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

David Ciprés[1], José Luis López[1] and Teresa de la Cruz[2]
1. Instituto Tecnológico de Aragón, Zaragoza, Spain
2. Zaragoza Logistics Center, Zaragoza, Spain

ITAINNOVA INSTITUTO TECNOLÓGICO DE ARAGÓN

ZLC TALENT HUB FOR SUPPLY CHAIN
Zaragoza Logistics Center

Introduction

- **Supply chain disruptions and the need for resilience:** European economies face potential losses of €920 billion by 2023 due to supply chain disruptions, highlighting the importance of resilient supply chains and risk management.
- **The impact of the Physical Internet (PI):** The PI offers an adaptable logistics system that enhances supply chain reliability and resilience, leveraging IoT, AI, and Blockchain technologies.
- **Enabling technologies:** IoT enables real-time data collection for optimized logistics, AI optimizes the network with data analysis, and Blockchain ensures secure and transparent data transactions.
- **Digital twins and multi-agent simulation:** Digital twins and multi-agent simulation techniques enable forecasting, scenario testing, and optimization of supply chain dynamics.
- **Culture and collaboration:** A shift in business culture and collaboration among stakeholders are essential for successful PI implementation and driving supply chain resilience.

Objectives

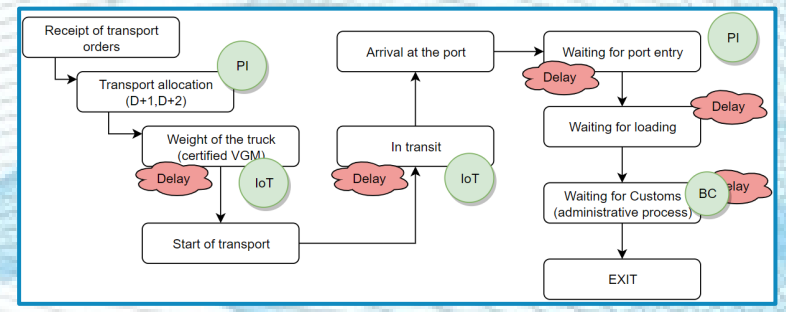
- **Assess the impact** of collaborative transport strategies and emerging technologies on an intercontinental transport network with a digital twin.
- **Evaluate** the potential of the Physical Internet (PI) concept in enhancing supply chain **reliability** and **resilience**.
- Investigate the **role of key technologies** (IoT, AI, Blockchain) in improving the environmental, operational, and economic performance of the supply chain.

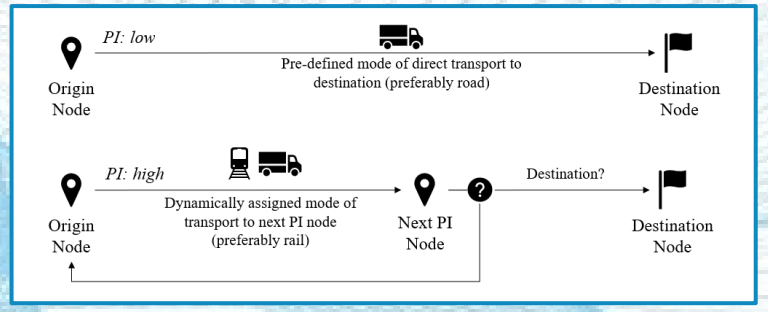
Methodology

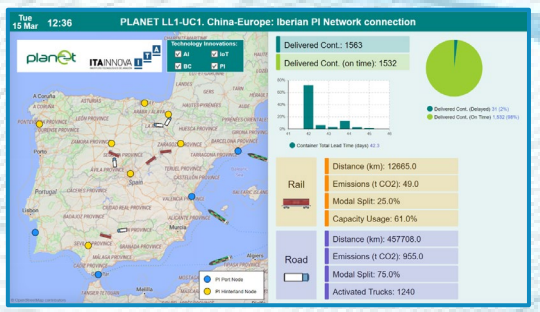
1) Logistics Process Analysis and Identification of Potential Technology Impacts

2) Logical Rule Modeling of Technologies

3) Creation of Digital Twin for Scenario Analysis







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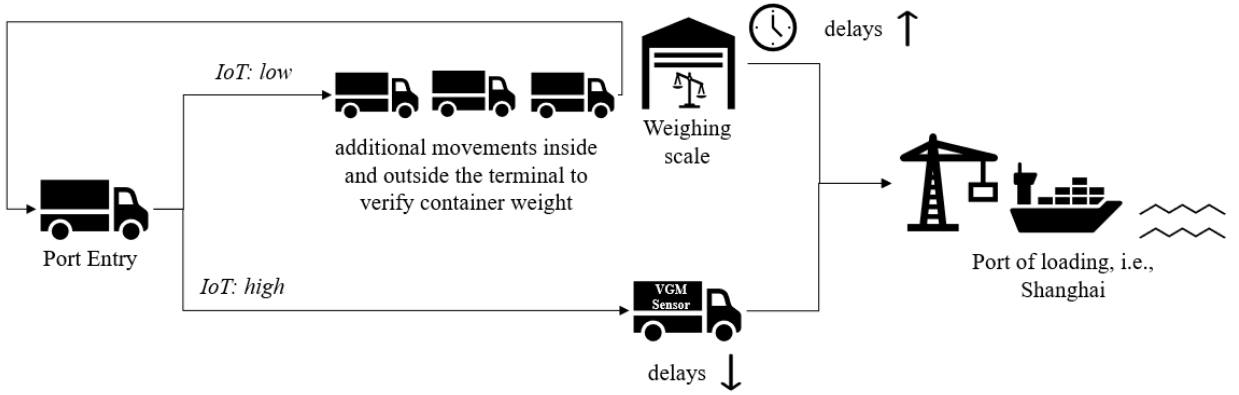
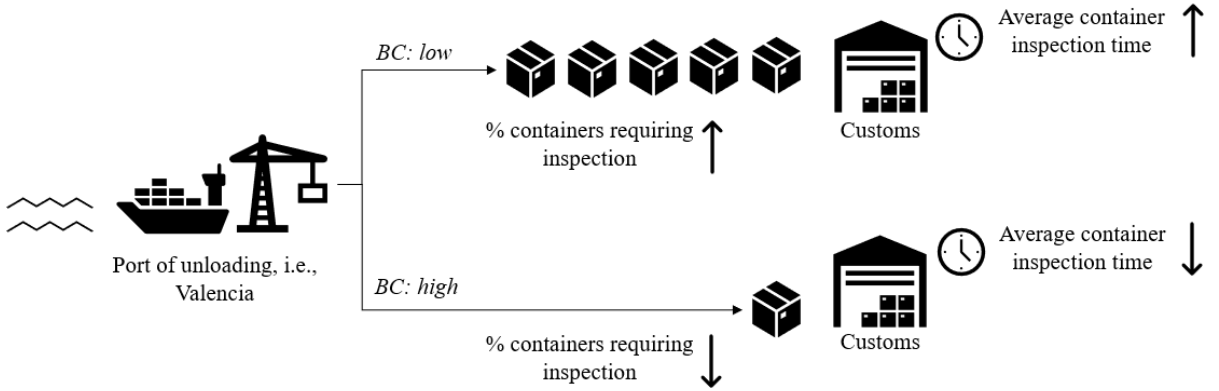
IoT-based track and trace services improve transportation efficiency by enabling real-time monitoring, accurate predictions, and better resource management. Weight sensors potentially enhance port operations by reducing waiting times and unnecessary movements.

Blockchain technology enables the use of smart contracts to automate and streamline logistics operations, facilitating customs clearance at nearby dry ports and reducing paperwork, queues, and delays.

Potential impact of IoT on port operations



Potential impact of blockchain on customs clearance process



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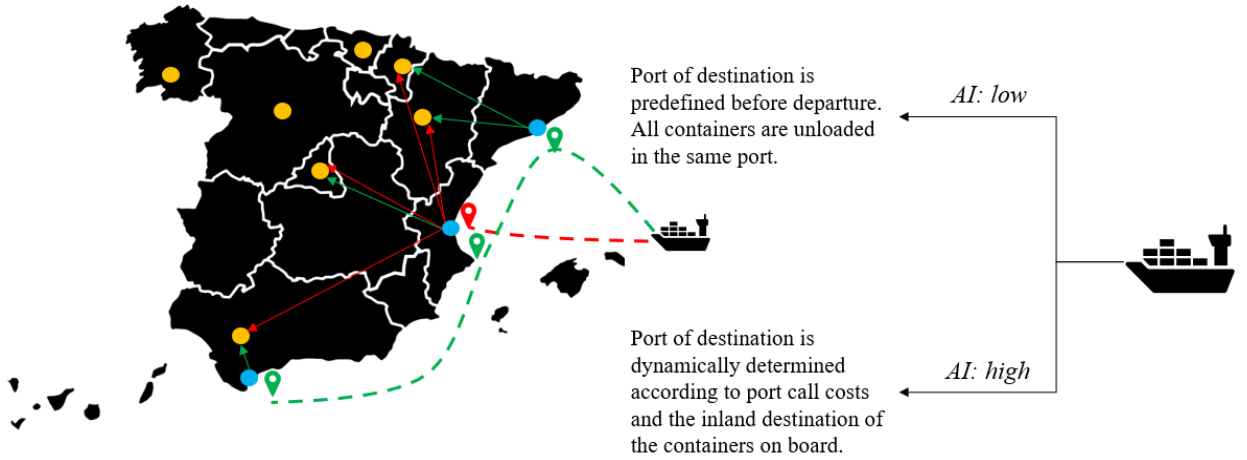
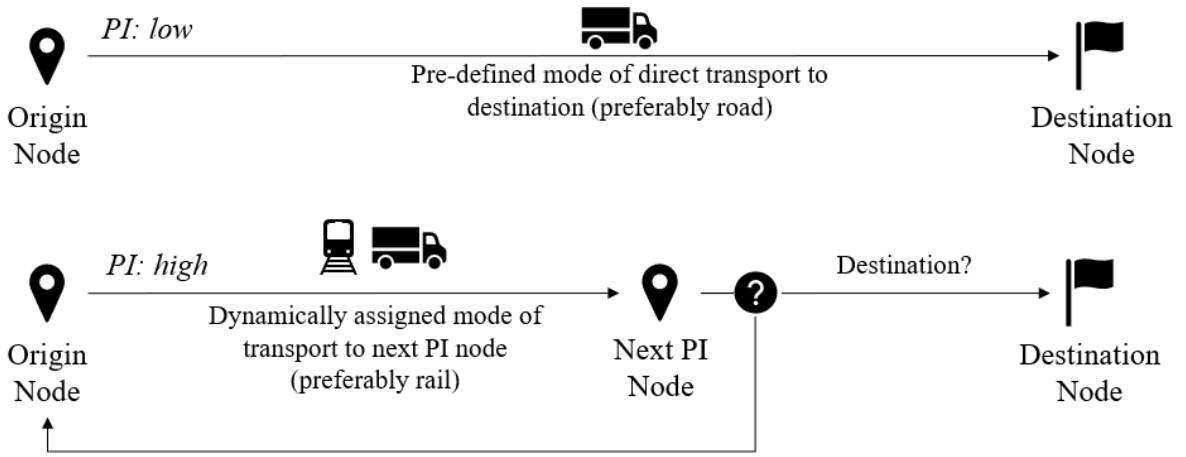
Artificial intelligence is utilized to optimize liner shipping routes for containerships by employing algorithms that consider costs and potential delays, resulting in minimized overall transportation costs.

The integration of advanced technologies enables the transition from a traditional logistics network to a **PI framework**, where Smart Logistics Units autonomously make decisions on route selection and transportation modes for the most efficient journey to their final destination.

Potential impact of AI algorithms on containership routes



Potential impact of PI on routing



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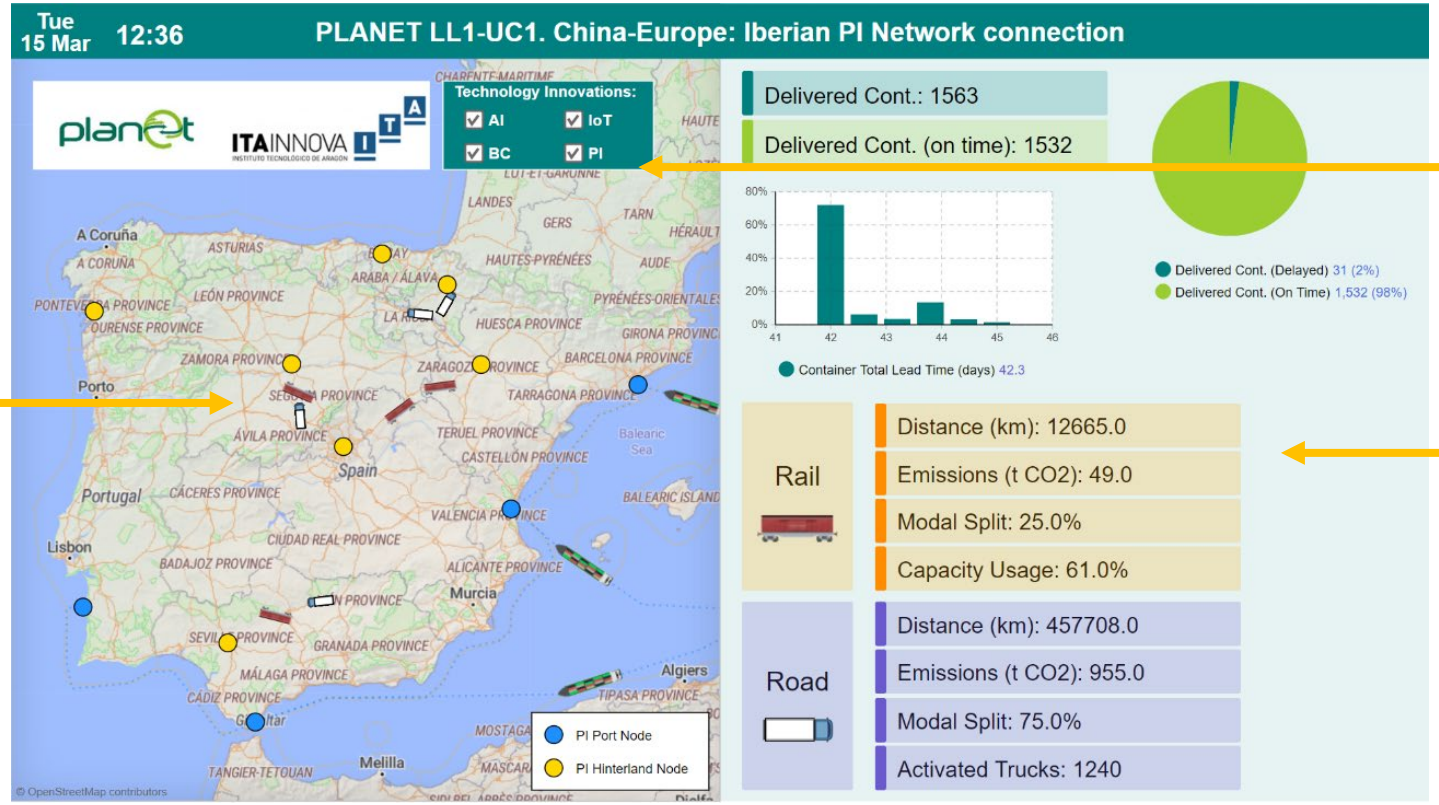
Digital Twin

A **digital twin** was developed using **multi-agent simulation** techniques, incorporating information about the logistics network, process characterization, parameters, algorithms, and logical rules. This approach enables the **simulation of complex scenarios**, testing of potential solutions, and provides insights into the network's performance and optimization possibilities.



Enable/Disable technology impact

Dynamics of the PI network

Collection of KPIs

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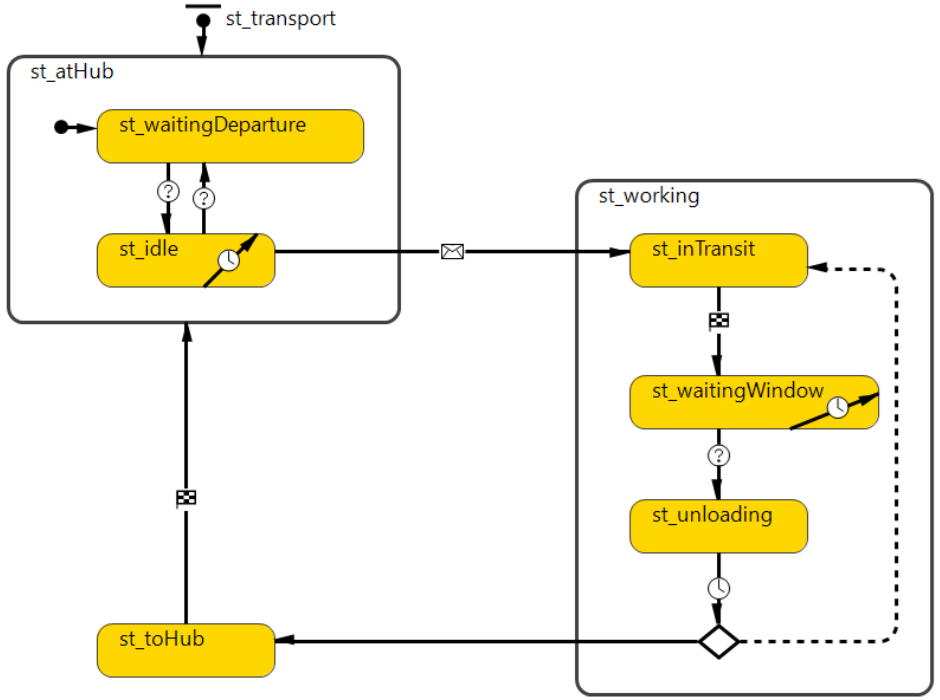
Digital Twin

The digital twin utilizes **multi-agent** simulation techniques to represent key agents and their **interactions within the Physical Internet network**. Agents have their own states, make intelligent decisions, communicate, and respond to changes and parameters.

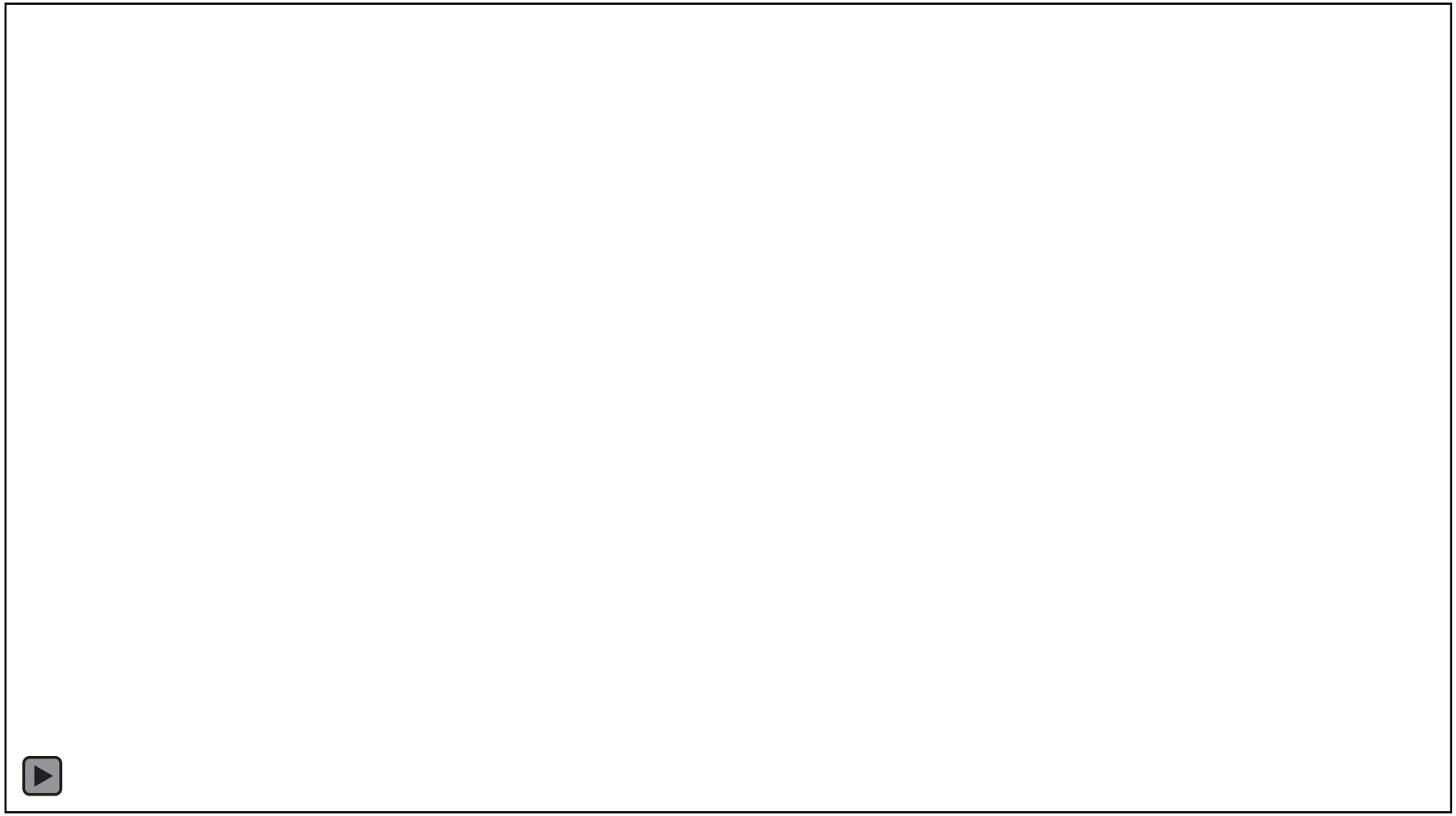
Example of state chart for transport agents



Main agents:

- **PI Nodes:** represent places where goods are stored, transferred, or handled in the network (e.g., port terminals, warehouses).
- **PI Containers:** encapsulate goods in intelligent and interconnectable modular containers, enabling efficient flow in hyperconnected logistics networks.
- **PI Services:** define transport services in the network with characteristics like origin/destination, frequency, transport type, and route.
- **PI Transports:** move and handle containers within and between nodes (trucks, trains, ships).

Digital Twin (Video)



Results

- **Two scenarios** evaluated: current logistics network and a PI-enabled network with different technologies.
- Evaluation based on demand data for container shipments from China to key ports in Spain (Valencia, Barcelona, and Algeciras).
- Scaling factor of 10% applied to actual volume of container shipments for comprehensive evaluation.
- Simulation involved approximately 3,500 containers delivered over one week.

Comparison of results between scenarios

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

- The technology-enabled PI framework achieved a 12% increase in on-time delivery of containers, attributed to the positive effects of IoT and blockchain in reducing disruptions and delays.
- The dynamic allocation of transport resources led to an 18% increase in rail share, reducing distance and CO2 emissions by 32%.
- Identifying and addressing inefficiencies in the logistics network resulted in up to a 25% reduction in transportation costs.

Conclusions

- The paper evaluates how Digital Technologies like IoT, blockchain, and artificial intelligence improve the environmental, operational, and economic performance of the supply chain in an intercontinental transport network with a digital twin under the PI framework.
- Challenges to realizing the potential of these technologies include integration into existing logistics systems, stakeholder coordination, data privacy and security, interoperability, and the need for supportive regulations and policies.
- Success depends on both technical capabilities and a shift towards a collaborative and innovative organizational culture in adopting the PI-based supply chain system.

Aknowledgements

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Thank you for the attention

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David Ciprés: dcipres@itainnova.es
José Luis López: jlopez@itainnova.es
Teresa de la Cruz: mdelacruz@zlc.edu.es

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