Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 72 (2023) 2022–2029

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

A blockchain-based architecture and smart contracts for an interoperable Physical Internet

Harris Niavis[a*], Aristea M. Zafeiropoulou[b]

[a]*Inlecom Innovation, Tatoiou 11, Athens, 14561, Greece*

[b]*Konnecta Systems Limited, Core B, Block 71, The Plaza Park West, Dublin, Ireland*

Abstract

Transport and Logistics stakeholders utilise Blockchain to interact within their networks in a transparent and secure manner. This creates islands of disconnected communities which prohibits visibility across the entire supply chain. This paper introduces a framework, which aims at unifying multiple proprietary Blockchain systems, offering an opportunity to empower stakeholders across the entire supply chain to collaborate and exchange information seamlessly. The Blockchain Interoperability framework employs smart contracts, which aspire to automate previously cumbersome processes and bring value to the Physical Internet (PI) paradigm. Smart contracts guarantee a trustworthy and distributed process of contract negotiation and execution that significantly reduces time, administrative overheads, and costs which are currently typically spent on manual inter-organisational processes.

Keywords: Blockchain interoperability; supply chain; smart contract; Physical Internet; logistics

1. Introduction

The Physical Internet (PI) is an emerging Transport & Logistics (T&L) paradigm that can be defined as an open global logistics system founded on physical, digital, and operational interconnectivity through encapsulation, interfaces, and protocols (Montreuil et al. (2013)). It is driven by technological, infrastructural, and business innovation, hence the emergence of Blockchain and smart contracts and most importantly their application in modern T&L networks is highly intertwined with the evolution of the PI. Blockchain features and functionalities have the potential not only to meet PI implementation requirements but also to overcome key PI barriers and deficiencies (Meyer et al. (2019)). Despite the advantages the PI may offer, it cannot continue relying on centralised networks nor on the

* Corresponding author. Tel.: +306973055822.
E-mail address: harris.niavis@inlecomsystems.com

10.1016/j.trpro.2023.11.684

existence of a leading authority (Hasan et al. (2021)). In this manner, the PI will be able to proliferate only if it follows a distributed and community driven concept and approach.

Smart contracts can play an instrumental role in the roadmap towards the PI. The Alliance for Logistics Innovation through Collaboration in Europe (ALICE) has proclaimed that they can achieve this goal in two ways: by creating seamless booking systems to increase response time and by becoming proactive in the smart use of resources employing fully autonomous services and operations with predefined smart contracts (Ballot et al. (2020)).

However, T&L stakeholders have already joined Blockchain consortia and/or deployed their own private, permissioned networks through which they exchange information with their partners in a trustful manner, thus creating disconnected networks that are impossible to bridge. Blockchain interoperability is a chief enabler for the PI, as it offers the ability for existing disparate Blockchain systems to interoperate and share data regarding shipping manifests, smart contracts, customs declarations, transport events and so on. The interconnection of these silos is a challenge tackled by the proposed blueprint architecture, which is deployed in the PLANET project, but can also be replicated in other supply chains to increase visibility and enhance the collaboration among the participants.

The PLANET project proposes an open-source architectural blueprint to empower organisations to build and implement T&L design tools, collaborative logistics and new e-commerce models underpinned by data-driven supply chain insights. It also formalises a set of guidelines to facilitate the realisation of an EU–Global T&L Network (EGTN) Platform. The EGTN Platform architecture integrates T&L data from heterogeneous sources, such as smart logistics assets (smart pallets, smart containers, and smart warehouses), logistics time schedules, and weather news. Following that, it augments the data using Knowledge Graphs and feeds them to other services, such as AI predictive analytics, Decision Support Systems, and smart contracts, as well as to the EGTN Dashboard for their visualisation. This paper describes the Blockchain and Data Aggregator components of the EGTN architecture which are employed together to enable interoperability between backend Blockchain systems hosted by different T&L stakeholders.

The main contributions include standardised interfaces that enable simple connection of Blockchain systems with the EGTN Interledger service as well as standardised smart contracts rules to enhance transparency and visibility across the supply chain. The EGTN Smart Contracts listen for logistics events in the individual Blockchain networks and forward these to other ones that can benefit from them by acting proactively and increasing response time.

2. Background

Interoperability is the capacity of computer systems to exchange and use data, but also the capacity to transfer an asset between different systems while keeping the state and uniqueness of the asset consistent. It is a key enabler for the PI (Pan et al. (2021)). In the case of Blockchain systems, interoperability is an emerging hot topic both in the academia and in the industry. Blockchain interoperability ranges from relatively simple - i.e., interoperability between smart contracts on the same ledger - to very complex – i.e., inter-Blockchain interoperability or between a Blockchain network and a legacy system. A different challenge that Blockchain interoperability addresses is to enable data exchanges between a public Blockchain where pseudonymous data are used and a private Blockchain where transactions require user identification. Multiple technical teams around the world are currently looking to solve the challenge of sharing transactions across Blockchain networks using advanced methods and propose innovative solutions. The objects exchanged in any Blockchain interoperability scenario can be of three types (Montgomery et al. (2022)): (i) FA: Fungible asset (value token/coin), cannot be duplicated on different ledgers - e.g., currency and ERC 20 tokens, (ii) NFA: Non-fungible asset, cannot be duplicated on different ledgers, it is unique, and it cannot be swapped - e.g., ERC 721 tokens (Entriken et al. (2018)), and (iii) D: Data, which can be duplicated on different ledgers.

The employed interoperability framework should guarantee that FAs and NFAs have only one valid representation of a given asset in the system. On the other hand, Data (third type above) exchanged in an interoperability scenario can be duplicated on different ledgers. According to surveys and analysis in the literature (Belchior et al. (2021)), (Siris et al. (2019)) approaches looking to achieve Blockchain interoperability can be classified into the following high-level categories: Public Connectors, Blockchain of Blockchains, and Hybrid Connectors. Each category can be further divided into subcategories based on defined criteria while each category serves specific use cases. The Public Connectors are mostly cryptocurrency-related and deal with the movement of Fungible values from one ledger to another. The Blockchain of Blockchains category includes custom architectures that provide reusable data, network, consensus, and contract layers for the creation of customised Blockchain infrastructures and serve general use cases.

The Hybrid Connectors approach is an attempt at delivering a “Blockchain abstraction layer” (World Economic Forum (2020)) - that would be a “Blockchain front-end” in the case of PLANET - capable of exposing a set of uniform interfaces that allow stakeholders to interact with Blockchain systems without the need to use different APIs. The EGTN Platform follows a “Hybrid Connectors” approach in the architecture of its Interledger service, as it interconnects existing backend systems and exposes universal, standardised interfaces to actors of the supply chain.

2.1. Blockchain Interoperability Frameworks

The current state-of-the-art frameworks, protocols, and platforms that are used in the process of applying Blockchain interoperability solutions are the following:

The **SOFIE Interledger component** is an outcome of the H2020 SOFIE project, which ended in December 2020. The codebase is open source on GitHub. Through the SOFIE Interledger component, activity on an Initiator ledger triggers activity on one or more Responder ledgers in an atomic manner. It supports different types of ledgers (e.g., Ethereum, Hyperledger Fabric, Hyperledger Indy, KSI) and can be used in multiple use cases which fall under both the Hybrid Connectors and the Public Connectors categories, such as the following: (i) Transferring Data from one ledger to another. (ii) Storing Data Hashes in a (private) ledger while a hash of the information is consequently stored in a (public) ledger at suitable intervals using the Interledger component to benefit from the higher level of trust in a public ledger. (iii) Game Asset Transfer employing a state transfer protocol, which is used to manage in-game assets: the assets can either be used in a game or traded between gamers. In both activities, a separate ledger is used and the SOFIE Interledger ensures that each asset is active in only one of the ledgers. (iv) Hash Time Locked Contracts (HTLCs) to automate the asset exchange between two ledgers using Hash Time-Locked Contracts (HTLCs).

The **Hyperledger Cactus** project began in 2020, when Fujitsu open-sourced its Blockchain interoperability solution under the umbrella of the Hyperledger and Linux Foundation. It is currently in Incubation state, yet there is a clearly defined roadmap, which means that it will soon be qualified to pass to Graduated status. Cactus is a plugin-based framework that provides developers with an abstraction layer over protocol-specific implementations and in this manner allow for interoperability. This empowers solutions to adapt to new protocols and make transactions involving multiple public and/or permissioned ledgers more easily. Cactus consists of “business logic plugins,” which coordinate cross-Blockchain integration and “ledger plugins” that facilitate connections to specific ledgers. It supports multiple Blockchain systems, namely Hyperledger Besu/Fabric/Indy/Sawtooth/Iroha, Corda, Geth, and Quorum and it can be used in diverse use cases such as car trade, electricity trade, Ethereum to Quorum asset transfer, money exchanges, and integration of existing food traceability solutions. The key principles behind Cactus are: (i) plug-in architecture - i.e., it maximises flexibility and future-proofing through a plug-in architecture, (ii) security by design - i.e., there is no need for explicit user actions to ensure a secure Cactus deployment, (iii) toll free - i.e., users are not required to use tokens for transactions and operators are not required to take a cut of individual transactions, and finally (iv) low-impact deployment - i.e., it does not interfere with existing network requirements.

The **Interledger protocol (ILP)** is an open-source protocol and W3C standard, designed and developed by the Interledger Foundation to connect cryptocurrencies (Bitcoin, Ethereum). The Interledger Foundation is building pathways to financial access and opportunity across the world, towards a more equitable and creative global society through an open payments network in which anyone can seamlessly earn, share, buy, sell, and trade with anyone else in the world. Although ILP initially focused exclusively on cryptocurrency-related ledgers, nowadays, it is technology agnostic, defining a “lowest unit common denominator” across distributed ledgers, Blockchains, Fiat payment networks, and the ILP packet. As an open-source protocol, it connects all types of ledgers, from digital wallets and national payment systems to others. The end goal is to transact easily with anyone, no matter the location nor the currency. ILP allows money reception from any ledger, without the need to set up accounts on different services. The Interledger protocol is not based on Blockchain, yet it employs key concepts of Blockchain technologies, such as the decentralised design and cryptography-based security. The ILP does not support non-Fungible tokens (such as ERC 721 tokens) and it cannot integrate with existing Blockchains, since each one must be adapted accordingly to use ILP.

Cosmos, launched in 2019, is a decentralised network of independent parallel Blockchains, called Zones. Zones are based on Tendermint, a fast and secure Byzantine Fault-Tolerant consensus engine, along with a peer-to-peer network gossiping protocol. Zones can transfer data to other Zones directly or via hubs. Hubs minimise the number of connections between Zones and avoid double spending. The communication between hubs and the central Cosmos Network (Cosmos hub) uses the Inter Blockchain Communication (IBC) protocol to allow Zones to interact with other Blockchains. Cosmos falls under the Blockchain of Blockchains category, therefore it requires setting up a separate Blockchain as the main chain to sustain all communication and synchronisation complexity, since each Zone maintains its own state. The support of additional non Tendermint-based Blockchain systems is a complex process that can be achieved via Peg zones, a functionality provided by Cosmos.

Polkadot is a sharded heterogeneous multi-chain architecture that enables external networks as well as customised layers i.e., "parachains" to communicate, thus creating an internet of Blockchains. The network uses an environmentally friendly proof of stake consensus algorithm and follows practices similar to the Cosmos network. It can be usedto interconnect permissionless and permissioned ledgers, while high scalability can be achieved using sharding by spreading transactions across the parachains -i.e., the equivalent to Cosmos Zones - allowing them to process transactions in parallel. It uses the Relay Chain, which is the central connector, that functions similarly to the Cosmos Hub and all other Blockchains need to connect to the Relay Chain. It also uses bridge-chains to connect to other type of ledgers in the same manner that Cosmos uses Peg zones.

The **Baseline** Protocol aims to address privacy issues to encourage enterprise adoption of the public Ethereum. The Baseline Protocol is an open-source initiative - started in 2020 and backed by big companies such as EY, Consensys, Microsoft - that combines advances in cryptography e.g., Zero Knowledge Proofs (ZKPs), messaging, and Blockchain to deliver secure and private business processes at low cost. The protocol enables confidential and complex collaboration between enterprises without leaving any sensitive data on-chain. Baseline addresses the challenge that modern enterprises face for secure and private synchronisation of systems of records and provides a low-cost, universal, strongly tamper-resistant solution that can prevent locking companies out of valid operations protocol. These requirements strongly suggest the use of a public Blockchain, or Layer-2 network anchored to a public Blockchain. It uses Ethereum Mainnet as a single point of reference for Blockchains, or local systems of record (Mongo, Oracle, SAP). Despite the privacy-by-design principles and the strong cryptography that is employed, Ethereum is a public network, therefore enterprises may be skeptical to store private data (even with ZKPs in place). Moreover, Baseline still faces all the Ethereum-related challenges and restrictions, such as reduced scalability, reduced performance, weak finality, and fees for transactions. The work is governed as an EEA Community Project, and it is managed by OASIS.

2.2. Blockchain, Smart Contracts and their contribution to the PI

Blockchain has the potential to redesign informational and financial flows, both of which supplement physical flows in the supply chain (Treiblmaier (2019)). Most importantly, the adoption of the latest distributed ledger technologies in T&L networks has laid the groundwork for innovative cross-organisational, collaborative, data sharing platforms.The emergence of smart contracts alongside Blockchain technologies has disrupted the operational flow and contract negotiation in several fields, including T&L. Through smart contracts the rules and conditions of an agreement are defined and agreed in advance between all parties involved. Once a smart contract is established, these cannot be altered without the consent of all parties. Smart contracts execute automatically upon event trigger (e.g., empty truck of freight forwarder arrives at a logistics warehouse triggers a new booking) and guarantee the consignor the acceptance and execution of the pre-agreed offer, but also enforce them to fulfill their own contractual obligations (e.g., fulfill a payment). These powerful benefits can contribute greatly and bring T&L a step closer to the PI.

Synchromodality, one of the roadmaps of the Physical Internet, is also heavily affected by Blockchain. Synchromodality can be defined as the provision of efficient, reliable, flexible, and sustainable services through the coordination and cooperation of stakeholders and the synchronisation of operations within one or more supply chains driven by information and communication technologies (ICT) and intelligent transportation system (ITS) technologies (Giusti et al. (2019)). Blockchain fosters collaboration by making stakeholders feel safe doing business on ICT platforms, as it dissolves information asymmetries between them (Henry et al. (2022)). Smart contracts have also the potential to contribute to a legal and political framework, by encouraging the definition of stakeholders' liabilities in a clear and transparent manner (Giusti et al. (2019)). The advantages of smart contracts in synchromodality are also evident when changes or unforeseen events occur at some point within the supply chain and certain actions need to take place (e.g., rerouting of goods). Blockchain enables new smart contracts to be issued (e.g., Bill of Lading) in a distributed manner, thus reducing the previously manual administrative overheads and avoiding delays. In addition to this, any interested party, such as customs officials, with the required permissions can access the updated information, facilitated by Blockchain Interoperability. This enables cross-organisation information flow, which means that decisions are data-driven and, therefore, can be changed at any step of the supply chain - e.g., in case of cargo damage during transport, rerouting the cargo from distribution to a repair centre; all this in real time (Wurst and Graf (2021)).

Another important aspect that shall contribute to the success of the PI is the inclusion of data integrity, protection, and sovereignty. All T&L stakeholders as data providers expect to maintain sovereignty over sensitive data especially in relation to data consumers i.e., other T&L actors (authorities, customs, other logistics companies). Finally, the entire T&L chain can be sped up using smart contracts that are executed based on shipping steps by offering: (i) real-time access to all the relevant information to all involved stakeholders of international trade processes - i.e., this can reduce administrative costs, (ii) increased transparency through asset tracking, which can also help avoid shipment delays, and (iii) optimised load capacity - i.e., this can minimise shipping costs of T&L (Copigneaux (2020)).

3. Methodology

The approach towards the connection of different Blockchains with the EGTN Interledger service included a survey of the state-of-the-art solutions and identification of the most appropriate one for PLANET, an in-depth understanding of the use case along with the design of the blueprint architecture and the relevant data flows, and, finally, the design of the structure of the smart contracts.

3.1. Ideal Candidate for the EGTN platform

Public Connectors focus on public Blockchains and cryptocurrencies, therefore they cannot be considered as candidate technologies to achieve Blockchain interoperability in PLANET and by extension in the T&L domain. Regarding the Blockchain of Blockchains category, while the provided features can be desirable for end-users, frameworks that fall under this category do not interoperate with each other. Taking this into account, end-users are forced to choose between existing solutions, leading to sub-optimal leveraging of the available resources. Furthermore, the Blockchain of Blockchains category involves the cost of transaction fees to keep the network in operation and to sustain a business model across several Blockchains, thus rendering its applicability questionable given enterprise Blockchain systems. For the purposes of the EGTN platform the SOFIE Interledger component is the ideal candidate to support the requirements, as these were set out by the PLANET partners, and at the same time to fit the specification of the EGTN platform. It adopts the Hybrid Connectors approach that provides an abstraction layer to underlying Blockchain systems. It also supports integration with several Blockchain systems such as Hyperledger Fabric and Ethereum, which are the most popular Blockchain systems used in the T&L domain, but also provides integrations with several other Blockchain systems. Finally, it features an extensible plugin-based architecture.

3.2. Use Case

The PLANET use case refers to the interactions and the exchange of data, included in a Transport Order, between Blockchain systems of different T&L stakeholders. It simulates a transport scenario in which a Shipper community manages shipments from Asia to Spain, while the inland transport is managed by a Freight Forwarder and a Carrier community. Table 1 presents a non-exhaustive list of information to be exchanged, including only non-confidential data, shareable by the stakeholders in accordance with GDPR. In terms of Blockchain technology, two backend Blockchain systems are involved; the first represents the Shippers community (Hyperledger Fabric), while the second one the Freight Forwarder community (Hyperledger Fabric).

Table 1. Non-confidential information exchanged between maritime and terrestrial stakeholders.

T&L Stakeholder	Information
Maritime port and Shipping lines	Fixed cost for merchant transport, Cargo destination (port of delivery, final destination, etc.), Container availability at the port terminal
Freight Forwarders, Logistics Operators	Truck arrival at port terminal according to instructions agreed, Container pick up, Any incidents/events during the transport, Container release at final destination, Empty container devolution

4. Architecture and Data Flows

The EGTN Interledger takes advantage of cutting edge microservices provided within the EGTN Platform i.e., Artificial Intelligence (AI) Analytics, Decision Support Systems (DSS), as well as the plethora of datasets available in the EGTN Data Lake to enable advanced functionalities.

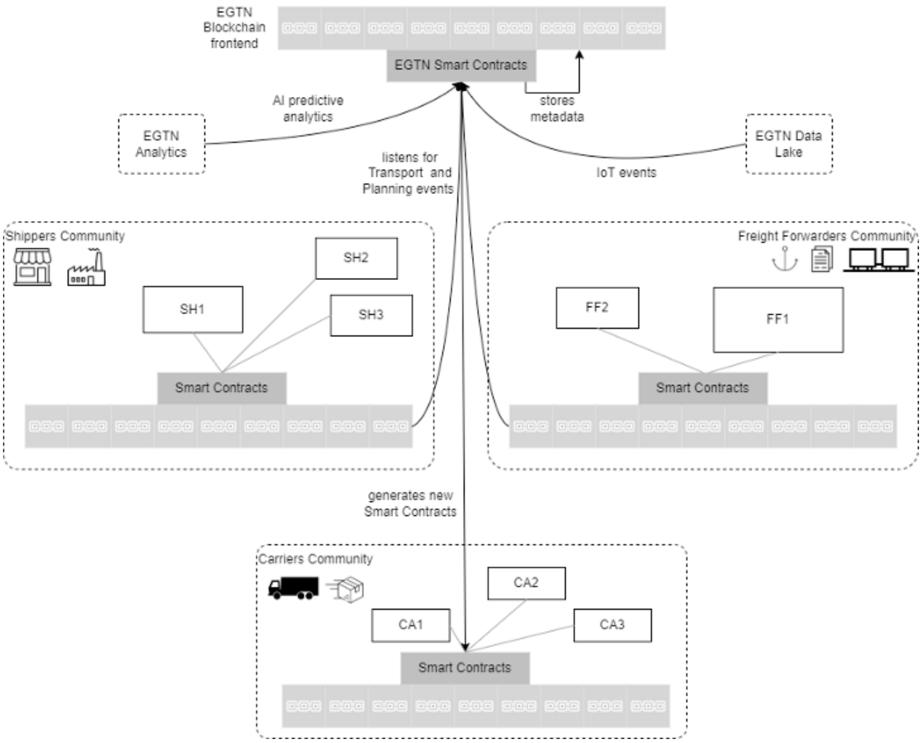

Figure 1. EGTN Interledger Service and Smart Contracts

4.1. Interconnecting Blockchain Systems within the EGTN Platform

The EGTN Interledger connects with the individual Blockchain networks, listens for logistics events and forwards them to other Blockchain communities that can benefit from them by acting proactively and increasing response time. Smart contracts are employed to guarantee the integrity of the data entering the ledger and to automateprocedures in the supply chain that are currently handled using paper-based documents. The goal of data integrity is achieved through the concurrent execution of the smart contracts by all the network participants.

As shown in Figure 1, the Data Lake provides an event-streaming service that ingests logistics events and IoT data from sensors, following the latest GS1 standards. The smart contracts consume data within the EGTN Platform, combine these with other information sources (e.g., outputs from AI predictive models), and automatically trigger actions, such as the creation of trusted metadata that can be used as a single source of truth in Blockchain communities or even the generation of new smart contracts that monitor and safeguard Service Level Agreements (SLAs) between logistics communities - i.e., Shippers (SHx), Carriers (CAx) and Freight Forwarders (FFx).

Smart contracts run when predetermined terms and conditions are met ("if-conditions") and execute actions or trigger events/alarms ("then-rules") without an intermediary's involvement or loss of time. The automatic execution of the actions by all the involved actors ensures the integrity of the data pushed to the Blockchain and ties them in secure and transparent agreements. EGTN Smart Contracts take advantage of the diverse data and knowledge residing within the EGTN Platform (output from backend Blockchain systems, IoT data, Big Data analytics) to enable reliable generation of metadata and trusted contract execution (see Figure 1).

4.2. Terms and Conditions

Table 2 presents the “if-then” rules (ITXX) that are followed in the EGTN Interledger service, which aim to standardise and streamline inter-organisational T&L workflows. The first two rules (IT01, IT02) aim to enhance the legitimacy of Dispatch claims from the Shipper, Freight Forwarder and Carrier Communities. The EGTN Interledger service monitors the backend systems of all communities and registers for events that prove the dispatch of cargo from the Shipper and the cargo pick-up from the Carrier (IT01) and the Proof of Delivery (PoD) reported by the Carrier and Freight Forwarder (IT02). Upon the collection of the corresponding events from the actors, the EGTN Smart Contracts emit a Cargo Dispatched event (IT01) and a trusted Cargo Delivered event (IT02). The remaining rules (IT03-IT06) compare data coming from legacy systems (backend blockchain systems) with IoT data coming from smart T&L assets. More specifically, IT03 guarantees the trusted execution of the smart contracts between the actors involved - e.g., legacy systems events are compared with “Reach a POI” records sent by smart pallets. The IT04 smart contracts compare system defined thresholds with IoT data from smart T&L assets to drive their decisions, e.g., if the vibration measurement in a smart pallet exceeds a predefined threshold, then break the contract. The IT05 smart contracts employ system data and forecasts from the EGTN AI Analytics components to streamline internal processes, e.g., hire more personnel when the forecasted incoming number of pallets exceeds a limit.

Table 2. Smart Contracts If-Then rules in the EGTN Use Case.

ID	Data & If condition	Then Description
IT01	Cargo Departure event reported from Shipper = Cargo Dep. from Carrier	Enhanced-trust Departure
IT02	PoD reported by Carrier = PoD reported by Consignee	Enhanced-trust Delivery
IT03	Delivery point/time = Unloading IoT coordinates/time	Contract fulfilled
IT04	System defined vibration/temperature tolerance = IoT sensors measurements	Contract violated
IT05	AI forecasts & System events	New Contract Generation

The “if-then” statements are written into code (smart contracts) and require a network of computers along with a Blockchain infrastructure to run. The smart contracts produce both static (master) and transactional data that are stored on-chain following T&L standards, such as the GS1 EPCIS and the Blockchain in Transport Alliance (BiTA).

5. Discussion & Conclusions

A key advantage of Blockchain is data sovereignty. However, data sovereignty concepts are currently mainly provided by (closed) communities with their own specific solutions (Dalmolen et al. (2019)). In addition to this, ensuring the integrity and protection of the data across the supply chain is of paramount importance. The advantages of Blockchain offer the potential to overcome these challenges.

An important hurdle the PI needs to overcome is the current attitudes and mindset of T&L stakeholders. Companies still prioritise more traditional procedures in international and inter-organisational exchanges. Convincing T&L actors to participate in the PI paradigm and showing them that it can be mutually financially beneficial to do so, while at the same time they can still maintain their competitive advantage and do not lose private data. In this sense, the data integrity characteristic of Blockchain can be instrumental, by increasing stakeholders’ confidence in technology and willingness to share data. To unveil maximum advantages of Blockchain in terms of rapid and trusted information sharing, enough participants (critical mass) of a blockchain-based platform are required (Copigneaux (2020)). Significantly, many supply chain and T&L stakeholders use and exploit proprietary Blockchain systems within their own, equally proprietary, ecosystems. This causes coordination and collaboration issues within the entire workflow. For instance, the clearance of goods in border crossings is often slow and susceptible to manipulation thanks to non-transparent border administration procedures and the lack of coordination between different border agencies. Blockchain solutions and, especially interoperability between different systems address such issues heads-on by simplifying, standardising, and streamlining inter-organisational workflows.

The real power of Blockchain also lies in scenarios when changes or unforeseen events occur at some point within the supply chain and certain actions need to take place (e.g., rerouting of goods). Significant reductions in terms of time and overhead can be achieved using automated smart contracts. In such occurrences and given the appropriate permissions, any relevant actor (e.g., freight forwarder) may access the newly updated information. Significantly, the combination of Blockchain with other technological advancements such as IoT data and AI models can make the step towards the realisation of the PI even smaller, by decreasing reaction time to such events (especially the use of real-time IoT data) and increasing efficiency in smart contract negotiations (through AI predictive models).

The combination of Blockchain and the PI is also capable of achieving triple bottom line sustainability; that is social, economic, and more importantly environmental gains (Treiblmaier (2019)). This is quite a milestone for a T&L network, as the existing TEN-T network4 is not linked to the EU's green strategy and does not consider innovations.

The solution offered by the EGTN platform offers a distributed and community-driven approach that ensures data integrity and immutability across the supply chain, automated and safe contract execution, and reduction of overheads and time delays. In this manner, the value of Blockchain interoperability and smart contracts to the PI paradigm are showcased through the application of the solution in real-life use cases. It is expected that the deployment of the infrastructure in the demo sites of PLANET will bring out further insights and inform the architectural blueprint.

Acknowledgements

This work has been conducted in the context of the PLANET project, which has received funding from the European Union's Horizon 2020 research and innovation program under the Grant Agreement No. 860274. We thank Makis Kouloumbis and John Farren for their participation in the definition of the smart contracts and the data flows and for sharing thoughtful and candid perspectives and insights.

References

B. Montreuil, R. D. Meller and E. Ballot, Physical Internet Foundations, in Studies in Computational Intelligence, vol. 472, Berlin, Heidelberg, Springer, 2013, pp. 151-166

T. Meyer, M. Kuhn and E. Hartmann, Blockchain technology enabling the Physical Internet: A synergetic application framework, in Computers Industrial Engineering, 2019

H. Hasan, K. Salah, R. Jayaraman, I. Yaqoob and M. Omar, Blockchain Architectures for Physical Internet: A Vision, Features, Requirements, and Applications, Networks, vol. 35, no. 2, pp. 174-181, March/April 2021

E. Ballot, S. Barbarino, B. van Bree, F. Liesa, J. R. Franklin, D. Hooft, A. Nettstrater, P. Paganelli and L. A. Tavasszy, Roadmap to the Physical Internet, ALICE-ETP, 2020

Pan, S., Trentesaux, D., McFarlane, D., Montreuil, B., Ballot, E., Huang, G. Q., Digital interoperability in logistics and supply chain management: state-of-the-art and research avenues towards Physical Internet, Computers in industry, 128, 103435, 2021

H. Montgomery, H. Borne-Pons, J. Hamilton, M. Bowman, P. Somogyvari, S. Fujimoto, T. Takeuchi, T. Kuhrt and R. Belchior, Hyperledger Cactus Whitepaper [White paper] version 0.2.

W. Entriken, D. Shirley, J. Evans and N. Sachs, EIP-721: Non-Fungible Token Standard, Ethereum Improvement Proposals, January 2018

R. Belchior,A. Vasconcelos, S. Guerreiro and M. Correia, A survey on blockchain interoperability: Past, present, and future trends, In ACM Computing Surveys (CSUR), 54(8), pp.1-41 2021.

V. Siris, P. Nikander, S. Voulgaris, N. Fotiou, D. Lagutin and G. Polyzos, Interledger Approaches, IEEE Access, vol. 7, pp. 89948 - 89966, 2019.

World Economic Forum, Bridging the Governance Gap: Interoperability for blockchain and legacy systems [White paper] December 2020.

H. Treiblmaier, Combining Blockchain Technology and the Physical Internet to Achieve Triple Bottom Line Sustainability: A Comprehensive Research Agenda for Modern Logistics and Supply Chain Management., Logistics, vol. 3, no. 10, 2019.

Henry, T., Beck, R., Laga, N., Gaaloul, W., Pan, S., Decentralized procurement mechanisms for efficient logistics services mapping-a design science research approach, 2022.

R. Giusti, D. Manerba, G. Bruno and R. Tadei, Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues, Transportation Research Part E: Logistics and Transportation Review, vol. 129, pp. 92-110, 2019.

C. Wurst and L. Graf, Disrupting Logistics: Startups, Technologies, and Investors Building Future Supply Chains, Springer, 2021.

N. V. E. B. Bertrand Copigneaux, Blockchain for supply chains and international trade, European Parliamentary Research Service Scientific Foresight Unit, 2020.

S. Dalmolen, H. J. M. Bastiaansen, E. J. J. Somers, S. Djafari, M. Kollenstart and M. Punter, Maintaining control over sensitive data in the Physical Internet: Towards an open, service oriented, network-model for infrastructural data sovereignty, in 6th International Physical Internet Conference (IPIC), 2019.