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ENHANCING SUPPLY CHAIN INTEROPERABILITY AND RESILIENCE THROUGH PI, DAO, AND SINGLE WINDOW: CASE SCENARIO OF EXPORTING PACKAGED MEDICAMENTS FROM SLOVENIA TO CHINA

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ABSTRACT

Global developments, such as trade tensions, energy crises, and logistics disruptions, necessitate that supply chains adapt quickly and maintain resilience. Due to the high interdependence of actors and the complexity of operations, interoperability has become essential for efficient coordination and information exchange. Solutions are needed that enhance interoperability and resilience through the digitalisation and decentralisation of processes. This paper proposes a model that integrates three existing concepts, Physical Internet (PI), Decentralised Autonomous Organisations (DAO), and Single Window (SW), into the structure of supply chains. The case scenario "Export of Packaged Medicaments from Slovenia to China" is used to illustrate the application of the model and its potential benefits. The proposed approach demonstrates how integrating these concepts can contribute to improved interoperability, process synchronisation, and system resilience, thereby supporting more efficient, transparent, and sustainable global logistics.

1. INTRODUCTION

Modern supply chains operate in highly complex and dynamic environments, where globalisation and technological advancement intersect with increasingly demanding market expectations. The growing number of actors, the diversity of operations, and rising demands for agility, sustainability, and transparency pose significant challenges for coordination and process optimisation. At the same time, geopolitical developments over the past five years, including trade tensions, energy crises, disruptions in international logistics, and regulatory changes, have further complicated supply chain operations, requiring rapid adaptation, resilience, and the capacity for sustainable growth. In this

context, contemporary supply chains must be designed to strike a balance between efficient operational management and strategic resilience to external pressures, thereby ensuring continuity of supply and long-term competitiveness in the global environment.

Modern supply networks are becoming increasingly interdependent and interconnected, relying on fast and efficient information exchange [1]. However, disruptions such as the Fukushima disaster (in 2011) and the COVID-19 pandemic have highlighted the vulnerability of global supply chains, primarily

due to a lack of complete visibility, weak traceability, and insufficiently transparent information, which are closely linked to interoperability issues [2].

Interoperability in supply chains refers to the ability of independent logistics networks to collaborate, exchange data, and utilise each other's capacities [3], [4], to enable more efficient, transparent, and coordinated operations. It encompasses physical, organisational, business, and digital levels, with digital interoperability facilitating fast, secure, and reliable information exchange between systems and actors, thereby supporting collaboration and coopetition [3], [5].

A key benefit of interoperability is the facilitation of resource and information sharing, which strengthens synergy and the efficiency of logistics operations within supply chains [6]. In this context, interoperability represents a fundamental prerequisite for building resilience, as it enables effective information exchange and coordination among independent logistics actors, supporting faster responses and adaptation to changing conditions within the supply chain.

From a systems theory perspective, certain conclusions can be drawn regarding the development of resilient supply chains. According to systems theory, the behaviour of a system is determined by its structure, which comprises the arrangement of elements within the system and their interconnections [7]. Viewing the supply chain as a system, it follows that its resilience depends on the system's structure, which shapes and enables such behaviour.

Accordingly, this paper aims to present a conceptual solution for a resilient supply chain structure that integrates the digital concepts of DAO, Physical Internet, and Single Window. Incorporating these concepts into the supply chain structure has the potential to enhance interoperability, process synchronisation, and overall system resilience.

The paper is structured to first review existing literature, highlighting the fundamental concepts of the proposed solution and its potential. It then presents a specific case scenario illustrating the application of the model, followed by an analysis of the key benefits of integrating DAO, Physical Internet, and Single Window in supply chains, with a focus on improving interoperability, process coordination, and system resilience.

2. LITERATURE REVIEW

Interoperability enables all parts of a supply chain to communicate effectively and operate together as a single, integrated system. A significant contribution to enhancing interoperability can be achieved through the implementation of the Physical Internet concept, representing a global paradigm shift in logistics. The Physical Internet aims to interconnect supply and logistics networks, allowing them to operate cohesively across physical, digital, business, and organisational levels [3]. This concept extends beyond mere connectivity to hyperconnectivity, where system components and actors are intensely linked across multiple levels and everywhere, enabling them to be managed as a unified system [8].

Since the Physical Internet (PI) can be regarded as a framework for the practical application of advanced technologies, a key question for researchers interested in PI is how to integrate existing innovative services into a PI system that enables the desired

hyperconnectivity of its elements [3]. Accordingly, there is a recognised need to evolve organisational models, shifting the focus from centralised to decentralised structures [9], which are based on collaboration rules, protocols, and mechanisms adopted by all involved actors.

A Decentralised Autonomous Organisation (DAO) represents a modern organisational form based on blockchain technology and smart contracts, enabling automated, transparent, and self-governing organisational processes [10]. Within a DAO, rules, procedures, and transactions are encoded in software and permanently recorded on the blockchain, ensuring their verifiability, integrity, and resistance to manipulation. Smart contracts, first introduced by Szabo [11], form the foundation of the DAO model by enabling automatic execution of business agreements without intermediaries, where all steps of the contracting process—from negotiation to execution—are conducted digitally and without human oversight. Leveraging blockchain technology, DAOs allow for the delegation of roles and tasks to participants (human actors) according to predefined rules and collaboration objectives [12]. This structure not only enhances transparency and trust among participants but also facilitates decentralised decision-making and high efficiency in coordinating complex interorganizational processes [13]. Successful applications of decentralised models can be found in transport planning [14] and real-time routing via PI cross-docking centres [15].

Blockchain technology and smart contracts represent key tools for enhancing interoperability and transparency in supply chains. Due to their ability to ensure secure, decentralised, and verifiable data exchange, blockchain systems enable the integration of different databases and the tracking of accountability among system actors [16], [17]. Smart contracts built on this technology further automate transactions and collaborative processes, contributing to the development of autonomous and selforganising logistics systems [18], [19], [20]. As a result, blockchain and smart contracts become key drivers of digital transformation and decentralised collaboration in supply chain ecosystems, opening new opportunities for traceability, security, and efficiency, particularly within concepts such as the Physical Internet and circular supply chains [21].

Pan and coauthors [3] highlight that, to address challenges of digital interoperability within the Physical Internet, one promising research direction is the development of autonomous and selforganising logistics systems. These systems are designed to enhance the efficiency of logistics services provided by individual operators, such as transportation and warehousing.

The Single Window concept enables all participants in the logistics process to submit data and documents only once through a single point of entry and data storage, facilitating seamless information exchange among transport actors, particularly in seaports. The implementation of a national Single Window enables the harmonisation and standardisation of data exchange between commercial and administrative participants, providing fast, reliable, paperless, and efficient transactions [22]. Digitalisation further expands the capabilities of this system, as seen in initiatives such as the Maritime Connectivity Platform (MCP), which enables the electronic exchange of information among all authorised maritime actors through various communication channels [23]. This improves system interoperability and facilitates data reuse, while the single interface serves as a key mechanism for coordinating and monitoring information.

At the European level, the European Maritime Single Window (EMSW) is being developed to achieve complete interface harmonisation for shipping operators, standardising the information required for port management and ensuring that all relevant actors have access to data [24], [25], [26]. National Single Windows continue to function as coordination mechanisms, enabling bidirectional information exchange between ship operators, port authorities, customs, and other systems. The implementation of the Single Window represents a crucial step toward enhancing interoperability among different systems,

enabling more efficient data exchange, and driving the digital transformation of maritime transport, thereby contributing to the sustainability and reliability of port operations [27], [28], [29].

3. PROPOSED SOLUTION

The integration of the concepts of Single Window, DAO (Decentralized Autonomous Organizations) and Physical Internet (PI) into a single platform would represent a radical transformation of global trade, logistics and supply chain management. This combination of three powerful yet different paradigms would result in a synergistic system that is significantly more efficient, transparent, automated and resilient to disruption.

The following key impacts can be expected, categorized by area:

3.1 Impacts on efficiency and automation

- ***Radical process automation:*** Smart contracts (the foundation of DAO) would automate almost all administrative and operational steps that are currently performed manually. When a company enters shipment data through a Single Window-style interface, the DAO would autonomously:
  - Verify the compliance of documentation (customs declarations, certificates of origin, etc.).
  - Reserve capacity in standardized PI containers.
  - Optimize and reserve transportation routes across an open network of PI providers.
  - Calculate duties, taxes and shipping costs.
  - Hold payment in an escrow account and automatically release it after the sensor confirms delivery from the PI container.
- ***Reduction of administrative burdens:*** The concept of a single window would be improved. Instead of simply forwarding data to various agencies (customs, inspections), the information would be recorded in a blockchain, allowing immediate, secure and immutable access for all authorized stakeholders. This eliminates redundant data entry and physical handling of documents.
- ***Optimal resource utilization:*** The physical internet operates on the principle of shared, optimally utilized logistics assets (warehouses, trucks, ships), similar to data packets traveling over the internet. The DAO would act as an autonomous "exchange mechanism" that would dynamically identify the most cost-effective routes for "packages" (physical goods) in real time, drastically reducing empty miles and unnecessary warehousing.

3.2 Impact on Transparency, Security and Trust

- ***Full traceability and immutability:*** Every step in the supply chain – from the production and encapsulation of PI containers to transportation and final delivery – would be recorded as a blockchain transaction, creating an unadulterated digital audit trail. This would dramatically increase trust between partners, while reducing fraud, theft and errors.
- ***Decentralized trust:*** The system would not rely on a single central intermediary (bank, freight forwarder or government agency) requiring universal trust. Trust is built into the code (smart contracts) and the network itself. Rules are transparent and enforced automatically, reducing the risks of corruption and human error.
- ***Improved data security:*** Sensitive trade data would be cryptographically protected and distributed across the network, rather than stored in vulnerable centralized databases that only those with the appropriate permissions would have access to.

3.3 Impacts on System Governance and Resilience

- ***Decentralized Autonomous Governance:*** The platform would be governed by a DAO, meaning that stakeholders (platform users, logistics providers, ports, etc.) would decide on operating rules, system upgrades, and dispute resolution through voting. This promotes a more democratic, flexible, and fair system, independent of any single corporation or country.
- ***Extreme Resilience:*** Without a central point of failure, the system would be highly robust to disruptions such as political crises, natural disasters, or outages of individual logistics providers. If one carrier fails, the DAO would immediately reroute the shipment through the PI network, preventing shipment delays.
- ***Dispute Resolution:*** Smart contracts could include pre-defined automated mechanisms. For example, if PI container sensors detect excessive temperature exposure, insurance compensation could be automatically triggered.

3.4 Economic and strategic impacts

- ***Democratization of access to global trade:*** Small and medium-sized enterprises would gain equal footing with large companies in global logistics networks. The complexity and costs of international trade would be greatly reduced, as the platform would automate most of the processes.
- ***Emergence of new business models:*** The platform would unlock innovative services, including:
- ***Fractional ownership of logistics assets:*** Investors could own shares in trucks or warehouses and receive dividends based on utilization, which would be managed by a DAO.
- ***Autonomous markets for logistics capacity:*** Transportation prices would dynamically fluctuate in real time based on supply and demand.
- ***DeFi in logistics:*** Supply chain financing, insurance, and payments would be handled directly through the platform, bypassing traditional financial intermediaries.
- ***Decentralized autonomous governance:*** Governed by a DAO, the platform's operations and protocol changes will be decided directly by its diverse stakeholders, including platform users, logistics providers, and ports.

4. A CASE STUDY - EXPORT OF PACKAGED MEDICAMENTS FROM SLOVENIA TO CHINA

Data and Context: Slovenia exported USD 31.3 million worth of packaged medicaments to China. Pharmaceutical products, such as packaged medicines, have consistently been among Slovenia's top three exports to China. Slovenia has a strong pharmaceutical sector; meanwhile, China represents a growing market due to its ageing population and increasing demand for high-quality medicines.

4.1 Application in Our Platform (Single Window + DAO + PI)

This case illustrates the transformative potential of integrating Single Window, DAO, and Physical Internet concepts. Currently, exporting to China involves weeks of manual document entry, multiple customs checks, and the risk of rejection due to China's strict regulations on food and medicines. The difference is shown in the table below.

Table 1: Single Window Entry

Step	Current (Manual)	In Platform (Automated)
Data Entry	Manual input in Slovenian customs + repeated entry in the Chinese system	Single submission: shipment data (USD 31.3M medicines, GMP/EU origin certificates)
Verification	SI Customs + CIQ (China inspection), up to 2 weeks	DAO verifies compliance instantly using smart contracts

4.2 DAO Automation and PI Integration

- ***PI Container Booking:*** Standardised PI π-container with temperature control, critical for sensitive medicines.
- ***Route Optimisation:*** DAO identifies the most cost-effective path (e.g., Koper → Piraeus → Shanghai) via the PI network, reducing empty kilometres by 50%.
- ***Duties & Taxes:*** Automatic calculation of export/import fees (EU: 0%, China: ~3–6% + VAT) with escrow payments released on verified delivery via sensors. The difference between the estimated costs is shown in the table below.

Table 2: Cost Comparison

Component	Current	In Platform
Administration	5-10% of shipment value	<1%
Transport	€20,000/container	€12,000 optimised

4.3 Traceability & Resilience

Some of the system functionalities that affect the traceability and resilience of the supply chain are listed in the Table 3.

Table 3: System functionalities

Supply Chain Step	Blockchain Record
Packaging (Krka)	Temperature and humidity sensors
Transport (PI)	Real-time IoT tracking
Shanghai Customs	Immutable blockchain verification

In case of disruptions, such as a monsoon in Shanghai, the DAO can reroute the shipment within five minutes through an alternate PI path (e.g., via Ningbo). If temperature sensors detect conditions above 25°C, automated compensation is triggered via DeFi insurance.

5. CONCLUSION

Modern global supply chains operate in complex and dynamic environments, where geopolitical disruptions, energy crises, and increasing market demands require continuous adaptation and a higher degree of resilience. Given the strong interdependence among actors and the complexity of logistics operations, interoperability and effective process coordination represent important factors influencing supply chain performance. In this context, this study proposes a conceptual model that combines the Single Window, Decentralised Autonomous Organisations (DAO), and the Physical Internet (PI) to support improved digital coordination, interoperability, and resilience in logistics systems.

The case scenario of exporting packaged medicaments from Slovenia to China illustrates the potential applicability of the proposed model in a realistic international trade context. The Single Window approach enables data to be submitted once and reused by multiple

stakeholders, including customs authorities, transport operators, and port administrations, thereby contributing to improved coordination across heterogeneous systems. DAO-based smart contracts enable automated compliance verification, payment execution, and conditional rerouting in the event of disruptions, thereby indicating a possible enhancement of supply chain resilience. In addition, the PI network, supported by sensor technologies, facilitates real-time tracking and increased transparency, which can support more secure and efficient logistics operations.

Overall, the scenario suggests that the integrated application of Single Window, DAO, and Physical Internet concepts has the potential to support improvements in global logistics by enhancing interoperability, enabling automated process coordination, and supporting more timely responses to disruptions. While the findings are based on a conceptual case scenario, they provide a basis for further research and empirical validation of the proposed approach.

6. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

During the preparation of this work, the author(s) used a Grammarly EDU license to assist with language editing and clarity. After using this tool/service, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.

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