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Blockchain Technology for Logistics Collaboration in Physical Internet

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Abstract—This paper examines the potential contribution of blockchain (BC) technology to the Physical Internet (PI) for enhancing logistics collaboration management, and proposes a forward-looking deployment framework. Inspired by the digital internet, PI is a worldwide emerging logistics paradigm that advocates the interconnection of independent and heterogeneous logistics networks for the mutual sharing of services and assets. Such a paradigm will fundamentally challenge current operations management models and practices to achieve PI-based cooperation and co-opetition. New information technologies, notably BC technology including smart contracts and tokens, are considered promising in this regard. This paper aims to contribute to research by investigating why and how BC can be used in PI from the perspective of collaboration management. We then propose a framework for the deployment of BC in PI from operational to strategic levels. The key requirements as well as challenges to applying state-of-the-art BC technology to PI are also investigated.

Keywords—logistics, supply chain, Blockchain, Smart Contract, Token incentives, Physical Internet, collaboration management, digital interoperability.

I. INTRODUCTION

Physical Internet (hereafter PI) is a worldwide innovative logistics paradigm proposed to improve the sustainability of the current global supply chain and logistics networks. The concept was firstly coined around 2009 by [1]. Then, it has been rapidly developed worldwide, in both communities of academia and industry. See the related research and development works published in the recent special issues in the flagship journals of the domain, [2], [3], [4] and [5].

In essence, the vision of PI is to mimic the principles of data packet transmission over the digital internet and apply them to freight transportation and logistics in the physical world. The objective is to collaboratively improve the overall efficiency, sustainability, and resilience of global and local logistics services, yielding mutual benefits for key stakeholders in PI, such as service providers, shippers, and clients. It is foreseeable that such a paradigm will fundamentally challenge current operations management models and practices, as it requires key stakeholders, especially service providers, to shift their mindset from competition to cooperation and co-opetition—cooperating with rivals—when mutual benefits are achievable. This evolution has already been underway, as described in the PI European Roadmap and demonstrated by the PI-related industrial projects listed on www.etp-logistics.eu.

One key challenge in achieving PI is interoperability between networks or systems, encompassing physical,

informational, and business aspects. This paper pays particular attention to digital interoperability, which is critical to PI, as argued in [3]. Historically, data exchange within or across companies has relied on traditional methods such as paper-based solutions and emails, or advanced technologies like EDI (Electronic Data Interchange) systems and APIs (Application Programming Interfaces). However, these methods show significant limitations in the era of digitization in logistics and supply chain management [6]. Emerging solutions to address this challenge include data platforms, particularly those based on blockchain technology.

Blockchain (hereafter BC) technologies have been rapidly developing and evolving over the past ten years. New concepts and technological innovations have already made impacts on different areas, such as *DeFi* (Decentralized Finance) in the financial sector, *NFTs* (Non-Fungible Tokens) in digital art and asset management, *Web3* and *DeSoc* (Decentralized Social Networks), *DePIN* (Decentralized Physical Infrastructure Networks) in crowdsourcing, among many others. However, applications in logistics are still in their infancy, with little attention paid to PI. For example, [7] examines the use of BC for PI-container routing, [8] investigates the application of BC in PI-cross-docking centers, and [9] designs smart contracts for automated transportation service procurement in PI-hubs.

This paper aims to examine the potential contribution of BC technology to collaboration management in PI. We investigate the motivation for adopting various BC technologies (i.e., BC networks, smart contracts, Tokens) from the perspective of collaboration management, spanning operational to strategic levels. We then explore the state-of-the-art solutions that are considered promising to overcome collaboration barriers and innovate new operations management models or services. Building upon these findings, we propose a forward-looking framework designed to provide a high-level roadmap for the application of BC in PI, while also identifying actual requirements and major challenges. Through this, the paper aims to investigate the following research questions: 1) *What are the appropriate BC technologies to address related collaboration issues in PI?* 2) *How can they be adopted at different collaboration levels?* 3) *What current challenges and issues exist in technology adoption?* However, it should be noted that financial aspects, such as supply chain finance and payment, are not within the scope of this paper, as they are outside the focus of PI.

Section II discusses concisely significant collaboration management issues related to PI and BC simultaneously. Section III investigates the state-of-the-art BC technology and their potential to address these issues. Section IV analyzes the

challenges of adopting the technologies in the current logistics models and practices. Section V concludes this work.

II. COLLABORATION MANAGEMENT IN PHYSICAL INTERNET

PI was inspired by the digital internet which is one of the most successful stories of service cooperation among independent providers. However, the well-established cooperative models from the internet, such as the OSI (Open Systems Interconnection) model and TCP/IP routing protocols, may not be simply and fully applicable to PI. Significant differences between the digital and physical worlds should be considered in the analogy, such as the time required for freight transportation compared to data transmission, the storage of freight compared to data, and the different classes of services in logistics compared to the internet. Collaboration management in PI must take these differences into account. Therefore, the development and innovation of new models are particularly appealing.

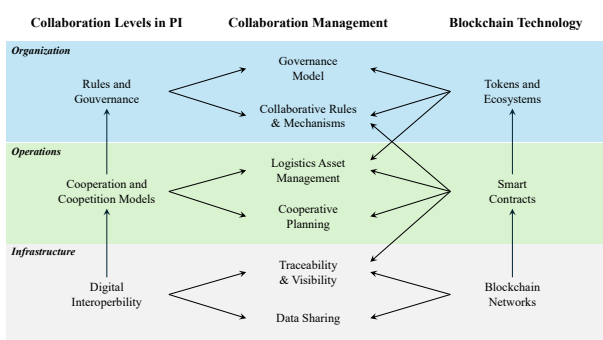


Fig. 1. Fromwork of Blockchain technologies for collaboration management in Physical Internet

Figure 1 displays the proposed framework of various BC technologies for collaboration management in PI. It illustrates the major challenges related to collaboration management in PI and the relevance of these technologies to each challenge. In the following sections, the discussion will adhere to this framework.

A. Digital Interoperability

For the sake of consistency, this paper adheres to the definition of digital interoperability given by [3], which defines it as “*the ability to achieve quick, seamless, secure, and reliable data and information exchange between computing devices (viz. devices being able to transfer data), between information systems (of organizations, infrastructures, logistics networks), or between devices and systems, for the aim of enhancing cooperation or cooptition of independent logistics parties or networks*”. Broadly speaking, it involves data or information communication within and between organizations across supply chains.

While digital interoperability has long been recognized as a challenge in traditional logistics systems, it should even embrace a bolder vision in PI. PI emphasizes not only vertical collaboration (e.g., through supplier-carrier-client) but also horizontal cooperation or cooptition (e.g., among carriers). We consider digital interoperability at the infrastructure level in PI, as it underpins essential functions such as data sharing and traceability, which are crucial for collaborative operations within the PI network.

Within PI, data sharing gives access to asset pools shared by multiple parties, such as transportation means and storage

facilities. This forms the basis for collaborative operations management and planning. Additionally, traceability is critical for effective collaboration. Traceability in PI broadly refers to tracing logistics objects (e.g., PI containers, shipments), operations (e.g., temperature or vibration during transportation), and responsibility (e.g., product damaged or missed, ownership transfers) across logistics activities, as well as across supply chains. Adequate traceability, based on reliable authenticity data, builds trust among stakeholders in PI and enhances the system’s reliability. Moreover, it also enables end-to-end visibility of logistics and process flows through PI, which is essential for monitoring, dynamic decision-making, and planning.

B. Cooperation and Cooptition Models

Given that PI represents a disruptive innovation in collaborative logistics, it necessitates the development of more efficient and effective collaborative models for this novel environment. Specifically, PI underscores the significance of horizontal collaboration, also referred to as *cooptition* in both literature and practice, which entails cooperation between two rivals who collaborate for mutual benefits while simultaneously competing with each other [10]. See some actual examples presented in the survey [11].

Among others, two significant problems related to collaboration management in the context of PI with BC technology can be discussed here. The first is cooperative planning, which involves the optimized coordination and planning of operations and assets among collaborators, relying on efficient tools and models. In the literature, two types of coordination models are predominantly used: centralized and decentralized. The centralized model employs optimization models to centrally optimize cooperative planning for all participating collaborators, such as linear programming models for multi-shipper joint route planning [12]. In contrast, the decentralized model involves rule- or protocol-based decision making, which uses pre-defined consensual rules to coordinate operations without relying on central optimization models. Each collaborator can make their own decisions based on these common rules. A notable example in practice can be referred to the *Universal Post Union*. It is foreseeable that both types can be used in PI, depending on the objectives and configuration of collaboration.

The second significant problem is collaborative logistics asset management. Recall that we focus solely on physical assets in this paper (for examples of BC applications for logistics digital assets see [13]). Asset management poses a well-known challenge in logistics operations. Since PI further emphasizes the importance of servicetization and service-orientation towards the *Logistics-as-a-Service* model, transparency and visibility of asset utilization across service providers need enhancement. For example, in PI-container pool management (utilization and repositioning), sharing of truck capacity, and crowdsourced transportation. Ensuring transparency and visibility of shared assets is crucial for value co-creation and sharing through PI, such as cost or benefit sharing, reporting of CO₂ emission of shipper (especially Scope 3).

C. Governance and Incentives

Governance is a high-level management issue in PI, encompassing the design of governance models, consensual rules, and collaborative mechanisms for global or local PI-networks. As defined by the European PI roadmap, this

encompasses practical considerations such as rules for asset sharing, competition and conflict management, and the development of open network models, for example. These questions are evidently critical to incentivizing stakeholders to utilize PI.

Reference [11] propose that two governance models can be used in logistics collaboration as well as in PI: corporate and cooperative. In the corporate model, collaborators operate as one single integrated entity, whereas in the cooperative model, they act as independent companies adhering to consensual rules. These terms are sometimes interchangeable with centralization and decentralization models in practices. These models can be jointly used in PI, for instance, the corporate models for local or small-scale sub-networks, and cooperative models for the interconnection of sub-networks (just like digital internet does). However, it should be noted that governance models have not been adequately studied in the PI community yet, despite its significance. Section III will further examine how Smart Contracts can contribute to each while playing different role.

III. POTENTIAL OF BROCKCHAIN TECHNOLOGY IN PI

This section discussed the most relevant state-of-the-art BC technology to address the collaboration management issues in PI outlined above. It is worth noting that the section aims to offer a perspective and prospective discussion on the potential of the key technologies. We refer to the surveys [14] and [15], for example, for an exhaustive list of solutions and use cases of BC in logistics and supply chain management.

A. Blockchain Networks

Essentially, BC is an encrypted and immutable distributed transaction ledger. Various BC networks have been devised based on different configurations of architectures and distributed ledger technologies (public, private, consortium, or hybrid), as well as consensus mechanisms (e.g., proof-of-work and proof-of-stake models). These networks include well-known public chains like Bitcoin, Ethereum, and Solana, as well as industrial chains like VeChainThor or IOTA Tangle [16]. Notably, Hyperledger Fabric is a business BC framework and platform for private and permissioned BC, which has been increasingly used in projects and pilot studies in the field of logistics and supply chain, such as the examples discussed in the surveys [14] and [15], and [13] comparing IOTA/Hyperledger/Ethereum in logistics.

cross-chain functionality such as data transactions and smart contract execution, the so-called “bridge” between BC networks. Regarding logistics applications, another important function of Layer 0 is data feeds, involving the transmission of real-world dynamic data onto the BCs. While data registered on BCs (on-chain data) is static, real-world data/information (off-chain data) is dynamic. BCs or Smart contract themselves cannot access external real-world data. Oracles are used to feed off-chain data onto BCs for data storage, sometimes also for smart contract execution, such as automatic payment upon delivery completion. Layer 0 once again serves as the “bridge” between BCs and external world. Furthermore, Layer 2 involves sidechains of BCs aimed at addressing scalability issues by processing transactions at a much higher capacity. For example, Lighten Network built on Bitcoin, and Polygon built on Ethereum, both aim to scale up (thousands of times) the Transactions per second (TPS) of the BCs and improve cost-efficiency. Finally, Layer 3 deals with decentralized applications for service and value delivery, such as the applications for DeFi or Web3.

In the field of logistics and supply chain, the literature has already revealed that BC technology may significantly contribute to the issues of data sharing and traceability in PI. As discussed in [3], data sharing involves different aspects, including data content (what data to share), data format (how to present data), communication channel (what solutions for sharing). BC technology primarily addresses the communication channel aspect, considering that data content is often defined by company business requirements, and data format often determined by data standards (e.g., GS1 standards) or models (e.g., semantics and ontology). The latter two aspects are not addressed in this work.

BC-based solutions for data communication have important advantages compared to traditional solutions. First, they are able to enhance data security, immutability, authenticity and transparency for logistics operations, which are intrinsic qualities of BC technology (more details in [15]). Such qualities are of particular importance for PI systems, as they will ensure the reliable tractability in PI to build up the trust. Nowadays, collaborative logistics are mostly upon a central authority such as trustee or 5PL, who are a third party ensuring the trust and coordination among collaborators. BC technology may play a similar role, but in a decentralized way without requiring the presence of a central authority. Consequently, operating costs can be reduced. Moreover, data transparency will also enhance the end-to-end visibility of objects and operations within PI, at low cost and with reliable data.

As mentioned earlier, digital interoperability is crucial for PI that involves multiple logistics operations and companies across supply chains. The issue persists in BC-based PI systems, as companies within PI may have deployed various types of BCs. Layer 0 provides solutions to alleviate the problem by bridging the chains as well as bridging external world with the chains. It is likely that Layer 0 would enhance the interoperability and data authenticity in BC-based PI systems, simultaneously. Although promising, there is a paucity of research focusing on Layer 0 for logistics operations.

B. Smart Contracts

Smart Contracts can simply be seen as multi-party, autonomously executing digital contracts built on a BC, which should be immutable and therefore reliable. They have pre-

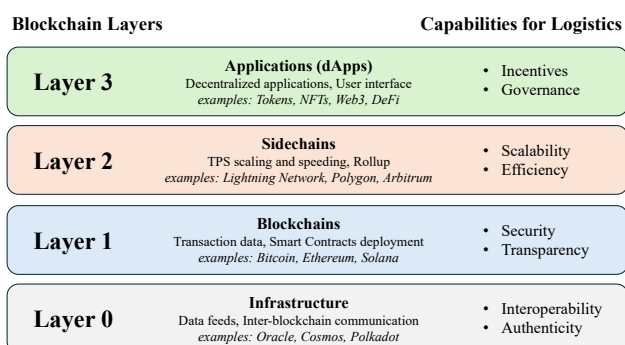


Fig. 2. Blockchain layers with the key capabilities in logistics systems

BC networks and platforms are conventionally referred to as Layer 1, as indicated in Figure 2. They are built upon the infrastructure often referred to as Layer 0, which provides a communication protocol across multiple chains to enable

defined terms and conditions, enabling them to automatically come into effect upon the completion of all conditions. A rich literature has demonstrated its great potential for logistics and supply chain. However, its applications in collaboration management in PI have been barely studied.

Smart contract technology shows promising potential for addressing critical management issues in the Physical Internet (PI). Firstly, it can enhance the traceability of objects (cargo, assets, etc.) and operations related to collaborative operations in PI. As the parties (represented by pseudonymous accounts) involved in contracts are transparent to all stakeholders, and responsibility transfer is explicitly defined in the contract, this enables reliable traceability throughout the entire system, particularly in identifying the origin of problems and errors.

Secondly, rule-based cooperative planning in PI can also be relying on smart contracts. A practical example of freight transportation service procurement in PI hubs is investigated in [9], which suggests using smart contracts to decentralize and automate the procurement process. This use case also highlights another important capability of smart contracts: automating business processes through auto-execution, as discussed in [14].

Thirdly, smart contracts can help asset management, especially for assets sharing in PI systems. As mentioned earlier, PI advocates servicetization and service-orientation towards the *Logistics-as-a-Service* model, where payment (per service or by contract) should be swift and reliable upon the completion of the service. Smart contract technology significantly facilitates the payment process, speeding it up and reducing paperwork (or going paperless). Examples include work employment in the spot market [17]. Furthermore, smart contracts also enable NFT technology, which shows promising potential in asset management [18]. NFTs can give the right to use a specific asset or resource, thus avoiding confusion and misuse, for example, by integrating NFT with digital twin of an object in use.

Lastly, smart contracts can contribute to the design and execution of collaborative rules or protocols in PI. As mentioned, a breakthrough application of smart contracts is in the DeFi market, where currency exchanges or investments rely on smart contract-based protocols, without a central platform or authority. This use case is inspirable for PI to achieve efficient, reliable, and low-cost collaboration management.

C. Token Incentives

Token technology, mostly referred to as Tokenization, is a breakthrough innovation and application of BC technology. Originally, a token is the native cryptocurrency of a BC, like ETH in Ethereum, used to incentivize miners to work for the BC. In the context of this research, a token may represent the right to use an object or resource (in asset management), voting power in governance models, or native cryptocurrency representing monetary value as a form of payment for services or resources provided. The latter two applications are related to the governance and incentive models of PI systems. This topic has been increasingly studied by the crypto or gaming community, introducing emerging concepts like the DAO (decentralized autonomous organization) model or the DePIN (Decentralized Physical Infrastructure Networks) model. Despite its promise, token technology has not yet been adequately studied in logistics systems, or within the PI community.

IV. KEY CHALLENGES OF BROCKCHAIN TECHNOLOGY IN PI

Despite the promising potential of BC technology in logistics and supply chain, its real-life application remains rare due to critical issues and problems. From a management perspective, this section discusses the key challenges and issues related to the adoption of BC technology in PI systems. Technological perspectives are not the focus here, as they have been well studied by the communities of computer science and information science.

A. On-chain or Off-chain

The well-known BC networks (Layer 1) are often criticized for their low capacity of data storage and transactions per second (TPS), for example, the Bitcoin chain with 7 TPS and the Ethereum chain with 13 TPS. Some layer 1 platforms claim to have much higher TPS, like Solana, but congestion issues still arise when mass mining events occur on the chain (see the congestion incident on the Solana chain in early 2024). Layer 2 solutions are currently the most adapted to alleviate the scalability issues of Layer 1. However, to achieve scalable and cost-efficient solutions for logistics operations at large scale systems, the fundamental question is what data need to be on-chain and what data are better kept off-chain. Moreover, this question is also significant for privacy issues. Essentially, only data necessary for operations management should be put onto the chain, but there must be solutions to bridge, or map, off-chain data to on-chain data. Currently, APIs are the most applied solution to this end [19]. Innovative solutions are appealing to achieve secure, seamless, efficient, and effective bridging.

B. BC Network Design

As mentioned earlier, there are different types of BC platforms that can be applied to various use cases, such as public, private, consortium, or hybrid chains. For example, Hyperledger Fabric platform is mostly studied for logistics and supply chain applications due to the outstanding qualities in privacy protection, flexible modular architecture, and cost-efficiency. However, they have been criticized for shortages in scalability, stability, and interoperability with other chains in some use cases. Some industrial Layer 1 solutions show good potential in scalability, such as IOTA, but may have disadvantages in smart contract deployment. One rising trend is to use Layer 2 solutions to roll up Layer 1 data transactions, such as CargoX using Polygon's scaling solution for Ethereum transactions to digitalize the Bill of Lading document in the shipping industry. However, it is important to note that a Layer 2 should incorporate the same consensual mechanisms as its Layer 1. Since the technology is still rapidly evolving, it is not yet possible to draw conclusions on the most appropriate BC solutions for the logistics industry.

C. Commercial Viability

Since the rise of BC technology, numerous proof-of-concept studies and pilot projects have been conducted in the logistics industry. However, successful stories remain limited. A notable example is the TradeLens project initiated by Maersk and IBM, which aimed to enhance traceability of shipping containers using BC for public registry data. The platform charged users a fee of \$25 per container per journey [20]. The project began in 2018 and ended in 2022 due to the failure to achieve commercial viability [21]. The business model and story have garnered significant attention from both academia and industry practitioners. Some argued that the fee

was set too high, while others believed that the project failed because it was led by a giant company which is a major competitor of other carriers in the shipping industry. A key lesson from the case is that the adoption of BC technology should provide greater value than merely ensuring container traceability to offset the cost of BC. For example, the digitization of bills of lading (BoL) proposed by startups like CargoX and GSBN may inspire the applications of BC technology in other logistics activities for higher added value.

D. Barriers to Technology Adoption

BC technology in the logistics industry is still in its infancy. Today, most companies in logistics and supply chain are not yet ready to embrace the new technologies and paradigm. There are several important barriers to adopting the technology, which are even more severe than those for other digitalization solutions.

The related literature has shown intensive interest in studying this issue, notably using Technology-organization-environment (TEO) Framework to understand the key factors in the adoption process [22]. Most research confirms that a top-down approach is essential for adopting BC technology in organizations, meaning it should be initiated by high-level top management. However, many logistics firms still need to further develop IT resources to seamlessly accommodate new technologies. This is even more critical for small-sized firms that form the backbone of logistics activities worldwide. This challenge is particularly critical to PI systems, as they aim at interconnecting heterogeneous logistics firms regardless of size. It is foreseeable that external IT resources, such as consultancy or BC solution providers (also called 6PL in practice), will have an increasingly important role to play. Another external barrier is that the use of smart contracts in some logistics operations may not be conceivable due to the lack of a legal framework. For example, the issue has been discussed in the use case of employment. Although smart contracts could be considered as digital binding contracts, their legal legitimacy is still controversial worldwide.

E. Integration with Other Technologies

Further investigation is needed to explore the compatibility and integration of BC technology with other digitalization tools and solutions, particularly the two rising concepts: Artificial Intelligence (AI) and Metaverse. Recently AI has become the hottest topic in the field of logistics and supply chain management. The combination of AI and BC, both cutting-edge technologies, remains debatable. Some believe that BC technology can prove secure authenticity data for AI models, and that Smart Contracts can autonomously execute AI-made (or AI-aided) decisions. However, the efficiency and tractability of such combination have been challenged. As discussed above, it is critical to have appropriate on-chain data for AI models, as well as effective and efficient interaction with external off-chain data for smart contract execution.

On the other hand, Metaverse (often including Digital Twins which can be seen as a pillar of Metaverse) is another concept commonly combined with BC technology for both academic and practical research [23]. BC is often considered as backbone infrastructure of Metaverse, providing data authenticity, Web3-based data management, or secure payment solutions. Successful applications have been witnessed in the gaming industry; however, they are still rare in the logistics industry.,

Lastly, despite the promising solutions of Layer 0, interoperability between BCs, or between BC and other digital systems or tools, remains a significant challenge. The literature clearly shows a lack of application research on Layer 0 solutions in the logistics industry. Secure, privacy-preserving, reliable, and cost-efficient solutions are yet to be developed for the logistics industry as well as PI systems.

V. CONCLUSION

The paper discusses the perspectives and prospects of adopting blockchain (BC) technology for collaboration management in the Physical Internet. It provides a forward-looking deployment framework, with a profound investigation into the key challenges and issues based on the current landscape of research and application. Upon the research, several conclusions can be drawn to advance the research. Firstly, BC technology may have a broader vision in logistics than solely for data transaction or traceability of products. More attention should be paid to smart contracts for collaborative planning and asset sharing. Moreover, tokenization should be further explored for the design of governance models and incentive mechanisms of Physical Internet systems for logistics collaboration. Secondly, the adoption of BC in the logistics industry still faces critical challenges, most importantly, interoperability with other digital systems, synergies with other digitalization solutions, and the lack of a legal framework for some valuable use cases. We believe that this work may outline promising avenues for future research.

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