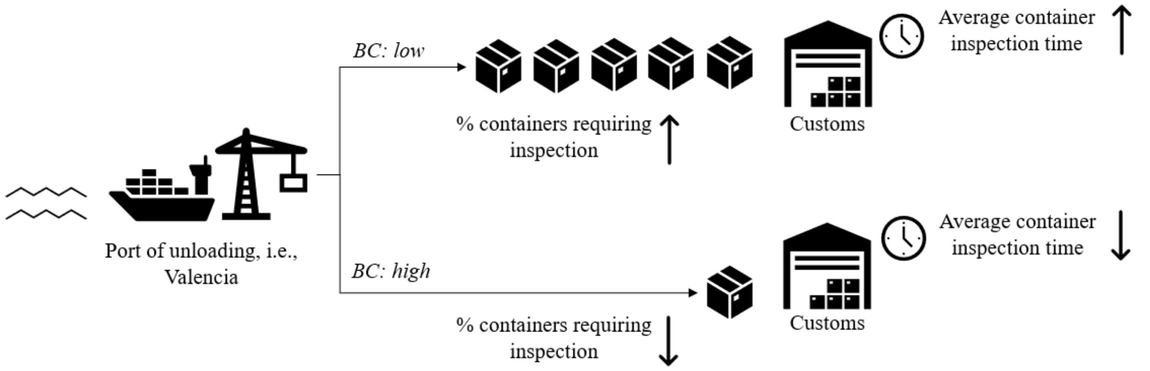

Figure 3: Potential impact of blockchain on customs clearance process

Artificial intelligence has been considered in this study as a potential technology to optimize liner shipping routes for containerships. Specifically, algorithms have been utilized to decide which ports to call at within the route. These algorithms take into account various factors, such as the costs of maritime and hinterland transport, port handling costs, and potential delays, in order to minimize the overall transportation cost. It is worth noting that when such algorithms are not employed, the destination port for the ship is typically predetermined from the origin, as shown in Figure 4.

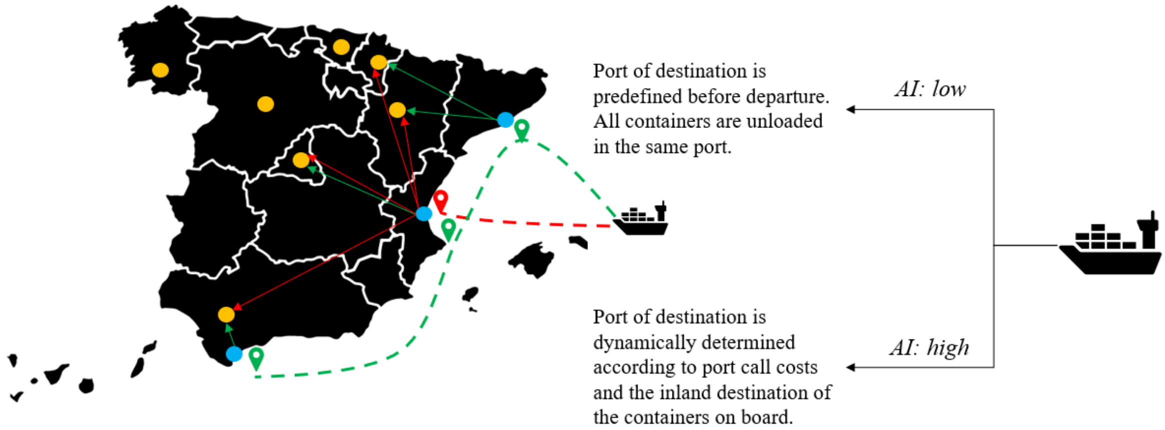

Figure 4: Potential impact of AI algorithms on containership routes

The integration of these advanced technologies described above paves the way for a transition from a traditional logistics network to a PI framework, where containers are "Smart Logistics Units" expected to make autonomous decisions at each node, such as selecting the optimal route to their final destination and the most suitable means of transportation for the next leg of the journey (Figure 5). By prioritizing collaboration and leveraging more efficient and sustainable transportation options, logistics providers can build a more agile and environmentally conscious supply chain ecosystem.

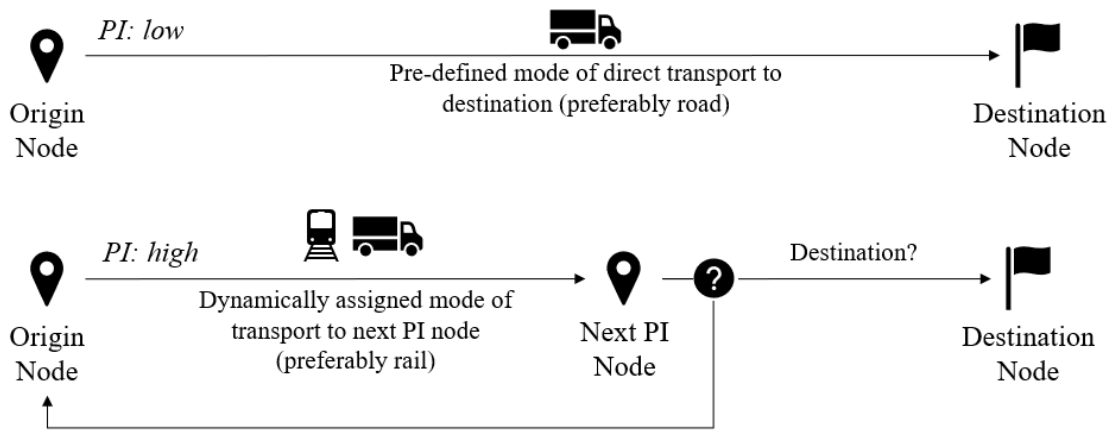

Figure 5: Conventional transport compared to PI-enabled transport

Based on the information gathered about the logistics network, the characterization of the relevant processes, and the definition of the parameters, algorithms, and logical rules that model the impact of the different technologies, a digital twin has been developed using multi-agent simulation techniques. This approach allows for the simulation of complex scenarios and the testing of potential solutions to logistical challenges. In the digital twin, agents representing different actors in the logistics network interact with each other, following the rules and processes defined in the model, and providing insights into the performance of the network under different conditions. The use of multi-agent simulation techniques allows for a more comprehensive and dynamic representation of the logistics system, enabling a better understanding of its behavior and potential for optimization.

In Figure 6, the main view of the digital twin (PI Network Simulator) is displayed. The dashboard depicts a map of the logistics network, with various transport services operating within it (maritime, rail, road). The digital twin allows for the dynamic collection of statistics, and on the right-hand side of the figure, several KPIs related to containers and transport services are presented, such as containers delivered on time, lead time or the distance, cost and emissions of the different hinterland transport modes. This information can be used to analyze the performance of the logistics network, identify potential bottlenecks, and test different scenarios to optimize its operation. The digital twin also provides a powerful tool for decision-making, as it allows logistics providers to evaluate the impact of different strategies and technologies in a safe and controlled environment.

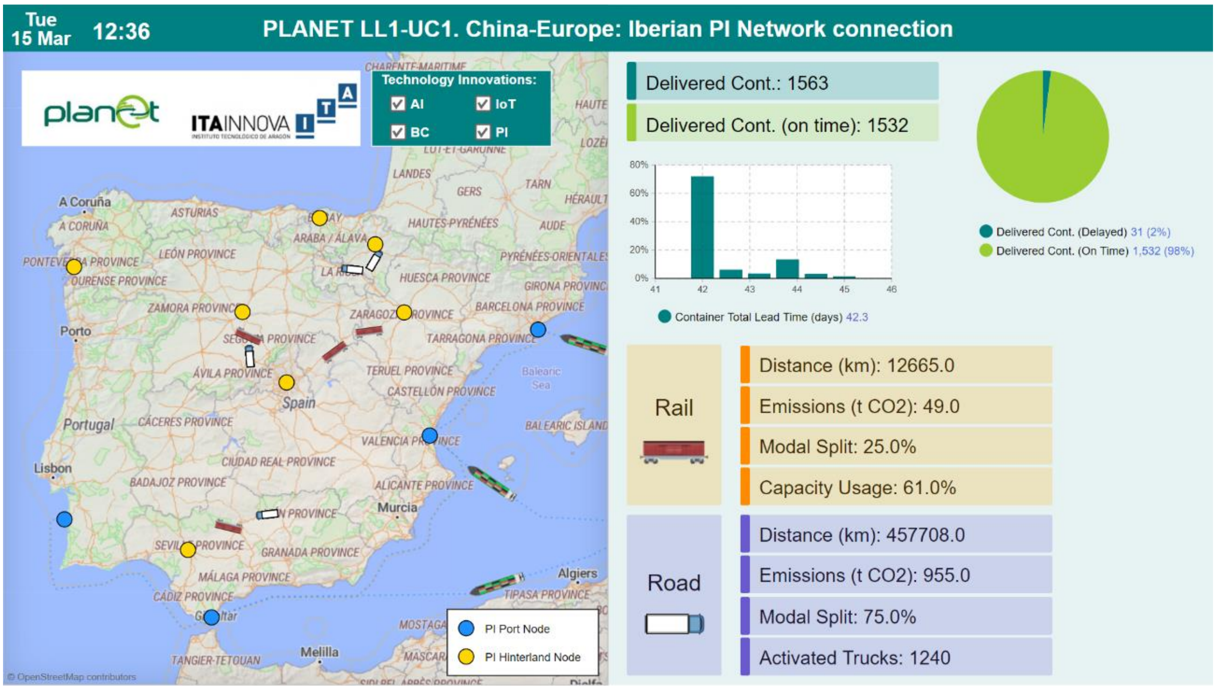

Figure 6: PI Network Simulator

4 Results

Two scenarios were considered in this study. The first scenario modeled the logistics network as it currently operates, while the second scenario simulated a network enabled by different technologies under the PI framework. Both scenarios were evaluated based on the demand data for container shipments originating from China and destined for the three most important ports in Spain, namely Valencia, Barcelona, and Algeciras, as collected in the statistical bulletins of the ports (Fundación Valenciaport, 2021; Port of Barcelona, 2021; Puerto de Algeciras, 2021). In order to ensure a comprehensive evaluation, a scaling factor of 10% was applied to the actual volume of container shipments between China and Spain. This resulted in a simulation of the total delivery of approximately 3,500 containers over the course of one week. Table 1 presents a comparison of the results obtained between the two scenarios evaluated.

Table 1: Comparison of results between scenarios

Scenario	Containers on-time	Rail share	Transport distance (km)	Transport Cost (€)	Transport emissions (t CO_2)
S1) Business as usual	87%	7%	621 250	940 625	1 825
S2) PI framework	99%	25%	420 000	700 000	1 230

The results clearly indicate that the scenario operating under a technology-enabled PI framework is considerably more advantageous. Notably, the scenario achieved a 12% increase in the on-time delivery of containers. This can be attributed to the positive effects of IoT in reducing delivery disruptions and delays and the efficiency of blockchain in streamlining procedures. Furthermore, the dynamic allocation of transport resources for containers allows for a more efficient use of available capacity, resulting in an 18% increase in rail share, a more sustainable mode of transport, which leads to a significant reduction in both distance and CO_2 emissions by 32%. Finally, by identifying and addressing inefficiencies in the logistics network, such as empty trips or inefficient routing, the overall costs of transportation can be reduced by up to 25%.

It should be mentioned that, although the simulation included the maritime transport segment, the performance indicators were exclusively computed for the inland transportation part. Thus, a road transport cost of 1.57€/km and a rail transport cost of 498€ + 1.2€/km per container were assumed, according to data from the European Intermodal Association (2012) and AECOM (2014). In addition, regarding the calculation of CO_2 emissions, 150g/tkm has been considered for road transport and 20 g/tkm for rail transport, according to data from the European Environment Agency (2014).

5 Conclusions

This paper assessed the impact of collaborative transport strategies and emerging technologies on an intercontinental transport network with a digital twin. Through the case study of the China-Spain container transport network, the paper has demonstrated how IoT, blockchain, and artificial intelligence can improve the environmental, operational, and economic performance of the supply chain.

The study found that the implementation of IoT technologies, such as track and trace services and weight sensors, can lead to greater visibility and control over transportation operations. By identifying potential issues before they escalate, these technologies can help minimize disruption and prevent delays. Additionally, the use of weight sensors in port operations can improve efficiency and reduce waiting times, leading to better lead times and delivery performance.

With the adoption of blockchain technology, the contracting process can be automated and streamlined, guaranteeing consensus among all parties and ensuring compliance with the agreed-upon terms and conditions. As a result, it can contribute to minimizing waiting times and disruptions during customs clearance, ultimately leading to a more efficient supply chain.

Moreover, the study has demonstrated how artificial intelligence can optimize liner shipping routes for containerships. By using algorithms to decide which ports to call and in which order, the supply chain can be optimized to achieve the lowest possible carbon footprint while meeting customer requirements.

In addition to the benefits outlined, several challenges must be addressed in order to fully realize the potential of these technologies and concepts in an intercontinental transportation network. These include the integration of these technologies and concepts into existing logistics systems and infrastructure, the coordination and collaboration among various stakeholders, data privacy and security concerns, interoperability issues, and the need for new regulations and policies to support the adoption of these technologies and PI.

Furthermore, it is important to note that the success of these technologies depends not only on their technical capabilities but also on the mindset and culture of the organizations involved. A shift towards a more collaborative and innovative culture is needed to fully realize the benefits of the PI-based supply chain system.

Overall, this paper has contributed to the growing body of literature on the Physical Internet concept and the adoption of enabling technologies in supply chain management. It has demonstrated how the integration of IoT, blockchain, and artificial intelligence can lead to a more efficient, sustainable, and resilient supply chain system, but also highlighted the challenges that need to be addressed for successful implementation.

6 Acknowledgements

The work described in this article has been developed in the framework of the European Project "PLANET: Progress towards Federated Logistics Through The Integration Of TEN-T into A Global Trade Network", funded by the European Commission under the European Union's Horizon 2020 research and innovation program. Grant agreement No 860274.

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