FROM GROUND TO CLOUD: THE IMPACT OF THE PHYSICAL INTERNET ON AIR CARGO OPERATION

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Abstract

Purpose: This paper aims to explore how the emerging concept of the Physical Internet can transform traditional air cargo operations by enabling standardized, modular, and interconnected logistics networks. It seeks to provide an accessible overview of the Physical Internet's core principles and assess its potential to enhance operational efficiency, streamline workflows, and improve data visibility in air cargo logistics.
Design/ methodology/ approach: The study adopts a conceptual and case study-based approach, reviewing current literature and practical examples from the industry. It examines the transition from conventional, siloed systems ("ground") to integrated, cloud-based networks that facilitate real-time data exchange and collaborative decision-making. The analysis focuses on identifying the challenges and opportunities associated with adopting the Physical Internet in air cargo operations.
Findings: Preliminary findings suggest that integrating Physical Internet concepts into air cargo operations can significantly reduce operational inefficiencies, improve capacity management, and enhance sustainability. The approach enables more effective data sharing and coordination across stakeholders, thereby driving smarter decision-making and increased operational resilience.
Originality/ value: This research offers a novel perspective by linking the transformative potential of the Physical Internet directly to air cargo operations. It contributes to the field by providing actionable insights for industry professionals, academics, and policymakers on leveraging digital transformation to create a more connected and efficient air cargo network. The research underscores the value of digitalization in overcoming longstanding operational challenges in the logistics sector.

Keywords: Air Cargo, Physical Internet, Digital Transformation, Logistics, Operational Efficiency, Sustainability

Introduction

Air cargo constitutes a fundamental component of the global supply chain, ensuring the expeditious movement of goods across international borders and supporting industries reliant on just-in-time delivery. Its importance was particularly pronounced during the post-COVID-19 economic recovery, facilitating international trade and the distribution of vital commodities. The ongoing growth of e-commerce has further underscored its significance, allowing for the swift delivery of high-value, time-sensitive products to consumers worldwide. Moreover, air cargo has played a crucial role in humanitarian response initiatives, transporting medical supplies, vaccines, and emergency relief to communities affected by crises, conflicts, and natural disasters. Air cargo remains essential for fostering economic growth, as it broadens market access and enhances global trade connections (ICAO, 2025). Air cargo services expand businesses' global reach by allowing reliable, faster, and more cost-effective transportation of products to distant markets.

The air cargo industry is currently challenged by a supply-demand imbalance, compounded by significant geopolitical and structural obstacles. Increased e-commerce activity and recent ocean freight disruptions, such as the Red Sea crisis, have shifted demand toward air freight. However, capacity growth remains below demand growth. This mismatch results in ongoing upward pressure on freight rates and load factors(Logicall, 2025). This market tightness is compounded by global supply chain and political fragility, specifically where the Russia-Ukraine conflict forces European carriers to reroute, adding cost and time to Europe-Asia transit, and where the shift in trade policy (e.g., potential U.S. tariff changes and scrutiny of Chinese e-commerce) creates significant regulatory and market uncertainty (FreightAmigo, 2025).

Confronted with these challenges, this research is motivated to apply the concept of the Physical Internet to air cargo operations in order to enhance efficiency and effectiveness. This paper aims to explore how the emerging concept of the Physical Internet can revolutionize traditional air cargo operations by fostering standardized, modular, and interconnected logistics networks. It seeks to provide an accessible overview of the core principles of the Physical Internet and evaluate its potential to improve operational efficiency, streamline workflows, and augment data visibility in air cargo logistics. This research introduces a novel perspective by directly linking the transformative potential of the Physical Internet to air cargo operations. It contributes to the field by offering actionable insights for industry professionals, academics, and policymakers on harnessing digital transformation to develop a more connected and efficient air cargo network. The study underscores the importance of digitalization in overcoming longstanding operational challenges within the logistics sector.

The Air Cargo Ecosystem: Constraints and Imperatives

According to IATA (2022), Cargo handling constitutes the segment of the supply chain responsible for processing goods landside within the cargo facility. From the point of delivery at the airport of origin until the cargo is prepared for loading onto the aircraft, and subsequently from the unloading at the destination to the handover to the consignee or freight forwarder, numerous procedures are involved. These procedures must be meticulously observed to guarantee the safe and secure delivery of shipments. Such procedures are delineated in the Cargo Master Operating Plan (MOP) as presented in figure 1.

The Master Operating Plan (MOP) is a helpful guide that outlines the main processes and sub-processes involved in safely and efficiently transporting air cargo from the shipper to the consignee. It offers the air cargo supply chain the very first industry-endorsed, clear, and standard description of the entire air cargo transportation journey.

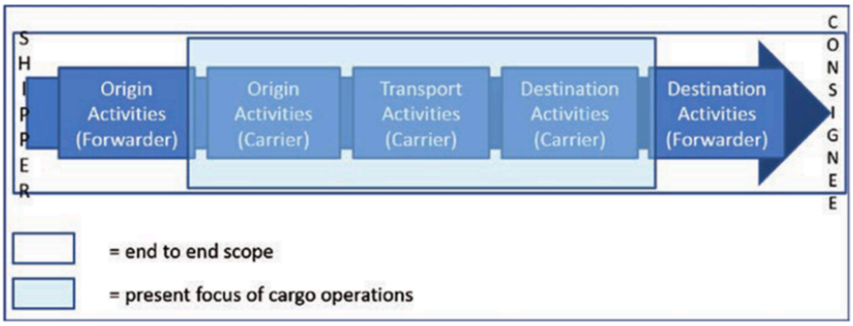

Figure 1: Air Cargo Master Operating Plan
Source: IATA (2022)

The main goal of air cargo acceptance and handling is to ensure consignments are prepared for transport according to operator and IATA standards, as well as the export and import regulations of countries the cargo will pass through. Typically, all items transported on commercial aircraft undergo an acceptance process. While some procedures must be followed for all cargo types, others may only apply to specific types of cargo. This research examined the process from the beginning until the shipment arrived at the destination airport.

The Physical Internet (π): Vision and Requirements

The Physical Internet (PI, π) is a global open logistics system that relies on physical, digital, and operational interconnectivity via encapsulation, interfaces, and protocols. It continuously evolves through technological, infrastructural, and business innovations. Montreuil (2011, 2012) thoroughly justified, positioned, and characterized the concept. The Physical Internet seeks to create an efficient and sustainable Logistics Web, consisting of interconnected actors and networks (Montreuil, 2012). A Web (with capital W) is here differentiated from any web by the fact that a Web is both open and global. Globalism here infers both a universal worldwide scope A 'Web' (with a capital W) is distinguished from any other web by being both open and global. In this context, 'global' signifies a universal, worldwide reach as well as a scope that ranges from microscopic to macroscopic levels. 'Openness' describes how accessible, willing, and available actors and networks are to engage with each other. A logistics web refers to an online platform designed to address the logistics needs of individuals, organizations, communities, and society at large. An effective Logistics Web is characterized by being open and global in scope.

The requirement

According to Montreuil (2011), The Physical Internet (π) presents a groundbreaking, long-term vision to revolutionize the global logistics system by utilizing the core principles and protocols of the Digital Internet for the movement of physical goods. Its primary aim is to drastically enhance the efficiency, sustainability, and resilience of worldwide supply chains. There are some requirement for the physical Internet which are;

1. *Physical Requirement:* The Physical Internet necessitates a fundamental change in the way goods are packaged and managed, shifting from proprietary, non-standardized containers to universal, interoperable units. This is the fundamental physical asset. Goods are enclosed within a standardized, finite set of containers that act as the "packets" of the Physical Internet. They should be modular, meaning they can interlock and adjust in size like Lego blocks to optimize volume use. Additionally, they must be smart, featuring unique IDs, GPS, and IoT sensors for real-time tracking. Reusability and eco-friendliness are also essential.

2. *Infrastructure Requirement:* The PI requires creating a global, interconnected network that is open and accessible, replacing the current isolated, company-specific systems. Existing warehouses, distribution centers, and intermodal terminals (such as ports, rail yards, and air hubs) should be transformed into π-Nodes. These π-Nodes must be accessible to all certified PI users, enable rapid, automated transshipment between modes and vehicles (called π-Movers), and provide seamless "plug-and-play" logistics services like storage and cross-docking.

3. *Digital Requirement***:** The PI requires a universal digital language and an added trust layer to independently manage the physical movement of goods. A worldwide set of standards is crucial for uniform packaging, addressing, handling, and routing of -containers across networks. These standards must ensure seamless interoperability across all modes, support the dynamic assignment of π-containers to π-Movers, and securely transfer liability and trust among different service providers. A federated governance model is essential to oversee the open network, control asset use and payments, and guarantee all participants trust that the network remains fair, secure, and compliant with service-level agreements, even when goods are managed by competitors.

Essentially, the Physical Internet aims to transform logistics by standardizing capacity and assets, while enabling each shipment to be intelligent and self-aware (Montreuil, 2011).

Methodology

This study adopts a qualitative conceptual framework, anchored by a systematic literature review and in-depth interviews. The literature review covers foundational and recent research across three key areas: (1) the Physical Internet (π) vision and its technological enablers such as modularity and open protocols; (2) the operational, safety, and security constraints specific to the air cargo industry, including ULD certification and IATA/ICAO regulations; and (3) emerging digital supply chain models like synchromodality and hyperconnectivity. The analysis then uses in-depth interviews—focusing on real-world examples such as digital-hub initiatives—to examine the transition from traditional, asset-based, siloed systems ("ground") to integrated, cloud-based networks. The core analysis identifies four types of friction—structural, regulatory, economic, and digital—to thoroughly explore the challenges and opportunities of applying the Physical Internet principles in high-speed, high-stakes air cargo operations, and to develop a new research agenda.

This study employed a qualitative research design using expert interviews and content analysis to examine the anticipated impact of the Physical Internet (PI) on air cargo operations. Given that PI remains an emerging concept in the aviation logistics domain, expert insight was essential to uncover practical implications, operational challenges, and organizational readiness factors. Participants were selected through purposive sampling to ensure representation from key stakeholder groups, including air cargo terminal managers, airline cargo planners, ground handling supervisors, digital transformation specialists, and technology solution providers. In total, eight experts were interviewed, with each interview lasting between 45 and 60 minutes. A semi-structured interview format was used to allow flexibility while maintaining consistency across core topics such as modularity, visibility, automation, and organizational transformation related to PI adoption.

All interviews were audio-recorded, transcribed verbatim, and analyzed using a multi-stage content analysis approach. During open coding, initial concepts were identified from the transcripts, including modular ULD design, real-time visibility, automation opportunities, interoperability requirements, cybersecurity concerns, and workforce skill gaps. These codes were further refined through axial coding, resulting in Three overarching categories: physical constraints, regulatory strictness, and operational differences. Selective coding was subsequently employed to synthesize these categories into a central emerging theme: the Physical Internet represents a shift from siloed and manually intensive processes toward a hyper-connected, data-driven, and modular air cargo ecosystem. To enhance reliability, coding decisions were discussed iteratively, and thematic patterns were cross-checked against the interview data to ensure consistency.

This methodological approach enables a structured yet flexible examination of expert perspectives, providing nuanced insights into how PI principles may reshape air cargo operations at both the physical and digital levels. The use of content analysis not only supports transparency in the analytical process but also facilitates the emergence of grounded, evidence-based themes that inform the study’s findings and implications.

Result: Critical challenges analysis

Implementing the Physical Internet (π) in air cargo involves not just adopting new technology but also navigating a core clash between two operational philosophies: the open, shared, and modular nature of π versus the closed, safety-critical, and tightly regulated environment of air transport.

The content analysis of expert interviews reveals that the Physical Internet (PI) is perceived as a transformative framework that will fundamentally reshape air cargo operations by enabling seamless, modular, and data-driven logistics. Experts emphasized that PI-inspired modularity and standardization—particularly in ULD design and handling—can significantly reduce build-up time, enhance load accuracy, and improve interoperability across airlines and cargo terminals. Equally critical is the shift toward cloud-based visibility systems, which experts identified as the “backbone” of PI implementation. Such platforms support real-time cargo tracking, dynamic space allocation, and predictive disruption management, although concerns remain regarding legacy IT limitations and hesitancy in data sharing. Automation also emerged as a recurring theme; participants highlighted the increasing role of autonomous equipment, AI-assisted acceptance, and robotic inspection in reducing manual labor demands and improving handling consistency. Despite these technological advancements, experts consistently underscored that organizational readiness—not technology—will ultimately determine the success of PI adoption. Cultural resistance, siloed processes, limited cross-stakeholder collaboration, and gaps in digital competencies were identified as major obstacles. Overall, the findings suggest that while PI offers substantial opportunities to enhance efficiency, visibility, and resilience in air cargo operations, its realization requires integrated technological investment and a fundamental shift in organizational mindset toward openness, interoperability, and collaborative digital ecosystems.

The main challenges arise in three interconnected areas: physical constraints, regulatory strictness, and operational differences.

1. *Physical Modularity vs. Airworthiness and ULD Certification*

The most evident and costly obstacle stems from the mismatch between physical assets and safety regulations. The PI calls for a universally standardized set of interlocking rectangular π-containers to enhance cubic efficiency across all transport modes—including road, rail, sea, and air—and to facilitate automation. However, air freight employs specialized Unit Load Devices (ULDs), such as LD-3/AKE, which are contoured to fit the cylindrical fuselage of aircraft. While this design optimizes lift capacity and volume, it is inherently non-modular and incompatible with the Palm's core rectangular standards. Placing a rectangular container inside a contoured ULD results in significant unused volume, which drastically reduces efficiency and impacts the high cost-per-kilogram revenue model of air transport.

Introducing a new modular family of π-containers into the air ecosystem would entail a lengthy and expensive re-certification process by TSO/EASA. This involves verifying the container's structure, base, and tie-down mechanisms to ensure they can endure all flight conditions while maintaining structural integrity and load security. These requirements complicate the use of lightweight, collapsible, or universally designed units. A ULD is not just packaging; it is recognized by authorities (EASA, FAA, IATA) as a certified secondary restraint system for cargo, ensuring flight safety by securing the load against extreme g-forces. Non-certified ULDs are generally not permitted in the aircraft's cargo loading system.

2. *Operational Openness vs. Security and Regulatory Constraints*

The PI promotes an open, collaborative "network of networks" where shipments are dynamically routed through various open-access π-Nodes, which may even be in competition. This system needs to allow for seamless transfer of a π-container to the most suitable handler or mover at any time. However, international air cargo operations are governed by strict, linear Chain of Custody (CoC) rules, such as the Regulated Agent and Known Consignor schemes, aimed at preventing contraband or explosives (ICAO, 2025). These rules demand a traceable, continuous, and validated security audit trail. Dynamic re-routing across a shared, multi-party network challenges the traditional, linear CoC. Developing trust and liability transfer mechanisms that meet federal security standards (like the Consignment Security Declaration or CSD) within a constantly changing PI infrastructure poses significant regulatory and legal challenges.

The effectiveness of synchromodality depends on the widespread exchange of real-time data—such as container status, priority, and available capacity—using open standards and Digital Twins. Although the air industry is advancing in digitalization, exemplified by IATA's ONE Record initiative to replace legacy messaging systems like Cargo-IMP/XML, adoption remains inconsistent (IATA, 2025). Additionally, air carriers tend to protect commercially sensitive information—like customer details and actual capacity figures—that is vital for efficient PI routing but is kept confidential due to competitive reasons. This reluctance to share open data necessary for the PI hampers the autonomous, system-wide optimization anticipated by the π model.

3. *High-Speed Operation vs. Synchromodality and Hyperconnectivity*

This highlights the tension between air cargo's premium value and the fundamental PI goal of optimizing costs and the environment across the system. Air cargo is a high-profit product where customers pay extra for guaranteed, timely delivery. Routing choices that risk delays or opt for slower, eco-friendly options can reduce carrier revenue and undermine the high-speed air service's value. Therefore, the PI needs to create a 'Premium PI' protocol that enables air cargo to avoid congestion and prioritize speed above all other network factors.

Most air cargo infrastructure, including handling terminals, ULDs, and ground support equipment, is mostly proprietary and vertically integrated, controlled by airlines, ground handlers, or freight forwarders. These entities have little economic motivation to invest in open-access π-Hubs mandated by the PI, especially since the main advantages of these hubs—load consolidation and modal shift—may decrease the demand for their lucrative point-to-point services. To foster systemic collaboration, new financial and governance models, like revenue sharing for shared assets, are necessary to promote a shift in mindset.

The Physical Internet (π) symbolizes the future of logistics—a revolutionary idea needed to combat growing inefficiencies and environmental issues in global freight transport. Nevertheless, this research finds that implementing it smoothly within the air cargo industry—the most time-sensitive, heavily regulated, and safety-critical mode—is not just an incremental change but a fundamental clash of paradigms.

Recommendation

Given the severity of the challenges—from capacity constraints and geopolitical rerouting to the core mismatch with π's modularity—the air cargo industry needs to prioritize resilience, digitalization, and strategic collaboration. Here are the main recommendations for the industry to tackle these current issues and effectively prepare for the future integration envisioned by the Physical Internet:

1. ***Enhance Supply Chain Resilience through Multimodal Integration***: The industry needs to shift from an air-only perspective to more effectively manage capacity and geopolitical risks. Develop integrated solutions that combine air, ground, and air again (Synchromodal), using the air segment only when essential — for speed or high-value shipments. This involves establishing stable, reliable interfaces (both virtual and physical) with high-speed rail and trusted trucking partners to shift volumes efficiently, handle peak demand, and prevent airspace closures. Additionally, reduce dependence on congested main passenger hubs. Airlines and forwarders should prioritize using cargo-friendly secondary airports (such as Rickenbacker and East Midlands), which facilitate quick freighter turnaround and have direct road access, significantly decreasing ground handling and first-mile congestion common at major gateways.

2. ***Accelerate Digital Transformation and Data Standardization:*** Digital maturity is vital for gaining a competitive edge and establishing the Physical Internet foundation. Accelerate the implementation of IATA's ONE Record data sharing standard to achieve a unified, unchangeable digital overview of shipments. This key step helps eliminate paper-based processes, simplifies customs procedures, and creates the digital infrastructure needed for π's real-time routing. Additionally, use Artificial Intelligence and advanced analytics to enhance capacity forecasting and dynamic pricing for both belly hold and freighter spaces. This enables carriers to anticipate supply-demand fluctuations and optimize the multi-dimensional capacity (such as weight, volume, and ULD configurations) of aircraft.

3. ***Collaborate on Physical Standardization and Safety***: Airlines, ULD manufacturers, and IATA should work together with Physical Internet research groups like ALICE to fund and develop a standardized Hybrid π-ULD design. This design must meet airworthiness standards while supporting intermodal flexibility. Additionally, it is essential to address the significant human resource shortages and the inconsistent application of safety standards. Investing in comprehensive, standardized training programs for all ground handlers and freight forwarders involved in ULD assembly can help reduce damage, improve security compliance, and maintain the integrity of the air cargo chain.

Ultimately, the success of a sustainable and efficient global logistics system hinges on addressing this integration challenge. Future research should move beyond merely advocating for PI implementation to focus on creating specific, certified, and economically feasible governance and engineering frameworks. These frameworks will allow the air freight sector to safeguard its key assets—speed and safety—while integrating its capacity into the universal Physical Internet network. The key is developing protocols that position air cargo as a premium component within the π ecosystem, leveraging its speed when needed, and efficiently shifting volume to slower, greener modes for better optimization.

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