The Physical Internet in the Era of Digital Transformation: Perspectives and Open Issues

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ABSTRACT The Physical Internet (PI, or π) paradigm has been developed for a global logistics system that aims to move, handle, store, and transport logistics products in a sustainable and efficient way. To achieve this goal, the PI requires a higher level of interconnectivity and interoperability in terms of physical, informational, and operational aspects, which, by following the principle of the digital Internet (DI), is enabled by an interconnected network of intermodal hubs, collaborative protocols, and standardized, modular, and smart containers. Meanwhile, digital transformation (DT) has become mainstream in Industry 4.0 to innovate many industries, including logistics and supply chains, through the use of breakthrough digital technologies in the fields of information, communication, connectivity, analytics, and computing, such as the next generation of communication and networking (i.e., 5G), the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), big data analytics (BDA), and cloud computing (CC). In this context, the introduction of DT in the PI vision has many implications for the development and realization of an efficient and sustainable global logistics system. This study investigated the perspectives of PI under the impact of DT. The major challenges and associated open research regarding the adoption of DT in PI have been thoroughly investigated.

INDEX TERMS Digital transformation, digital technologies, physical internet, data-driven systems, Internet of Things (IoT), logistics system, efficiency and sustainability.

I. INTRODUCTION

Industry 4.0 has been revolutionizing all aspects of the global economy and society through innovative methods for producing and delivering products [1]. In the light of this revolution, digital transformation (DT) has become mainstream for organizations, businesses, and industries, playing an essential role in their development strategy to adapt to change and stay competitive [2]. Generally, DT can be defined as a process that significantly improves the operational performance of these entities through the joint use of digital technologies in the fields of information, communication, computing, and connectivity technology [3]. In particular, the emerging technologies such as 5G, IoT, AI, ML, BDA, CC, BlockChain (BC), Digital Twin, and Digital Reality create innovations in information sharing, advanced data processing and analytics, and decision-making [4], which eventually drive a significant growth in industries [5].

The implementation of DT has been considered in many industries, including marketing [6], smart cities [7], and energy [8]. In particular, digitalizing the supply chain and logistics service industry is recognized as one of the ten successful factors of Industry 4.0 [9] as digitalization creates a major improvement not only in the business models but also in the values to meet the increasing demands of customers and enhance customer experiences [10]. Many conceptual
definitions and frameworks have been introduced in both academic and practical aspects to cover and examine the perspectives of the logistics and supply chain industry under the impact of DT and Industry 4.0. Digital supply chains (DSCs) [11], and Logistics 4.0 [12] are some of these concepts, which commonly emphasize the importance of using digital technologies to generate a huge volume of data, extract many insights and knowledge from these data, and then leverage these powers to derive optimization and better decision-making [13], [14]. Consequently, the modern logistics service and supply chain industry is reshaped in a data-driven form with improved efficiency, agility, and resilience [15].

Although DT provides many potential capabilities to achieve unprecedented operation performance, there are many obstacles to its implementation in existing logistics systems, such as the lack of openness, interconnectivity, and interoperability [16]. Recently, PI [17] has been emerged as an innovative paradigm toward a global efficient and sustainable logistics network, which is considered a logistics response to Industry 4.0 [18]. Fundamentally, PI is constructed to become a network of logistics networks [19], which aims to remove the high fragmentation of existing logistics networks based on inter-connectivity and inter-operation [20]. In addition, the openness of shared and global PI networks encourages actors and stakeholders to join and exploit shared resources to maximize the value of the chain. These perspectives strongly emphasize the need for information sharing, which is assertively achieved through DT in the increasing digital era. In this sense, the joint implementation of PI and DT has many implications for shaping the PI concept. PI provides a suitable environment and framework for DT adoption. On the other hand, DT can serve as a key factor in accelerating the roll-out of PI in practice. In particular, DT technologies can serve as a means to construct the interconnectivity and interoperation foundations for the PI. In addition, the digital technologies enabling DT significantly contribute to achieve the sustainability and efficiency objective since they can be used to maximize the logistics resource sharing and utilization, minimize the impacts on the environment and society. However, to achieve these mutual benefits of joint implementation of PI and DT, there requires to overcome challenges and barriers due to the novelty characteristics of PI and DT.

While PI has been promoted to implement in the practical use cases, there is no study in the literature that examines the current situation of such interrelationships between PI and DT, especially their mutual benefits, and inherent challenges. In this regard, this paper aims to conduct such examination studies, providing the following five main contributions:

* The fundamental concept and development state of the PI are highlighted.
* The concepts of DT and associated technologies for enabling DT in the logistics context are discussed.
* The roles and impacts of digital technologies on the implementation of PI are analyzed.
* The PI paradigm promises a potential foundation for leveraging DT to achieve efficiency and sustainability objectives. This study identifies and examines the key perspectives of PI in the era of DT.
* While DT has the potential to accelerate PI realization, the co-implementation of PI and DT faces many critical challenges and barriers. This paper identifies such major challenges and discusses open research to resolve them.

To obtain the proposed objectives, the rest of the paper is structured as follows: Section II provides a basic concept, key components, and the state of development of PI vision. Section III emphasizes on the DT concept and identifies key enabling technologies in the logistics and PI context. Section IV enumerates potential perspectives as PI is driven by DT. Section V discusses the important issues to simultaneous implementation of PI and DI aspects. The paper is concluded in Section VI.

II. PHYSICAL INTERNET VISION

A. BASIC CONCEPT

Initially, the ultimate objective of PI is to tackle the grand challenge, which is characterized by the unsustainability and inefficiency of current logistics operations in the economic, environmental, and social dimensions [17]. Notably, the high fragmentation of different logistics networks is the root cause of this issue. To reverse this situation, PI follows the principle of the digital Internet (DI) to store, move, handle, and transport physical goods from one place to another in a sustainable and efficient way. By referencing the structure of the DI network with data packets, hubs, and the TCP/IP protocol, the PI network includes π-containers, π-nodes, and π-protocols, which are innovated to leverage the features of its reference components [19]. The PI network is constructed as a network of logistics networks based on the interconnection and interoperation of π-nodes following the standardized π-protoocols for handling, transporting, and storing π-containers [20]. Basically, the π-containers are standardized globally in terms of physical specification (i.e., smart, green, and modular), informational features (e.g., identity), and functions [21], such as the data packets in the DI network. In parallel, the π-nodes represent facilities such as transit centers, distribution centers (DC), and warehouses, which are necessarily innovated to enable the smooth flows of physical π-containers and accompanying information. Equivalent to the TCP/IP protocol used in DI, the π-protocols encompass the standardized rules, agreements, and contracts, aiming to control and manage the physical flows between the π-nodes efficiently and reliably. Finally, the PI network also requires π-movers to perform physical operations such as loading, sorting, composing, and transporting. Fig. 1 depicts the conceptual model, features, and principal operation of the PI network to transport freight from the Plant 1 to DC2 through π-nodes 1, 3, and 4 following the optimized π-protocol.

Many studies have been conducted to evaluate the performance of PI in both experiments [22], [23] and simulation methods [21], [24]. As reported in [19] and [25], the early
demonstrations of PI operation across several logistics scenarios suggest that PI has the potential to achieve its full sustainability and efficiency objective in terms of economy, environment, and society. For example, PI can increase the fill rate of transportation up to 17%, while saving 60% carbon-dioxide emissions from the freight transportation sector. In addition, PI can reduce up to 35% total logistics costs due to the collaboration and resource sharing of stake holders [26]. Based on these reported results, several alliances, including Material Handling Industry Association (MHI) in the US and the Alliance for Logistics Innovation through Collaboration in Europe (ALICE) have declared PI as a long-term vision for an end-to-end global logistics network, and have promoted PI implementation in practice. Fig. 2 shows a roadmap for implementing and developing PI.\(^1\)

According to the timeline model, PI requires a tremendous innovation framework encompassing the application of advanced technologies, a high level of cooperation and collaboration in both horizontal and vertical sectors, strategic planning and management, and excellent governance to achieve interconnectivity and interoperationality in physical, informational, and operational aspects. In line with the current revolution of Industry 4.0, the digital transformation approach emphasizing the usage of emerging digital technologies has great potential to support and accelerate the implementation of PI to achieve the objective.

**B. KEY COMPONENTS OF PI AND STATE OF DEVELOPMENT**

This section describes four key components of PI: \(\pi\)-containers, \(\pi\)-nodes, \(\pi\)-movers, and \(\pi\)-protocols regarding their characteristics and state of development.

1) \(\pi\)-CONTAINERS

By referencing the advantageous features of data packets in the DI network, the \(\pi\)-containers in the PI network are designed to be world-standardized, smart, green, and modular [17]. The global standard enables the \(\pi\)-containers to be moved, handled, stored, and transported smoothly and efficiently through the interconnected networks of the PI network. In addition, the other characteristics of \(\pi\)-containers aim to tackle the grand challenge. For example, \(\pi\)-containers are made of environmentally friendly materials that can be recycled and reused to minimize their impact on the environment. Notably, the modularity of \(\pi\)-containers mitigates the diversity of boxes and containers in terms of the shape and size used in existing logistics. In PI, the \(\pi\)-containers are classified into three categories: transportation, handling, and packaging containers (termed as T/H/P-containers, respectively) characterized by specific functions and associated sizes [27]. Accordingly, the P-containers with the smallest sizes are used to pack the physical goods directly. Meanwhile, medium-sized H-containers are used for handling purposes such as moving, carrying, and storing a set of P-containers temporarily to facilitate the associated logistics operations. Finally, the largest T-containers carried by large vehicles, ships, or transport airplanes are used to transport a large volume of H-containers and/or P-containers across cities, countries, and continents. The CELDI PI project formulates an optimization to derive efficient sizes for \(\pi\)-containers, which can maximize the overall space utilization at any unit load level [28]. Accordingly, the height, width, and depth of a \(\pi\)-container can be selected from the set: \{0.12m, 0.24m, 0.36m, 0.48m, 0.6m, 1.2m, 2.4m, 3.6m, 4.8m, 6m, 12m, 18m\} [21]. Following this result, the MODULUSCA project designs M-box (i.e., H-containers), as shown in Fig. 3, which are used for handling fast-moving consumer goods (FMCG).

In particular, the modularity feature enables a set of \(\pi\)-containers to be encapsulated to form an efficient unit load, which is then handled easily to improve the operational efficiency and productivity [20], as illustrated in Fig. 4.

As demonstrated in [30], [31], using \(\pi\)-containers increases the resource utilization and efficiency of freight transportation activities in the PI network owing to the distinct advantages of modularity and encapsulation. In addition to the physical aspect, PI also emphasizes the importance of informational instrumentation to make the \(\pi\)-containers smart and massively active using the information and communication technology (ICT) [32]. In a complex and dynamic logistics environment, the smartness and activeness of \(\pi\)-containers are important because they provide a source of useful information to improve decision-making and operational performance. Four typical types of information embedded in the \(\pi\)-containers include identifiers, specifications, operation states, and ambient sensing conditions [17], [19]. Each \(\pi\)-container is associated with unique identifiers that are required to adequately track, trace, and handle by any IoT-connected stakeholder in the global PI network [33], [34].

The specification information encompasses an important description of \(\pi\)-containers such as dimensions, content, and functionality (i.e., transportation, handling, or packaging). In fact, AUTO-ID technologies such as radio frequency

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1\(^1\) PI Roadmap by ALICE, http://www.etp-logistics.eu/alice-physical-internet-roadmap-released/
identification (RFID), and barcode are widely used in the logistics and supply chain industry to provide these two types of information. Sensor technologies are mainly responsible for sensing the ambient environment as well as the operation states of $\pi$-containers [35]. Furthermore, device-to-device (D2D) and machine-to-machine (M2M) communication technologies supported by 5G technology can be deployed to enhance the interaction between $\pi$-containers and between $\pi$-containers with other management and autonomous systems. For the purposes of security and privacy, a data model was proposed in [36] to restrict information access for different involved actors, including manufacturers, drivers, and shippers.

2) $\pi$-MOVERS

In the PI network, $\pi$-movers encompass all material handling equipment and systems used to perform a movement of $\pi$-containers between two different places such as transporting, conveying, handling, lifting, and storing. The main types of $\pi$-movers include $\pi$-transporters (e.g., $\pi$-trucks, $\pi$-trailers, etc.), $\pi$-conveyors, and $\pi$-handlers (e.g., $\pi$-lift-trucks) [29].

Because the $\pi$-movers deal directly with the $\pi$-containers, they are innovated to exploit the features of $\pi$-containers the best way possible to facilitate the activities and thus improve overall performance. From a physical perspective, the dimensions of $\pi$-movers should be modular so that they can carry $\pi$-containers or composite $\pi$-containers easily and efficiently. Fig. 5 shows the prototypes of $\pi$-lift-truck and $\pi$-robotic movers that account for the modular sizes of composite $\pi$-containers.
Since \( \pi \)-movers are valuable assets, the management systems require a source of relevant information to monitor and manage them in real time. Similar to the designs of \( \pi \)-containers, integrating ICT into the \( \pi \)-movers has been recognized as an effective solution. For example, many types of embedded sensors are able to sense and provide important information related to the operational and health states of \( \pi \)-movers as well as the ambient environment and status, allowing the derivation of efficient planning by the management system. Intelligent \( \pi \)-trucks can be adopted from the model of existing intelligent trucks [37] to promote intelligent freight transportation [38], [39] using wireless sensor networks (WSN) and IoT technologies. In addition, automatic control and advanced intelligence are increasingly embedded in the physical \( \pi \)-mover to enhance its capability and operational performance. Intelligence enabled by AI, computer vision, and ML enhance automatic control such as smart robots in warehouses. Swarm intelligence provides self-organization and self-configuration capabilities to enhance the responsiveness of robotics groups to uncertain situations. Edge computing and fog computing are also integrated in \( \pi \)-transportation to process the sensor data provided by \( \pi \)-containers locally in real time. In the next sections, the implications of these technologies in PI are further discussed.

3) \( \pi \)-NODES

Equivalent to the transit centers, cross-docking hubs, distribution centers, and warehouses in the existing logistics systems, \( \pi \)-nodes in the PI vision are physical facilities and locations with many types and specific roles. Regarding the physical aspect, the structure of \( \pi \)-nodes should exploit the advantageous features of \( \pi \)-containers to improve the efficiency and productivity of operations. In addition, the \( \pi \)-nodes are to be open so they can flexibly adapt to any change, such as advancement of technologies and business models. Table 1 lists the key \( \pi \)-nodes and their main functions [29].

The \( \pi \)-nodes rely on \( \pi \)-movers to perform a set of complex and dynamic operations on \( \pi \)-containers such as receiving, loading, unloading, routing, storing, and picking. Therefore, their information management systems must be designed appropriately to constantly interact with \( \pi \)-movers and \( \pi \)-containers, thus enabling real-time monitoring of the operation states of \( \pi \)-movers. Such a system using IoT technology was developed to provide an end-to-end visibility of the logistics assets in the supply hub in industrial parks (SHIP) [40], [41]. Through real-time monitoring, the \( \pi \)-nodes can improve the resource utilization of \( \pi \)-movers, thus enhancing productivity and performance efficiency. For instance, a multi-agent system (MAS)-based method was developed in [42] to optimize the distance traveled by each \( \pi \)-container to the dock, as well as the number of \( \pi \)-trucks used to move these \( \pi \)-containers in the road-rail \( \pi \)-hub. Optimizing the operation schedule of \( \pi \)-trucks to minimize the energy consumption was taken into account in the work [43] to improve the efficiency and sustainability of \( \pi \)-hubs. Furthermore, information sharing between \( \pi \)-nodes plays a key role in achieving the seamless and efficient transshipment of \( \pi \)-container flows. The information includes the key attributes of \( \pi \)-nodes such as speed, service level, capacity, modal interface, and average duration of stay, which are necessary to make decisions related to routing. In particular, the arrival and depart times of \( \pi \)-containers can be predicted by \( \pi \)-nodes in facing dynamic uncertainty to derive efficient scheduling and planning for subsequent activities within them. From a designing perspective, the shared information is leveraged to construct the layouts of real \( \pi \)-nodes, which arrange functional sites appropriately. Fig. 6 shows the prototype design for a rail-road \( \pi \)-hub that optimally allocates storage sites, road-rail sorters, and rail-rail sorters and parking areas of \( \pi \)-movers (e.g., \( \pi \)-trucks) [42].

4) \( \pi \)-PROTOCOLS

Complementary to the standard physical facilities (i.e., \( \pi \)-containers, \( \pi \)-movers, and \( \pi \)-nodes), the PI relies on \( \pi \)-protocols consisting of sets of standardized rules, agreements to move, handle, store, and transport \( \pi \)-containers between \( \pi \)-nodes to achieve the maximal efficiency and sustainability. The \( \pi \)-protocols are formulated based on inheriting the features of the TCP/IP protocol in the DI network to sustain smooth physical flows in the logistics network [19]. Accordingly, the \( \pi \)-protocols are built on an open logistics

| \( \pi \)-node | Primary functionality |
|---|---|
| \( \pi \)-transits | Transferring \( \pi \)-carriers from inbound \( \pi \)-vehicles to outbound \( \pi \)-vehicles |
| \( \pi \)-switch | Unimodal transfer of \( \pi \)-containers from an incoming \( \pi \)-mover to a departing \( \pi \)-mover |
| \( \pi \)-bridge | One-to-one multi-modal transfer of \( \pi \)-containers from an incoming \( \pi \)-mover to a departing \( \pi \)-mover |
| \( \pi \)-sorter | Receiving \( \pi \)-containers from one/multiple entry points and sort them in a specified order |
| \( \pi \)-composer | Constructing composite \( \pi \)-containers from specified sets of \( \pi \)-containers |
| \( \pi \)-store | Storing \( \pi \)-containers within a specific time duration |
| \( \pi \)-gateway | Receive \( \pi \)-containers and release them so they can be accessed in a private network |
| \( \pi \)-hub | Transfer of \( \pi \)-containers from incoming \( \pi \)-movers to outgoing \( \pi \)-movers |
interconnection (OLI) model with seven layers. The layers of OLI model include a physical layer, a link, a network, routing, shipping, encapsulation, and a logistics web, which are equivalent to the layer of the open system interconnection (OSI) used in the TCP/IP protocol. Accordingly, each layer is responsible for providing specific services to support the particular logistics activities such as procurement, handling, realization (production, assembly, finishing, etc.), storage, and transportation. Table 2 presents the layered structures of two models OSI and OLI [19].

The benefit of layering services is to distribute logistics management, and the efficiency of logistics activities is optimized [19]. For example, the physical layer is responsible for ensuring the smooth physical movement of \( \pi \)-containers. The layer provides information relating to the handling equipment (e.g., \( \pi \)-trucks, \( \pi \)-mover, etc.) and then guarantees the physical conditions (mechanical and electric) to accomplish the logistics activities of this layer (e.g., unloading, storing, and composing). As the layer accounts these services solely, they are developed such that the quality of services is maximized. For example, as illustrated in Fig. 7, to construct an efficient \( \pi \)-protocol for transporting the FMCG, three factors jointly considered include: (1) selection of \( \pi \)-container type (e.g., H- or P-containers or combined), (2) composition of \( \pi \)-containers, and (3) the best route of the freight flow (i.e., selection of \( \pi \)-nodes along the entire transportation path) [44].

### III. DT AND KEY ENABLING TECHNOLOGIES IN THE PI CONTEXT

#### A. DT CONCEPT AND OBJECTIVES

The extant literature has introduced a variety of DT conceptualizations discriminated by many aspects, such as specific application domains, technologies used, and objectives [3], [45]. As stated in [3], DT is defined as “a process that aims to improve an entity by triggering significant changes to its properties by using a combination of digital technologies in the fields of information, computing, communication, and connectivity”. Accordingly, this definition embraces five key terms: process, entity, digital technologies, change, and improvement, which are used to clarify the fundamental concepts, implications, and objectives of DT.

First, DT is a continuous process that takes time, cost, and effort [46]. Since there is no unified framework and formula to be applied in practical use cases, the implementation of DT progresses through many stages (e.g., plan, test, and deployment), and is subject to dynamic changes in the operational environment, technology advancement, and objectives. Therefore, DT must be integrated into a long-term development strategy.

Second, entity is used in a broader context to indicate any individual, organization, business, or industry that undertakes DT as part of its development strategy. In light of the increasingly digital era, this key term purposefully presents the wide impact of emerging technologies on every aspect of society; hence, entities at different scales consider DT as essential to react to the changes.

Third, DT is about digital technologies, especially in the fields of information, communication, connectivity, and computing. There is no unified list of technologies discussed among the various conceptualizations of DT in the literature. However, most of them embody the SMACIT acronym, which includes technologies related to social network, mobile devices, analytics, cloud, and IoT [47]. The next section identifies and investigates key digital technologies that derive DT and potentially create significant impacts on logistics operations.

Fourth, a change, and even a significant change certainly resulted from DT. A transformation can change an entity at all levels synchronously, including organizational structure [48], systematic processes, and culture [49]. For example, online shopping represents a new culture of customers in digital society because of the increasing availability of Internet-connected mobile devices and the growth of e-commerce.

Finally, DT must create values and substantial improvements in terms of productivity, operational efficiency, customer experience, business models, resource management,
and competitive advantage [50]. From the business perspective, the improvement is evaluated by the return on investment (ROI) indicator, which shows the profit that a business can gain from adopting a DT solution [51]. The last decade has witnessed the success of adopting ICT to tackle the inherent challenges of logistics and supply chain management, characterized by different processes performed by different actors in different geographical locations [52]. Real-time information-sharing and informed decision-making typically represent two key implications of ICT in developing management approaches [53]. In particular, the adoption of advanced ICT has been recognized as a switch point for value differentiation and innovation in logistics operations [54], [55], which can gradually shape a model of modern logistics with a higher level of sustainability, efficiency, and responsiveness. On the path of technology evolution, the presence of emerging technologies in the digital era is expected to bring about further disruptive improvements for the logistics service and supply chain industry.

### B. KEY ENABLING DIGITAL TECHNOLOGIES IN THE PI IMPLEMENTATION CONTEXT

This section discusses key enabling technologies for DT and their impacts on the implementation of PI.

#### 1) INTERNET OF THINGS

Today, IoT is widely adopted as an ultimate solution to revolutionize the way things collect and share real-time data through the Internet [56]. Fundamentally, IoT is not a single technology but uses a collection of relevant technologies to realize the interconnectivity and interoperability objectives between entities (e.g., objects, devices, organizations, and systems) [57]. Data acquisition, communication and networking, middleware, software, and application platforms are among the technological components that constitute a typical IoT system with a corresponding layer-based architecture. In the IoT context, things are steadily transformed into smart entities by integrating ICT, such as RFID, WSN, global positioning system (GPS), powerful embedded microelectronic modules (e.g., intelligent chips for computation, and radio frequency wireless transceivers for wireless communication), and cyber-physical systems (CPS). Smart objects can sense ambient environmental conditions, monitor their operation status, determine their spatial locations, process data, make decisions, and communicate and cooperate to perform many advanced tasks [58].

In this context, IoT serves as a driver to digitize physical objects, enabling them to be represented by digital platforms. Logistics assets and items such as packages, containers, and vehicles are equipped with IoT technologies to become smart objects, which significantly improve operational efficiency. For example, smart packaging [59] and smart containers [60] can monitor the status of products during transportation processes to protect valuable items from damage and theft. Smart vehicles such as automated guided vehicles (AGVs) and robots can optimize the routes for moving and handling the material in the warehouse to save energy and operation time [61]. All these features are exploited in the PI vision to design smart \( \pi \)-containers, smart \( \pi \)-movers, and \( \pi \)-nodes.

IoT further helps in digitizing logistics-related processes to facilitate and enhance management and decision-making. Various studies have proposed IoT-based solutions to efficiently support the logistics operations such as transportation, warehousing management, and last-mile delivery, which also assert the potential benefits gained from the application of IoT [62], [63]. For example, IoT-based tracking systems, including RFID and GPS, probably provide end-to-end visibility for logistics activities, which ensures that shipments have been handled adequately without degrading the quality [64]. In parallel, WSNs are used to constantly monitor the status of shipments and the ambient environment, thus avoiding situations where the products can be exposed to harmful environmental conditions. In addition, real-time monitoring and control systems using Auto-ID, sensor, and actor technologies are capable of detecting and localizing any disruption in many activities, such as fleet, traffic management, and inventory control [65], thereby enabling timely responses [66]. Furthermore, the emergence of semantic-oriented technologies in IoT scenarios is to address the interoperability issues of understanding data generated by connected heterogeneous sensors and smart objects. These technologies can extract sets of raw data into homogeneous and heterogeneous formats, and then process them into meaningful representations and interpretations [67]. The service-oriented architecture is applied in the IoT system to exploit these semantic data to develop IoT intelligent services, which effectively support logistics processes [68]. From the PI perspective, the work [69] proposed \( \pi \)-IoT as a framework for developing an IoT ecosystem that is dedicated to providing intelligent management services, especially in the \( \pi \)-nodes. The \( \pi \)-IoT system consists of three main smart components: smart objects, smart networks, and smart PI management system (PIMS), leveraging their interconnection and interoperation to exchange, and analyzing the data to generate added-value services and improve decision-making. A typical service is to create a three-dimensional virtual layout that captures the real arrangement of \( \pi \)-containers using WSNs [33]. The layout is further displayed on the PIMS through IoT-connected channels to monitor and support the loading and unloading processes [70]. In addition, the \( \pi \)-nodes can be modeled as a CPS, which can use honolc approaches to optimize the multicriteria decision problems such as \( \pi \)-truck loading and transportation [71].

From a business perspective, as one of the objectives of DT is to bring the business closer to the customers, IoT serves as a perfect role in this context. The business can create digital platforms that connect and interact with customers through the Internet and Internet-connected devices such as smartphones and tablets. In particular, the business collects data regarding customer behavior and requirements, which are then processed and analyzed using intelligent data processing and analytics technologies (e.g., AI and BDA).
to predict customer demands and simultaneously improve customer experiences. Consequently, smart objects and DT driven by IoT are steadily transforming business models from physical products into data-driven services [72].

2) ARTIFICIAL INTELLIGENCE (AI)

The increasing adoption of digital technologies, especially in the field of ICT in computer-based systems inherently generates a huge amount of digital data that naturally reflects the real operation performance of systems. In this context, the resulting data-driven systems no longer recognize the importance of the collected dataset because they become the most valuable asset, playing a central role in making decisions. In the field of logistics and supply chains, the volume of data is further amplified over time because of the data generated by various sources (e.g., embedded sensors, machines, devices, and customers) through many daily activities (e.g., loading, transportation, inventory control, and online shopping). In addition, the coexistence of various data types (i.e., text, image, audio, and video) combined with the structured, semi-structured, and unstructured data format characterizes the complexity of the dataset, which in turn makes it challenging to process it using traditional approaches. This context highlights the need for novel technologies, techniques, and sophisticated algorithms to address this challenge and make full use of the data. AI fits perfectly with this type of mission.

By stimulating human intelligence, AI is referred to as intelligent applications, which can perceive every input data, automatically learn from the data by supervised, unsupervised, and reinforcement mechanisms, extract the patterns and insights from this data, and then create the knowledge and intelligence for problem solving [73], [74]. Generally, AI encompasses four major fields: machine learning (ML), deep learning (DL), natural language processing (NLP), and computer vision (CV), which have specific definitions and associated applications.

ML is referred to as “AI capability integrated to the computer-based systems”, which can draw inferences from the given input data of a specific domain after a learning process. These inferences are further used to output insights and decisions. DL employs continuous learning to deal with the huge and fast-moving datasets. By mimicking the operation of the human brain, DL uses neural networks to obtain new input data and automatically form new insights. NLP indicates AI applications from the perspective of linguistics. Language translation, text-to-voice, voice-to-text conversion, and automated conversational systems (e.g., chatbots) are some of the features developed and offered by AI-based NLP.

These powerful capabilities of AI stand for potential benefits in the logistics and supply chain. The current context witnesses the wide application of AI in logistics-related activities to improve operational performance. For example, AI has developed to extend the problem-solving capabilities of human beings, thus executing repetitive tasks automatically in many back-office processes. Sorting and classifying unstructured data can be performed using combination of robotic process automation (RPA) and AI to reduce clerical labor. Moreover, the intelligence of AI algorithms also provides cleansing functions that detect the incompetence of datasets and remove fake information. CV has been increasingly considered in many logistics-related operations. For example, vision reality (VR) and augmented reality (AR) technology powered by CV can revolutionize the picking, packing, and commissioning processes in warehouses and cross-docking areas by automatically reading the barcode, and quick identification of products with voice-based picking. In addition, an AI-based approach [75] was developed for AGVs (Autonomous guided vehicles) to improve the efficiency of multi-pallet loading operations by learning and optimizing the routes over time. In practice, a French startup, Qopius2 is developing CV-based AI to measure shelf performance, track products, and improve retail store execution. In addition, they can also serve as a supervisor to monitor the warehouse perimeter and track the employees, analyze the data, and prevent theft and violation of safety rules. Regarding transportation-related activities, AI and ML can optimize transportation routes in real time with respect to the dynamic changes in customer demands and traffic conditions, which can influence the shipping time. The SmartTruck routing initiative 3 developed by DHL provides AI-powered optimal routing algorithms for transportation operations and drivers using a wealth of information such as digital and satellite maps, traffic patterns, and social media check-in locations.

From a business perspective, the powerful and unlimited capability of intelligent data processing techniques powered by AI technologies promises the essential need of DT to obtain multiple benefits for the business in terms of competitive advantage, profits, customer experience enhancement, and customer loyalty. AI is becoming an essential part of business intelligence (BI) providing a source of intelligent decision-making [76].

3) BIG DATA ANALYTICS (BDA)

As a complex set of data is characterized by huge volume, high velocity, and variety, it is described by an umbrella concept, big data (BD) [77]. The complex nature of BD with the coexistence of unstructured and structured forms urges the need for advanced data processing technologies to make full use of all of this data instead of traditional database management tools. Big data analytics (BDA) has emerged to include algorithms and techniques specially developed and used to process, study, and analyze BD. There are four typical types of BDA: descriptive, predictive, prescriptive, and diagnostic.

BDA approaches rely heavily on high-quality data sources to effectively derive the analysis outcomes. In this context, ML algorithms are effective during the phase of data preparation with the aim of detecting anomalies (e.g., missing values, duplicate records, and outliers), cleaning, and unifying data in a holistic manner. In parallel, while more data are used, more

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2 French startup Qopius, https://qopius.com/
3 SmartTruck by DHL, https://www.dhlsmartrucking.com/
effective insights are derived from the AI algorithm, and BD enables the maximization of the AI performance. In particular, as IoT has been increasingly adopted in logistics systems, the integration of AI and BDA is essential for optimizing systematic performance. Fig. 8 illustrates the convergence and relationships of these technologies.

![FIGURE 8. Relationship of IoT, BDA, and AI technologies and their roles in optimizing the performance of IoT-based system.](image-url)

Accordingly, the data pushed from the IoT layer were analyzed using various advanced analytical techniques to extract patterns and trends. This well-analyzed information is then used by ML algorithms and AI to accelerate time to extract valuable insights and knowledge, which is eventually exploited to support decision-making in logistics activities. Therefore, the integration of BDA, AI, and IoT is becoming essential in the logistics and supply chain to boost productivity and operational efficiency [78], [79]. In the PI context, the work [80] proposed a BDA framework for PI-based manufacturing shop floors to analyze every process in real time. In particular, the behaviors of workers, machines, and processes are accurately predicted to mitigate any risk during production.

4) CLOUD COMPUTING (CC)
These applications have concurrently used the cloud and IoT to streamline processes and simultaneously improve the operational performance [81]. Fundamentally, CC provides unlimited services (i.e., PaaS, or platform as a service; IaaS, or infrastructure as a service; SaaS, or service as a service) to store and process the massive volume of data generated by IoT devices in IoT-enabled systems. Therefore, the majority of data and processes can be mitigated to the remote cloud layer, aiming to make the system agile. In particular, because AI and BDA algorithms often require a vast amount of processing and computation resources, the cloud-based services can provide on-demand computing resources and services to meet the requirements. In addition, the pay-per-use model of CC can support the business in deploying AI- and BDA-based solutions in remote clouds without the need to build their own monolithic IT infrastructure, such as local databases, and computing servers. Furthermore, as integrated with a sophisticated API (application programming interface), the power of CC enables the creation of a BI dashboard, which can manage the logistics inventory, assets, operations, and KPIs from a centralized base station. For example, cloud-based platforms such as Shipwire and Freightly have been deployed and used practically in the small and medium enterprises (SMEs) to monitor and manage freight transportation processes in real time.

Ubiquitous Internet connectivity has paved the way for the pervasive computing, aiming to improve the quality of services. In such a trend, fog and edge computing architectures have been introduced and deployed recently as an extension of cloud computing that can provide the computation resources and services closer to the data generation sources (e.g., IoT devices, Internet-connected systems, CPS). The main objective of these two emerging technologies is to meet the delay-intensive requirements of services and applications by processing data locally. Moreover, mobile edge computing (MEC) has emerged to offer networking and computing services for the mobile end devices and users. Consequently, the integration of IoT, centralized CC, and distributed computing models (i.e., fog, edge, and MEC) can provide pervasive and accessible services that have significant implications for applications in the global PI network.

5) BLOCK CHAIN (BC)
Exchanging digital information and data through the Internet probably raises security and trust concerns. However, in the logistics industry, the value of shared data also makes it a lucrative target to threats. Fake shipping manifests, altered invoices, and tampered tracking data represent some of the growing concerns for IoT-based logistics and supply chain networks [82], [83]. Securing modern supply chains against such vulnerabilities requires significant investment in terms of human forces and resources, which can add to the overall economic cost and lead times in supply chain operations. In this context, the application of blockchain (BC) technology in supply chain data management can help mitigate such issues effectively [84].

BC is described as a virtual database stored by a distributed ledger technology (DLT) in an Internet-connected network where each participant can access and manage the same data locally using the granted unique key [85], [86]. There are four typical features of BC technology: data transparency, data security, traceability, and smart contracts [87]. One major advantage of BC is that it offers transparency, by which all the participants of the network can share and access the same data. In addition, the BC technology ensures a high level of trust in all P2P transactions without the need for third parties to monitor, coordinate, and verify the transaction processes [88], thus providing a single version of truth (SVOT) [86]. Furthermore, the dataset and transaction in the BC-based systems are further protected by cryptographic techniques and verified via a special proof-of-work (PoW) method. With this data security, BC can eliminate potential risks such as hacking, data manipulation, and data compromise.
However, to enhance the security and correctness of data shared in the BC network, it must be verified and validated by ML algorithms [89]. Because the shared data is transparent and secure, BC technology promises to provide many efficient services, in particular, traceability and smart contracts. For example, a BC-based digital trust network is developed the Walmart’s Food Traceability Initiative provide a full transparency and traceability of products across the entire supply chain. As a part of the network, customers are supported to verify the originality of products (i.e., authentic or not), the status of products, and their quality through some ML algorithms. Similarly, IBM and Twiga foods developed a BC-based microfinancing applications for food Kiosk owners in Kenya. The ML algorithms are integrated to analyze the purchased products and then predict credit scores and worthiness of kiosk owners. IBM and Maersk developed a similar method to settle a BC solution as a means of connecting the vast global network of shippers, carriers, ports, and customs. The status of the shipping container can be monitored in real time by the involved actors and analyzed by ML algorithms to detect and predict the anomalies. Typically, smart contracts are generated by self-executing computer programs that contain rules, which are agreed upon by the participants following a set of digital processes. Smart contracts are becoming prevalent to replace manual contracts because they facilitate and automate transaction processes [90], [91]. The concept of a smart contract is potentially applicable to remove lead times caused by administrative processes during transferring the shipments to other parties.

As the B2B and B2C sectors driven by digital technologies are gradually moving their services to a digital market, BC has become the key technology of DT as it offers top security and trust for consumers, clients, trade, and business partners within the world of unique cross-border digital networks. According to the BC spending quick look survey conducted by the International Data Corporation (IDC), up to 70% of companies across industries consider BC to be part of their DT strategy.

While the long-term objective of BC is not to completely replace the established public and private data storage approaches offered by cloud-based services, it has the potential to promote the exchange and storage of transaction data of global trade. Linked directly to the PI vision, and aligned with DT, BC promises to be a key factor in achieving a globally efficient and sustainable objective. The work [92] introduces a conceptual framework of BC to support four levels of interactions with real-time and security: \( \pi \)-organizations and governance at the highest level, \( \pi \)-nodes, \( \pi \)-movers, and finally \( \pi \)-containters at the lowest level. In addition, as the smart contract is launched, BC can lead to automatic payment and invoicing as soon as goods reach a pre-agreed destination. Thus, the concept of a smart contract is widely applicable in the global transactions of the PI business because it enables an efficient synchronization of physical, digital, and financial flows [93].

6) DIGITAL TWINS
A digital twin is defined as a virtual replica of a physical object that describes and stimulates the characteristics, states, and operations of its counterpart in a truly and comprehensive manner. Digital twins are not created by a single technology, but a fusion of multiple relevant technologies, such as IoT, AI, BDA, CC, and digital reality. IoT serves as a means to collect and transmit the object, context, and operation-related data to the data consumption station in real time. BDA and AI were used to analyze the data and predict possible events in future operation scenarios. CC technology provides efficient resources for the development, maintenance, and use of digital twins because these tasks are computing and storage intensive. Finally, digital reality such as augmented reality (AR) provides an environment for rendering, displaying, and interacting with digital twins. The presence of uncertainty in the logistics and supply chain environment stresses the need for a digital twin to simulate and predict the possible event and performance of operations in the future, thus enabling to effective management of disruption risks [94], [95].

The digital twin based simulation models also help in examining the efficiency of protocols, rules, and trust agreements established by the stakeholders in the PI networks. In addition, the barriers in terms of asset-sharing, service access, and competition rules are addressed to enable harmonizing the connected protocols, and collaboration frameworks in PI.

Table 3 summarizes the development areas of PI and the roles and impacts of digital technologies as enabling factors for the implementation.

IV. PERSPECTIVES OF PI ON THE STATE OF DT
According to the roadmap, the PI vision is still in the initial stage of development and realization, and DT probably plays an important role in accelerating these processes. In particular, the engagement of PI and DT promisingly provides multiple innovative logistics services and management capabilities that contribute to achieving sustainability and efficiency objective. This section identifies and examines these major perspectives by leveraging the innovative features of PI and the power of DT.

A. INNOVATIVE DELIVERY CAPABILITIES
Digital technologies promise a significant improvement in delivery capabilities in the PI context through data collection, data sharing, data analysis, predictive abilities, and optimized decision-making. For example, real-time information collected constantly during journeys is used by AI and BDA algorithms to derive the optimal delivery routes flexibly, which can minimize the impact of uncertain situations such as congestion, traffic jams, and bad weather conditions. The consolidation of \( \pi \)-containters from different cooperative stakeholders is essential to increase the fill rate, and asset

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4BlockChain Spending Quick Look Survey by IDC, https://www.idc.com/getdoc.jsp?containerId=US47039120
TABLE 3. PI development and enabling factors by means of digital technologies.

| Development Areas of PI | Implementation Objective | Digital Technology Roles and Impacts |
|-------------------------|--------------------------|-------------------------------------|
| π-nodes                 | Automated processes and standardized services | - IoT standardizes the data for sharing.  
- AI, ML provide efficient services, and enable automation (e.g., picking, loading, unloading). |
| Logistics networks of π-nodes | Seamless, flexible and resilient, door-to-door services for all shipments | - IoT enables data and information sharing.  
- AI and BDA provide continuous services.  
- Computing platforms (CC, fog and MEC) offer continuous services.  |
| Network of logistics networks (PI) | Secure, efficient and extensible services for the flow of goods, information, and finance across logistic networks. | - AI & BDA create the business intelligence for cooperation and inter-operation.  
- BC-based smart contracts synchronize the flows.  
- The ML integration ensures the correctness of data before shared in the BC networks.  |
| Access and adoption     | Accessible, non-discriminatory PI | - IoT and connectivity technologies (5G) optimizes coverage for PI service access.  
- Computing platforms offer pervasive & affordable services with the ease of access.  
- Digital Twins help in creating the adoption plan, guidance, and strategies for types of business models.  |
| Governance              | Governance bodies, collaboration frameworks, competition rules, and trust agreements | - Digital Twins-based simulation models examine and adjust the governance bodies.  
- Trust and secure collaborative frameworks are enabled by BC.  |

utilization as transporting them between π-nodes [96]. The next generation of wireless networks (i.e., 5G and beyond) creates smart ecosystems (e.g., smart cities) with ubiquitous connectivity through D2D and M2M communications. The delivery and transportation operations in the PI network have the potentials to exploit such smart infrastructure to optimize operational performance. For example, platooning enabled by V2V (vehicle-to-vehicle) and V2I (vehicle-to-infrastructure) communication is leveraged to consolidate and move the π-container flows to the next same destination (e.g., a certain π-node) efficiently. Platooning systems have potential opportunities to be applied in the PI environment, where the interconnection in all physical, informational, and organizational levels is set as a basic foundation. The connection between π-trucks, π-nodes, and π-trucks with π-nodes through unified platforms and languages contributes to effectively creating platoons [97]. Platooning further creates more benefits as the cooperation of platoons between stakeholders, including competitors is employed [98]. AI algorithm such as reinforcement learning (RL) are applied to platoons, enabling them to reconfigure and self-organize when facing the unknown disturbances [99]. The intelligence at the edge can also be adopted in π-vehicles by a combination of edge/fog computing with AI to make instant and efficient decisions in a distributed manner.

In last-mile operations, continuous interaction with customers enables the shippers to provide efficient and flexible solutions, meeting the changeable requirements of the intended recipients. Drones are also used explosively to deliver shipments to every place safely and in a timely manner, especially in emergency situations due to IoT, AI, and BDA.

B. AUTONOMOUS LOGISTICS

Standardization of physical, informational, interface, and process aspects is emphasized in constructing the PI network to ensure the seamless integration of physical, informational, and financial flows. In combination with digitalization, this feature promotes automation to be widely used in most PI-based logistics operations. So far, the perspectives of autonomous logistics have been studied and developed in many use cases, including indoor robotics and AGVs for material handling in warehouses and drones for last-mile delivery to reduce operational costs, risks, and lead times [100]. In the era of DT, autonomous systems have many more potential applications owing the emergence of advanced technologies such as IoT, AI, ML, robotic process automation (RPA), self-driving, and robotics, which can significantly improve the accuracy, productivity and efficiency of automatic processes. In the vision of PI, the success of DT further asserts this perspective toward autonomous logistics by exploiting the innovative features of PI to achieve it. Robots and robotic systems prevail in the π-nodes to perform many tasks such as unloading, sorting, composing, and loading π-containers automatically. The mobile robots, AGVs, and π-conveyors can move the π-containers to the right places within the π-nodes. Identification technologies (e.g., RFID, and even CV-based) enable them to identify exact π-containers that need to be handled. Additionally, the intelligence powered by the AI algorithms is integrated to optimize task performance, such as routing. Moreover, ubiquitous connectivity, especially via IoT, D2D, and M2M communication technologies, helps mobile robots and AGVs reach their destinations. In particular, full automation can be achieved by interconnecting autonomous systems to create end-to-end
logistics services in $\pi$-nodes. To transport the $\pi$-container flows between $\pi$-nodes, platoons with autonomous trucks are largely applied in city logistics models to achieve efficiency and sustainability objectives [101]. CPS-based solutions are also potential to synchronize and automate the order fulfillment in the city logistics [102]. Furthermore, BC-enabled smart contracts are an integral part of autonomous logistics because they enable performing the automatic execution of agreement-based processes between stakeholders [103].

C. OPTIMAL UTILIZATION AND SHARING OF LOGISTICS CAPABILITIES

Because digital data is a vital source for visualization, analysis, prediction, and decision-making, the assets and capabilities of logistics networks in the PI network will have better utilization and sharing by leveraging the shared data.

Through WSNs, IoT, and BDA, the operational states and health status of equipment, machines, and handling systems in logistics activities are monitored and predicted in real time to avoid interruptions. In particular, as autonomous systems (e.g., RPA, mobile robots, and AGV) prevail in logistics, the time intervals for processing tasks can be predicted precisely; hence, the assets and equipment can be scheduled appropriately to minimize idle time. So far, collaboration and cooperation in both the vertical and horizontal directions have been strategic factors that benefit from the sharing models of logistics capabilities, thus boosting performance in logistics and supply chain operations [104]. In the era of digital data, DT probably creates a means for real-time information sharing while ensuring the accuracy, privacy, transparency, and security enabled by IoT, AI, and BC, thus exposing the potential opportunities to strengthen collaboration to maximize the value of shared data and achieve unprecedented efficiency [105]. In this context, the logistics capabilities harnessing collaboration can be shared by two main approaches: transport and warehouse. In freight transport, the physical flows of $\pi$-containers can be managed in the form of consolidations to mitigate the volumes of air transport, consequently improving the efficiency. Platooning is another way to consolidate the flow of autonomous trucks to decrease operational costs. The $\pi$-nodes are willing to share their capabilities through services such as routing, and storage. In particular, interoperability is a type of logistics capability that can be shared with collaborative and cooperative partners in the PI vision. Fundamentally, a logistic network with interoperability can perform an operation on behalf of other connected networks to obtain many mutual benefits [106]. In the PI context, this concept is important because it can improve the resource utilization and logistics capability sharing through offshoring and outsourcing approaches.

D. INNOVATIVE BUSINESS MODEL

Business models are referred to as a collection of strategic plans used by businesses to stay or advance values in the competitive landscape [107]. To reap the full benefits of digitalization, business models must fundamentally redesign and upgrade their supply chain and logistics service provision strategies [108]. In the context of PI, there are two important types of business: $\pi$-enablers and $\pi$-enabled [109].

The first business group aims to provide baseline infrastructure, including $\pi$-containers, $\pi$-movers, $\pi$-nodes, basic services, and software for enabling PI. In line with the servitization trend in the manufacturing industries [110], [111], the innovative requirements of designing the PI infrastructure create a potential competitive landscape for service-oriented business to enrich value-added services supported by digital technologies. The product-service system (PSS) can be seen as a typical case of servitization as it aims to integrate tangible products and intangible services to improve the value asset performance [112], [113]. The concept of PSS offers many benefits for the application of the PI paradigm [114]. For example, suppliers including $\pi$-enablers of $\pi$-containers can provide three kinds of services to fulfill different customer demands, including selling, renting, or paying per use (i.e., metered services). While the first two modes (i.e., sell and rent) are available in the existing logistics and supply chain industry, the last mode emerges in the era of DT from the PI perspective. The integration of advanced ICT technologies such as sensors and IoT enables developing valuable services for $\pi$-containers such as real-time tracking, local computing and decision-making, and communication [32], [115]. Furthermore, by combining with the cloud computing technology, the PI-container-enabled PSS can be realized to provide innovative sustainable green logistics services, reduce logistics costs, and reduce environmental pollution through information-driven logistics operation optimization [116], [117]. The $\pi$-nodes can also provide various logistics services based on clients’ needs, including packaging and sorting, freight transit and rerouting, transport modal shift, warehousing, and inventorying. Fig. 9 illustrates a conceptual model of a road-based cross-docking $\pi$-hub that can offer freight transit and freight consolidation services in the PI network.

Based on this model, the startup CRC services (i.e., collaborative routing center$^5$) in France have developed a local

$^5$Collaborative Routing Center, crc-services.com
service to consolidate multi-supplier and multi-retailer freight flows to improve the efficiency of transport activities in the FMCG industry. In particular, no long-term contract is needed between the service providers and clients (i.e., suppliers and retailers), but paying per use and per pallet service. Such a model can be developed to provide additional innovative services such as digital connectivity and asset sharing, such as a supply hub in industrial park (SHIP) [40].

The growing demand for customized products has driven the emergence of 3D printing technology known as additive manufacturing (AM) or direct digital manufacturing (DDM), which probably has a significant impact on the logistics and supply chain industry [120], [121]. This method can produce on-demand products at places near customers, thus reducing the need for transportation and inventory control, which are the main activities of current logistics management. In this context, business organizations and strategies must be innovated to adapt changes. For instance, less physical space (e.g., shelves) is needed to store the same inventory or materials for printing, which means that more digital space in the \( \pi \)-nodes is required to store the digital blueprints. In addition, in collaboration with manufacturers \( \pi \)-nodes can provide 3D printing services. In this way, the manufacturers are responsible for providing the blueprint models, whereas the \( \pi \)-nodes create a network of 3D prints using the provided blueprints to produce the final products for customers. In particular, the products can be printed in \( \pi \)-transports (e.g., \( \pi \)-trucks) during delivery to customers to reduce lead times.

In a complementary fashion, the \( \pi \)-enabled business in the second group exploits the potential value creation capabilities of the PI network to create advanced services for very involved stakeholders. Control towers and analytics-as-a-services are typical services provided by these business models, which are created by advanced data processing, and analysis tools such as AI, ML, and BDA. In integration with cloud computing, such services are accessible and affordable for PI management systems.

E. REAL-TIME AND CIRCULAR ECONOMY

Two important implications of the PI network with DT support are the real-time and the circular economy. Digitalizing in the logistics and supply chain sectors enables a real-time economy, in which all processes and transactions can be accomplished in real time by the efficient and secure flows of material, information, and finance. Smart cross-border digital platforms with digital connectivity-enabled real-time logistic services can significantly remove the friction of administrative and verification processes along the physical flows, ensuring smooth operations [122]. Meanwhile, real-time transactions can be obtained through BC-based smart and secure contracts, thus enabling instant financial flows with, for example, automatic invoicing and billing [123]. Reducing the time to market through 3D printing-based logistic services presents a perspective to shape the real-time economy.

To effectively respond to the limitations of nature resources, the urgent demand to achieve sustainable development of the global economy has pushed the redesign of the traditional linear economy model (take, make, and dispose) to become a circular economy (CE) model [124]. The PI vision and DT have significant implications in shaping CE. On the one hand, PI can be considered as a holistic solution encompassing and leveraging the advantageous features of different logistics paradigms such as intelligent logistics [125], green logistics [126], and reverse logistics [127], [128] to achieve efficiency and sustainability objectives in terms of the economy, the environment, and the society. In this context, PI presents itself as an integral component to form a circular supply chain (CSC), which consequently enables CE [129]. Fig. 10 shows the conceptualization of CSC that keeps the product in a circular process, including recycling, remanufacturing, reuse, recovery, reduction, and redesign. To implement and realize CSC, four main components are needed: an intensive collaboration in the supply chain networks between manufacturers, suppliers, and customers; adaptive organizational management; application of disruptive and smart technologies; and development of a functioning environment [131], which are massively supported through DT.

On the other hand, digitalization is also recognized as an enabler for CE because of the integration of intelligence and visibility into the products and assets by using digital technologies such as IoT, AI, and BC [132], which provides a means to efficiently manage the life cycle of products [133], [134]. With these integrated capabilities, the life cycle of products can be efficiently managed to maximize usage value while minimizing the impact on the environment. In addition, CE-based business models can develop and provide additional services to extend the usage of products and maximize the value of products such as leasing, renting, or sharing instead of selling in the conventional linear economy model [135], [136]. Such a method is coined by PSS, which has been recognized as a key driving force to accelerate the transformation from a linear economy to a CE model [137]. Furthermore, 3D printing technology helps eliminating accumulated waste in manufacturing processes, thus substantially reducing the environmental footprint.
V. KEY CHALLENGES AND OPEN RESEARCH ISSUES

DT is not a single technology but a holistic strategy for a major change. Although the PI is on the way to be a reality, its concept promises a potential foundation and environment to adopt DT. However, to successfully implement both DT and PI, a substantial framework is required to overcome many obstacles, which are thoroughly explored and discussed in this section.

A. SYSTEM-RELATED ISSUES

The aforementioned perspectives illustrate the potential of DT in accelerating the implementation of PI to achieve a global, sustainable, and efficient objective. However, the implementation of PI and DT faces mutual challenges combined with the novelty of these two concepts. First, the novelty nature of the PI concept presents its own challenges for implementation, such as designing the enabling components (e.g., \( \pi \)-containers, and \( \pi \)-nodes) [25], [138], [139]. Indeed, there is a lack of a thorough framework for supporting and guiding the successful deployment of DT in any specific domain, especially in the PI context. Although the roadmap has been released to promote the research and development of PI, there are still limitations to projects, research, use cases, and practices to study the role of DT, especially the digital technologies in the implementation of PI. In particular, there is a lack of holistic and comprehensive assessments to evaluate the engagement of DT and PI, which leads to objective achievement. The extant literature provides many relevant works studying on the role of individual digital technologies in the logistics, and PI context. For example, the impact of IoT on economic growth was introduced in [140]. In addition, the works [141], [142] aim to establish and examine an efficient green computing platform based on fog and edge computing technologies that support the provisions of IoT applications. Likewise, the work [143] introduced a decision making trial and evaluation laboratory (DEMATEL) approach to evaluate the success factors of the application of digital twins in the PI. These individual assessments should be included in an integrated framework to measure and comprehensively evaluate the co-implementation of DT and PI. Digital twin-based solutions can be developed to simulate and examine the performance of PI network operations. The impact of DT was also investigated in digital twin simulation models. The outcomes of evaluation are meaningful for planning the implementation of DT along with the road map of PI in order to maximize their synergy. In addition, with the coexistence of an overwhelming number of technologies and developed solutions, the plan also determines which components and processes of PI networks use which technologies to maximize the operation efficiency while minimizing or reducing the cost.

B. BUSINESS-RELATED ISSUES

Although DT is well underway in the wave of the Industry 4.0 revolution, there are many factors that significantly cause resistance to adopting and implementing DT in the business environment [144], [145]. First, not every company, process, or business model requires DT to stay and enhance competitive advantage. Indeed, with up to 70% failure of DT as statistically evaluated in [146], the fear of failure impedes the business from considering DT as a strategic development plan. Moreover, the implementation of DT requires many resources, including time and cost for investing in transformation technologies and skilled labor. The business requires a sophisticated evaluation of their readiness to adopt emerging technologies [147]. Many legacy systems, such as transportation management systems, warehouse management systems, and financial systems in the logistics and supply chain may be unable to support digitalization, thus requiring a substantial cost for transformation. Therefore, SMEs with more limitations on financial, human resources, and technical skills and competences are likely to have a higher uncertainty in deploying DT. Meanwhile, the short-term impact of transformation mostly comes from conventional operational and strategic technology, not from the disruptive technologies required for enabling DT. Furthermore, DT requires advanced skills and competences in many aspects, especially leadership, business process management (BPM), technical engineering and technology [148]. Leadership is considered a key factor in DT success. Predicting technological advancement trends, markets, and customer demands are essential competencies of leadership boards needed to build a holistic plan for DT implementation. Using AI tools significantly enhances the accuracy rate of prediction as well as decision-making for leaders. The developed AI systems also require a robust engineering strategy to maintain, scale, and manage in an efficient and effective way to run successfully.

These aforementioned points assert that disruptive transformation is likely to be created in the leading business because they have the capability to pursue a long-term DT plan. There is a need to create conditions and environment for SMEs to join in this impending wave of transformation and innovation. Cloud-based solutions are increasingly affordable for new logistics companies (i.e., both \( \pi \)-enabling and \( \pi \)-enabled firms) because the construction of an IT infrastructure is time-consuming. It will also be possible to tackle the current shortage of skilled labor by developing and employing smart assistance systems powered by AI, ML, and intelligent agents.

C. DATA-RELATED ISSUES

BD is becoming a norm in the digital era to describe huge datasets generated by an enormous number of devices, systems, and organizations daily. Undoubtedly, it serves as the main source for creating unprecedented value and smart services. Despite its many advantages, the data itself exposes critical issues in the PI-based logistics context; hence, tackling them is seen as a challenging task.

The first issue relates to the data quality. The data in the logistics field can be obtained using by different methods, including manual laborers and automatic systems with
embedded sensors. In addition, a large volume of data can be obtained through the many data-sharing protocols of the connected actors. In the presence of uncertainty and dynamics of the logistics environment, the inconsistency and reliability of collected datasets are unavoidable because some missing and incomplete data may exist during data gathering and sharing. Indeed, not all data are available in digital forms such as papers, and transforming them into the corresponding digital forms can degrade the quality of information due to, for example, a noisy and low-quality scan. The AI and analytics algorithms require input datasets with standard quality to derive useful insights and remove possible faulty features. Although ML-based algorithms such as data cleansing and anomaly detection can be used to prepare the data effectively, improvements in data collection techniques and approaches are necessary to accelerate the extraction of insight, patterns, and decision-making.

The second issue is related to data sharing. There are many available technological solutions to enable inter-connectivity; however, achieving seamless, secure, and efficient data-sharing among the inter-connected players is difficult. Because an enormous number of devices, systems, and organizations generate a variety of data types with various formats and structures, standardizing the digital data format is a prerequisite for improving the data sharing. In practice, the organization GS1 has supported to create many logistics data standards such as RFID, EPCIS (Electronic Product Code Information Services) used in different levels including physical and operation levels. Because the PI network founded by openness and standardization of components (i.e., \( \pi \)-containers, \( \pi \)-nodes, and \( \pi \)-protocols) is built to encourage the development of plug-and-play services, the standardization of data format at all connected sites is of utmost importance. Meanwhile, connecting these standards in the PI context is still challenging. In addition, without a basic standard of digital data sharing across the flows of material (i.e., \( \pi \)-containers), other advanced technologies such as IoT, BDA, and AI could be severely limited in their capabilities. Developing a digital platform with API powered especially by AI-based image and natural language processing techniques is a potential solution. For example, the electronic Air Waybill (e-AWB) is a standardized digital version replacing the existing paper Air Waybill used in the air freight industry to improve efficiency in tracking and processing cargo data as well as to increase transparency, improve security, and reduce costs and lead times. The International Air Transport Association (IATA) declared e-AWB as a default carriage contract. Recently, the digital transport and logistics forum (DTLF\(^5\)) was launched to develop data-sharing mechanisms in the logistics and supply chain industry. Consistent with the PI implementation and development roadmap, two typical projects FENIX (European Federated Network of Information eXchange in LogistiX)\(^7\) and the FEDeRATED network of platforms,\(^8\) are promoted to implement practices that potentially support data sharing in the PI context.

Finally, data privacy and security are issues in the DT era. So far, collaboration and cooperation have been recognized as strategic business planning to achieve mutual development benefits and cope efficiently with dynamic uncertainty. In the digital era, such collaboration can be enhanced at different levels, including the physical, informational, and organizational levels. However, since the data are the most valuable assets, they are reluctant to share, except for their strategic and long-term partners, especially customer data. Weakening competitive advantage is the first foreseen disadvantage of information sharing. In addition, information can be lost at any border. Therefore, this calls for a holistic framework to promote data sharing while maintaining a competitive advantage. Federated learning techniques can be developed and used to determine which data must be exchanged [149]. AI also has a negative side. For example, cybercriminals can use AI and ML to create virtual hacked data and advanced harmful threats.

D. POLICY-RELATED ISSUES

Since logistics activities in global trade are closely related to many disciplinary sectors, countries, and continents, the presence of different regulations and policies has a huge impact on realizing the inter-connectivity and inter-operation foundation of PI networks. Although digital technologies in the field of information, communication, and connectivity can aid in achieving interconnection at information level, different policies can serve as barrier to the achievement of interconnection in physical, operational, and organizational level. For example, regulations of some countries, concerned about national safety and security, may establish cabotage rules,\(^9\) denying transnational transportation of \( \pi \)-containers because they might contain threat sources. Such inhibitory laws may indicate a major obstacle to the implementation of routing protocols for \( \pi \)-containers across international multi-modal transportation. Custom regulations can incur longer lead time when verifying the incoming flows of goods. Indeed, strict access is allowed to protect the content and final customer data. A unified digital platform is needed in these situations by the involved actors to support quick and secure access to validate and verify the originality of \( \pi \)-containers. Similarly, businesses also possess unique regulations that limit the sharing of valuable information and resources due to purposes to maintain and enhance their competitive advantages. All these issues require a call for building a framework agreed by the relevant actors in the PI network to coordinate and harmonize the different regulations and policies, aiming to facilitate the integration of physical, information, and financial flows.

\(^5\)The Digital Transport and Logistics Forum launched by European Commission, https://www.dtlf.eu/
\(^7\)Project FENIX, https://fenix-network.eu/
\(^8\)Project FEDeRATED, http://www.federatedplatforms.eu/
\(^9\)Cabotage rules by EU, https://ec.europa.eu/transport/modes/road/haulage/cabotage_en
By removing policy-related issues, the synthesis of PI and DT can be maximized in their capabilities.

VI. CONCLUSION

The innovative concept of PI promises to reshape the current logistics system toward a global sustainable and efficient logistics network. To achieve this goal, the PI network is built on the inter-connectivity and interoperability foundation, following the principle of the DI network. This is definitely linked to the use of digital technologies in the fields of information, communication, connectivity, and computing, which are recognized as the essence of DT.

In line with the revolution of Industry 4.0, DT has been widely adopted in many existing industries, including logistics service and supply chains. Likewise, the engagement of the PI and DT has many implications and contributions. First, the key DT enabling technologies that promote and accelerate the process of PI realization are identified and examined. For example, the IoT-relevant technologies provide an ultimate way to collect and share data ubiquitously and universally. Meanwhile, intelligent data processing tools such as AI, ML, and BDA extract insight from these data for predictive applications and improve decision-making. Moreover, BC offers a secure and trust mechanism to facilitate Internet-based transactions and exchanges. CC makes DT possible, as it can offer affordable and accessible services and resources for Internet-connected users. Second, four important perspectives including innovative delivery capabilities, autonomous logistics, optimal utilization and sharing of logistics capabilities, innovative business models, and real-time and circular economies, which can be achieved by the advantages of the PI network combined with the powerful capabilities of DT are identified and discussed. These perspectives potentially imply that the sustainability and efficiency objective of PI vision can be achieved with the means of DT and digital technologies.

However, PI is still in the initial stage of development and realization, and there is no reference model for successful implementation of DT in the logistics and PI contexts. Hence, the co-implementation of PI and DT faces many critical challenges and barriers related to system, business, data, and policy issues. The paper thoroughly examines these issues and proposes corresponding resolutions for open research. The analysis shows that besides the vital role of technologies, a mind shift in the business culture, policies, competition, and collaboration has a significant impact in the success of PI.

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