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Blockchain Implementations and Use Cases for Supply Chains – A Survey

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ABSTRACT Since Bitcoin's debut in 2008, blockchain, the technology behind the cryptocurrency, has been gaining increasing scientific and industrial interest. Due to the technology's innate distributed and immutable features, the adoption of blockchains on supply chains is one of the most promising recent applications. In this survey, we review academic researches and implementations of distributed ledgers on supply chains. We present the current state of research on the subject and summarize the benefits and the challenges of the distributed organization and management of supply chains. Focusing on industrial practices and use cases, we discuss the technical characteristics and maturity of the various industrial projects. Our goal is to assess the applicability of blockchains in the supply chain domain and to provide a foundation for practitioners and researchers to direct their future projects towards improving the technology and its applications.

INDEX TERMS blockchain, distributed ledger technology, implementations and use cases, supply chains

I. INTRODUCTION

DISTRIBUTED ledger technologies found themselves in the spotlight after the publication of Nakamoto's white paper on Bitcoin [1], the cryptocurrency that uses Blockchain, the most popular distributed ledger to this day. Ever since, thousands of scientific papers, blog articles, industry guides and financial reports have been written on what is a blockchain and the ways in which it has entered the industrial, financial and technological worlds.

Let us consider a network of entities engaged in exchanging assets, or making transactions, with each other. Traditionally, such activities would require a central organization to manage them and act as an intermediary for any payment or transaction. A blockchain provides the infrastructure for such activities to happen in a transparent, secure and reliable way, without the need of the central organization. For a transaction to be valid, it must be registered in a block, that the network has agreed upon through a consensus mechanism. After validation, the nodes append the block to their privately maintained chains. Because the blocks have been validated by the network, all chains are identical, providing a distributed ledger ensuring data synchronization across the network. The chain structure is a key characteristic that facilitates the reliability and immutability of the ledger, as each block contains a hash of the contents of the previous block on the chain. Therefore, once a transaction is registered on the blockchain it cannot be tampered with, as such a malicious act will manifest itself as an inconsistency between the block hashes of the individually maintained chains. This allows to trace down the origin and progression of all registered activities.

The traceability property of blockchains, as it is better known, is one of the features that attracted the attention of the business and financial worlds. Organizations in these regimes are often part of large and complex networks where transactions are happening for products and services to find their ways from production and creation to consumption and use. Consider for example a product such as a chair. The life cycle of a chair starts in a forest, in the form of a tree trunk and ends with the chair bought at a local retailer's. The journey from one end to the other involves many different stages, both industrial and financial. In terms of industrial activities, those include the cutting of the tree trunk, its shipment to a furniture factory, the design of the chair and the crafting of the log into the chair. In terms of the financial activities, those include the furniture manufacturer buying logs from a forestry supplier, the manufacturer employing shipment companies for the transfers etc. These are only but a few of the activities that happen in the life cycle of a product. In the business and financial worlds, the network of

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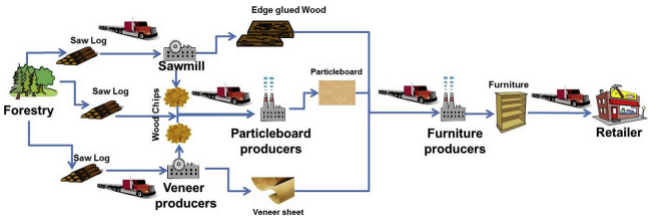

FIGURE 1. Example of a supply chain for furniture products [2]

organizations, companies, retailers, suppliers and consumers, as well as the activities and transactions between them, form the supply chain of a product or service. An example of a supply chain for furniture is shown in Figure 1, taken from Appelhanz et al. [2].

In this work, we present a holistic overview of the literature on blockchain adoption in supply chains. As such, we will discuss and summarize the adoption barriers, challenges and benefits that have been addressed in the related literature, from the point of view of the industrial world but also from the point of view of the technical experts. What is more, we will present and summarize actual implementations, use cases and proof of concepts of supply chains implemented on a blockchain system, and critically discuss their technical characteristics and limitations.

Contributions Our contributions are summarized as follows:

- We offer a holistic literature review of the recent works on blockchains in supply chains, including both the financial/business perspective and the technical one.
- We discuss and summarize adoption barriers and challenges as well as adoption benefits for supply chain manufacturers.
- We present actual industrial implementations and use cases as well as proof of concept cases, we discuss their technical characteristics, design choices and limitations.
- From the analysis of the related literature, we identify open issues and potential research directions for the advancement and improvement of the field, both for the industry and the scientific community.

Outline The rest of the paper is organized as follows. In Section II, we discuss preliminaries of supply chains and their implementation with the use of a distributed ledger, as well as we review existing surveys on the subject. In Section III, we describe the followed approach for selecting the works to be included in our review and pose the research questions we set forth in answering. Section IV hosts the body of reviewed works and our analysis for answering the posed research questions. Reflections and open research issues are discussed in Section V and we conclude the survey in Section VI.

II. BLOCKCHAINS AND SUPPLY CHAINS

Traditionally, a supply chain seeks to satisfy consumer's needs for a product or service with the least amount of inventory for the producer or/and retailer. Many supply chain management models have been designed since the 80's, when the term Supply Chain Management was introduced, trying to meet the needs of the various manufacturing networks. A few such requirements include (but are not limited to) the minimization of costs from transactions and inventories, the elimination of bottlenecks along a supply chain (due to delayed payments or supply deliveries, for example), the creation of chains resilient to changes due to bad economy or shortage of primary materials, the traceability of a product's origins in a secure and trustful way, the employment of local producers and labor force, the minimization of transportation needs and the delivery of the best quality products to the end consumer [3], [4].

The blockchain data structure by default satisfies many of these requirements for an effective and efficient supply chain; therefore, it is an obvious choice for industries and their financial partners to use it for managing their supply chains [5].

Traceability Tracing the origins of a product is especially important for the quality management of sensitive products, such as food or medicine. The recent history has unfortunately a few instances where food was tampered with, was expired or infected, yet promoted as fresh, causing diseases to consumers [6], [7]. With the current supply chain management solutions, it can take a long time to trace the infected batches or the origin of the problem, spreading the infected food and diseases to a larger percentage of the population. The timestamped registration of all information regarding the production, shipment and sales of any particular product on a blockchain would allow for identifying the roots of such cases instantly. Also, tampering with the quality of products in any way would be significantly more difficult when using blockchains for their supply chain, because the database requires constant validation of the transactions registered on it, not just by the network partner that handles the particular stage of the supply chain, but by the whole network. This guarantees a single truth and no need for negotiations and reconciliation between the various participants of the supply chain.

Distribution The distributed nature of the technology is one of the features that make blockchains attractive for supply chain implementations, as it implies a number of benefits. Firstly, since there is no central organization managing the transactions and storing the supply chain activities and every node in the network maintains a copy of these, fault or exclusion of some network nodes (e.g., bankruptcy of a supplier) would not cause the whole supply chain to collapse, nor the activities to be lost. Secondly, the fact that all transactions and information is stored on all nodes of the network, although it creates a kind of duplication of data, it also inspires trust and security between the cooperating partners, as not just a small group of them has access to sensitive data. Thirdly, costly transactions are avoided with the use of blockchain, as the system effectively decreases the need of intermediaries for every transaction and uses the same network for all its

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activities.

Immutability The immutability property is perhaps the most celebrated one, as it protects the users of a blockchain from numerous fraudulent attempts and adversaries. The traceability property is a direct consequence of the fact that once information is registered on the chain it cannot be altered. It is noted throughout literature that perfect immutability does not exist, since theoretically, a majority of the network can coordinate to tamper with the information on the chain. However, this is practically infeasible.

A. RELATED SURVEYS

The adoption of blockchain technology in supply chains is a relatively new subject and as such, there is only a small number of reviews of the related literature[1] [8]–[15].

In our view, the most comprehensive systematic literature review is the work of Wang et al. [8]. The key contributions in the review are the discussion of key adoption drivers, the identification of areas of most provided value, and the investigation of barriers of further diffusion of blockchain technology within the supply chain. A similar discussion is presented in [9], as part of a broader survey reviewing industrial applications across different domains.

Two recent works [10], [11] examine the enabling and constraining roles of the technology from a business/management oriented perspective, while [12] systematizes the theoretical implications of adopting blockchain in supply chains, again from the spectrum of industries and management. In another recent work [13] the authors analyse the impact of distributed ledger technology on different supply chain flows through case studies. Tribis et al. [14] offer a systematic mapping study focusing on the research aspect of blockchains, identifying research trends and challenges that remain unresolved. Saberi et al. [16] present a survey on the adoption of distributed ledger technology in various organizations and host in their work summary statistics useful in benchmarking the current practice. Finally, [15] conducts a brief literature review with the goal to introduce the blockchain technology and what it may be used for. However, the emphasis of the paper is on providing a reference implementation of a logistics monitoring system, and as such it will be further analyzed in later sections.

A technical perspective The above-mentioned reviews describe the impact of the technology from a financial, business and management oriented perspective. As such, the technical details of applying blockchain in supply chain are not sufficiently discussed. The desired properties of digital solutions, such as traceability and immutability, can be translated into specific software and tooling choices. These design decisions however are usually tradeoffs introducing new challenges to tackle, e.g the scalability of such systems and digital-physical product linkage. Hence, their use needs to be thoroughly assessed and understood before incorporating into existing software.

[1] By the time of writing this manuscript, which is early October 2019

III. RESEARCH METHODOLOGY

In this work, our goal is to review the existing scientific literature regarding supply chains designed based on the blockchain technology. One of the elements we wish to investigate is the type of research that has been conducted on the subject and the existing approaches so far. Exactly because this is a relatively new subject, coming from the increasing interest for blockchains from various areas where the technology can be applied, apart from cryptocurrencies, it is not a surprise to us that the vast majority of literature comes with a business and financial profile. Therefore, one of our research points is to separate the technical approaches from the conceptual ones, and further analyse the various research thematics within each category. Another research question we ask in this study has to do with the existence of implemented blockchain-based systems for supply chain cases and the technical details or/and limitations of such systems. Next, we want to identify the impact of the technology from its (potential) application on supply chains, as well as the various challenges that it poses. Finally, we discuss the various problems that remain unsolved after the application of blockchain technology in supply chains, as well as research gaps and open issues that literature has not addressed yet. We summarize our research points in the following questions:

RQ1 What are the existing research approaches on the subject of blockchains for supply chains?
RQ2 What type of supply chains can be implemented on a distributed ledger?
RQ3 What are the existing blockhain-based supply chain implemented systems? What are their design choices and technical characteristics?
RQ4 What are the benefits from the adoption of blockchain technology on supply chains?
RQ5 What are the challenges to be addressed?
RQ6 What are the current research gaps and open problems?

To answer these points, we perform a literature review by conducting two different searches: firstly, we search for peer-reviewed papers hosted in scientific databases. Secondly, we run a search on generic search engines for missed peer-reviewed papers and other articles. Next, we discuss the details and results of these searches.

Search for scientific papers In order to identify the useful peer-reviewed articles for our work, we looked in two different sources. Firstly, we applied the snow-balling technique on the existing literature reviews on the subject (presented in Subsection II-A), from where we acquired a total of 29 unique papers related to blockchain in supply chains. Secondly, we conducted keyword-based searches on the following databases: Google Scholar, IEEE, ACM, DTU Find-

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it[2]. For the purposes of our survey, the searches we conducted were combinations of the following keywords:

blockchain, distributed ledger, supply chain, implementation

With regards to the industry applications, in particular, apart from the peer reviewed studies we mined, there exist many useful articles published through university repositories, white papers/articles detailing the experiences of practitioners on the subject, industry white papers and short technical descriptions on project landing pages. Given the young age of the subject and the small number of good research existing on it, we decided to include such articles in our pool of mined related works, if by reading them we found their material and information invaluable, even though they are not peer-reviewed.

Search on generic engines By applying the same keywords as before, we conducted another search on the Google search engine. That resulted in a myriad of articles written in blogs and news portals. Apart from a few studies on the blockchain technology in the supply chain landscape [17]–[19] that we deemed interesting, we decided to ignore the rest of the search results since they massively represent non-reviewed author opinions.

By applying forward snowballing to the citations of the mined articles, we enriched our pool of mined papers with many papers and projects on the subject.

Inclusion and Exclusion Criteria We defined the following inclusion (IC) and exclusion (EC) criteria for considering, or not, a mined paper/project description in our review. We use the notations PROJ and PR to indicate criteria specific to implementation-related works and projects or peer-reviewed papers, respectively. Criteria without a notation were applied to all mined papers. We deliberately chose criteria that are *highly* permissive to avoid overseeing projects with advanced technology but sub-optimal communication. We note here, that as we include industrial projects and implementations, we do so *only* for cases where there is proof of the existence of the project (at some stage of its implementation) or/and sufficient documentation of the system's description.

IC1 The paper should be published after 2010.
IC2 From the title and abstract of the paper or the description of the project, it must be clear that the work considers the application of distributed ledger technologies on some type of supply chain.
IC3 [PROJ] There should exist a minimal description of the system.

EC1 Non accessible paper or non available full-paper document.
EC2 [PR] The length of paper is less than 4 pages.

[2]DTU Find-it is the scientific database offered by the Technical University of Denmark, which already contains publications from sources such as IEEE, ACM etc. For completion and to avoid cases of missed hits, we run all searches in all databases.

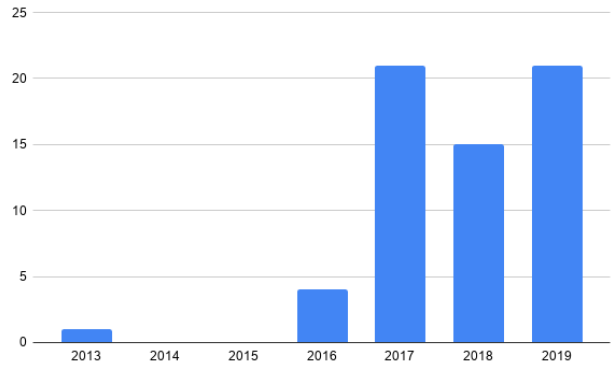

FIGURE 2. Number of published articles on blockchains for supply chains per year. The plot refers to the peer-reviewed papers included in this study.

EC3 [PROJ] The project is seemingly dead (i.e., no updates or existing systems that use it).

There are possible limitations to our research methodology, e.g it is rather subjective what qualifies as *minimal description* and there is high possibility that an existing project does not have enough traction to show up on our radar. We however feel that with our approach we have gathered the critical mass of the existing work, both in industry and the scientific community, on blockhains in supply chains, that allows as to perform a well-founded analysis of the subject from multiple perspectives.

IV. ANALYSIS

In this section we analyse the selected articles on the axes of the research questions posed earlier. Before we delve into the analysis, we underline the following observation: Although in the last three or four years there has been an explosion of interest in the application of distributed ledger technologies in supply chains, and an increasing number of relevant researches are published every year (Fig. 2), the vast majority of this literature coming from the academic world either takes a purely conceptual approach, without analyzing the details and performance of such a system, or discusses the different aspects of coupling blockchains with supply chains from philosophical, industrial or/and financial points of view. Only a few academic works detail their proposed blockchain-based system and implementation and the majority of use cases and implementation articles are coming as white papers or experience write-ups from the industry. As we explained in Section III, we include such articles and white papers as we deem necessary for the completion of this survey.

We use this observation in order to cluster the collection of works in a way that will assist us in better analysing them and discussing the research points RQ1-RQ6. Based on this, we can make a high level distinction of the literature into (G1) works that take a theoretical and less technical approach and (G2) academic and industrial works that include use cases and implemented blockchain systems for supply chains. G1

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can be further subdivided into categories based on the thematic taken in each article whereas the systemic works of G2 are subdivided into academic and industrial applications. A summary of these subdivisions is presented in Table 1.

From this table, we notice that blockchain-based use cases and system proposals for supply chains, both from groups G1 and G2, compose the bulk of the reviewed literature. That should not come as a surprise, since, as we have outlined already in the introduction, the technology offers a number of properties automatically (or by design) that find immediate application and improve the management of a supply chain (for example, the traceability property). This applicability is apparent across multiple industries, from food industry and pharmaceuticals to manufacturing and insurance services. In Table 2, we summarize the industries that have adopted blockchain technology for instances or parts of their supply chains. We divide the found use cases into two categories, namely the theoretical papers (including works from subdivisions G1A and G1B) and implementation papers (including works from subdivisions G2A and G2B). From this table we conclude that, although there are a few industrial applications where the blockchain adaptation seems to gain some significant ground, the technology has potential and can benefit the management of supply chains across many and diverse industries and services, either by providing theoretical discussions on the subject, or by proposing a blockchain-based system.

A. BLOCKCHAIN-BASED CONCEPTUAL SYSTEMS AND USE CASES (G1A & G1B)

The scientific world has shown a lot of interest in the blockchain technology and its application to supply chains [20]–[33]. None of these works, however, provide any technical details about their proposed system, nor address the characteristics and development issues of integrating blockchains and other technological tools (such as sensors, RFID tags, IoT configurations etc.) in supply chains, and use those as black boxes. This seems to be, nevertheless, a dominating research approach when it comes to asking the question *"How can a blockchain system be applied on a supply chain?"*.

In particular, some works [22], [25], [27]–[32] identify and discuss the different types of agents (or roles) at the different stages of a supply chain; such roles are physical entities or organizations/companies that can register or/and access information in the system. In the real life of a company, these agents can count in the dozens, creating a large and complex network of co-operations, dependencies, transactions and supplies. The majority of the existing scientific/conceptual works, however, take a rather abstract approach, where they only consider a handful of roles - namely those of the end consumers, the retailers, the suppliers etc., - in order to showcase the applicability of blockchains. From this we conclude that, although these approaches are too simplistic to realistically assist any company appreciate the benefits coming from adopting a distributed ledger technology for their supply chain, they do identify that most supply chains have a large portion of common and overlapping roles, actions and functionalities that can be implemented on a blockchain along with the use of some tool, such as RFID tags. A more technical approach is taken in the work of Leng et al. [33], where the focus of the paper is to propose a double chain architecture, where the activities of the different roles are divided between two chains.

The use cases discussed on a conceptual level [20]–[27] are application scenarios of supply chain examples where proposed frameworks or abstracted ideas of blockchain configurations could be applied. Usually, these use cases don't describe the complete network of a supply chain, rather they focus on a small branch of it, in order to showcase the applicability of the technology. For example in [22], the ready manufacturing concept uses as an example a short branch in the production of card-boxes, where the different stages of the process are identified (such as forestry, paper manufacturing, waste management etc) and the various actions between these stages are discussed in terms of the blockchain technology. In [27], a use case in textile industry is sketched and the various stages of processing yarn to creating and selling clothes are discussed in terms of integration in a blockchain. Following a similar approach, in [25] the authors sketch the process of acquiring and assembling parts for aircrafts on a blockchain.

In some cases, the actual supply chain and its integration on the blockchain is not even discussed; rather, a more philosophical approach is taken. For example, in [24], the authors consider the application of the blockchain in a chain of businesses (B2B supply chain) and discuss the benefits of applying the technology in this particular use case. In [21], the authors discuss the potential of applying blockchain technology for greening supply chains, and identify a number of use cases where this application could be beneficial, from vendor and supplier selection, to purchasing, material management, marketing, waste management and eco-design systems.

In [20], [23], [26], the authors review various use cases of supply chains and critically investigate the impact of integrating blockchain and other technologies. In particular, in [26], the authors review use cases of blockchain technology in food supply chains, they identify the various agents and stages of the process that could be integrated in the technology and review relevant implementations or examples of the real world (we discuss those in Section IV-B). In [20], authors present four use cases - namely paperwork processing, fraud, origin tracking and IoT operation - where the use of blockchain technology could contribute to improving them. The work focuses mainly in capturing the perspective of manufacturers and industry partners in the application of the technology to each of these four use cases. Finally, in [23], the authors review four use cases in the dairy food industry and through a number of interviews with industry partners, they identify boundary conditions that need to be met before blockchains can be successfully applied. The key boundary conditions found are related to the standardization of traceability pro-

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Group	Subdivision (code)	Papers
G1	Conceptual use cases (G1A)	[20]–[27]
	Conceptual system proposals (G1B)	[22], [25], [27]–[33]
	Adoption Requirements & Challenges (G1C)	[20], [22]–[24], [26], [34]–[36]
	User Perspective (G1D)	[37], [38]
	Adoption Facilitators & Benefits (G1E)	[20], [21], [24], [26], [27]
G2	Academic applications & use cases (G2A)	[15], [39]–[45]
	Industrial applications & use cases (G2B)	[46]–[69]

TABLE 1. Thematic categories identified in the body of reviewed papers

Supply chain type	Conceptual Papers	Implementation Papers
Aviation Parts	[25]	-
Businesses	[24]	-
Carboxes	[22]	-
Clothes & Textiles	[27], [29]	-
Diamonds / art / valuables	-	[49]
Drugs & Pharmaceuticals	-	[50], [52], [61], [68]
Food & Agriculture	[23], [26], [30], [33], [35]	[42], [45], [48]
Generic or not mentioned	[31], [32], [54]	[15], [41], [43], [44], [47], [51], [53], [56], [69]
Insurance	-	[60]
Laptop Parts	[28]	-
Manufacturing	-	[63]
Shipping & Transportation	-	[40], [46], [58], [59], [62], [64]–[67]
Trade finance	-	[57]
Wood	-	[39]

TABLE 2. Types of supply chains discussed in the reviewed literature.

cesses, quality requirements and compliance among all parties involved with the supply chain (we discuss those and other challenges in more detail in the following paragraphs).

B. APPLICATIONS AND USE CASES FROM INDUSTRY AND ACADEMIA (G2A & G2B)

There is a clear distinction between the implemented applications coming from academia and those coming from industry. On the one hand, the academic literature [15], [39]–[45] focuses on clearly defining the problems arising in the supply chain, then proposing a blockchain-based solution that addresses those requirements. On the other hand, most of the resources found regarding industry applications [46]–[69] have the ambition to make a strong case for sales, or simply announce the incorporation of blockchain technology by some company. Most commonly, they don't disclose the details of the system, and only a few aspire to build open ecosystems around open sourced protocols. On top of this, the industrial approaches put significant emphasis on making the design adoptable, compatible with current IT solutions and financially feasible across all applications.

In both approaches, nevertheless, there are certain properties of the blockchain technology, or opportunities - such as traceability, anti-fraud, trust management, transparency and IoT integration - around which the practitioners and researchers base their adoption of the technology to a supply chain and focus the description of their system.

Traceability/Provenance The most frequent use case for blockchain technology is undeniably the traceability of the product life-cycle throughout the supply chain. This is apparent across all industries, but is especially important in the food sector. In the case of Walmart [48], the transparency of the supply chain is not only a major way of preventing food-borne illness outbreaks, but also a tool to satisfy the increasing awareness around provable food quality, sustainability and fair trade. Similarly in medicine, PharmaTrace [68] claims to bring a combination of R&D knowledge sharing and auditable supply chain management solution to the same platform. Mediledger [50] provides a product verification system fulfilling the Drug Supply Chain Security Act in the US. It states that all prescription medicine returned to distributors must have their unique product identifiers verified with the manufacturer before being resold. Modum's [52] product aims to comply with the Good Distribution Practice (GDP) regulation's requirement of a proof that shipped medicinal products have not been exposed to conditions compromising their safety. This is currently done via expensive temperature-controlled vehicles, but Modum supplies a portable device that can feed measurements throughout transportation. The data is stored on the device until the receiver transfers it to their phone via Bluetooth, then registers it on the blockchain.

In the shipping industry, probably the most recognized blockchain solution is TradeLens [46], the result of a collaboration between IBM and Maersk. It is advertised as an open initiative to solve the lack of collaboration between different stakeholders involved in the journey of a shipment, providing a foundation of trust and breaking down information silos. It traces products from the time they are loaded onto a

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container until they arrive to the customer, registering various shipping events from numerous parties. OpenPort [62] and ShipChain [59] provide a similar solution, with the latter also incorporating a geofencing functionality. Wu et al. [40] aims to achieve near real-time visibility during the physical distribution of the products in the supply chain. These are usually tracked by a single source - the carrier - but there is often no information for the other stakeholders, and when there is, it cannot be validated by an independent party. In the transportation sector Helo et al. [15] propose a blockchain based logistics monitoring system for parcel tracking.

With the exception of Figorilli et al. [39] - who proposed a system tracking down wood from its tree form in the forest to the end product via QR codes and RFID tags as anchors - the rest of the applications in this category intend to stay industry agnostic, serving as a more generic solution. SmartLog [69], Ambrosus [54], PeerLedger [56], OriginTrail [47] and Provenance [70] share the goal of offering a universal platform applicable to various industries from food through mining to automotive. The latter also makes a case for transparency being a competitive advantage by recording the journey of products along their lifetime.

Transparency and counterfeit prevention Transparency goes hand in hand with anti-fraud and counterfeit prevention. Some projects –like Guardtime HSX [61] in pharma, and Everledger [49] that started off tracking the digital twin of each diamond contributing to higher confidence in purchasing and selling such products – put heavy emphasis on these activities. Everledger has recently expanded to gemstones, minerals, insurance, luxury, art and wines. Toyoda et al. [41] describe a novel framework for post-supply chains in order to prove possession of a product. The goal is to give the customer the ability to reject the purchase of counterfeits even with genuine RFID tag information if the seller cannot prove the ownership.

Trust management In some use cases, the focus is to achieve an accessible, trusted single source of truth across different stakeholders. A good example for this would be Insurwave [60], the joint project of Guardtime[3] and EY[4]. It automates the insurance process to meet the needs of the digital age with managing dynamic risk. Other applications are also aiming to automate the manual paperwork. CargoX [58] and CargoCoin [64] are heavily invested in digitizing the bills of lading documents, which are one of the main sources of inefficiency in modern shipping administration. On top of this, Skuchain [51] also offers the Empowered Collaborative Commerce Cloud (EC3) that claims to be the Swiss army knife of supply chain software. Providing a broad range of solutions – such as inventory tracking (the transformation of sub-assemblies, parts and raw materials used to make a finished product), digitizing invoices and other currently physical documentation. Morpheus.Network [57] approaches the technology from the trade finance perspective. They built a platform that allows rapid payment and conversion of funds through various partnerships at real world exchange rates, while incorporating a single network fee. It integrates with payment (SWIFT, Ripple, Stellar), transportation (FedEx, UPS) and CRM services (Salesforce). SyncFab [63] aims to use idling machines and connect available manufacturing capacity with production demand. The Fr8 network [65] connects carriers and brokers improving shipment coordination and management, adding tracking utilities. NextPakk [66] attempts to solve the last-mile logistics problem through the shared economy model similar to what Uber introduced to the taxi world.

Blockchain and IoT More and more researchers and practitioners realize how IoT and blockchain technology complement each other. In one example, Caro et al. [42] propose a traceability solution in the agri-food sector integrating IoT devices feeding onto and consuming from the chain. Similarly, Riddle & Code [53] offer - among many other products - NFC tagging then blockchain enrolling. A recurring theme in the literature is that the data on chain is as good as the data recorded. RFID tags and QR codes are notoriously unreliable trust anchors, and this is what Waltonchain [55] strives to fix. They developed a secure two-way authentication RFID design - with integrated encryption logic - that they claim to be tamper proof. The sensor itself can act like a node, and directly upload to the chain, making IoT measurements (temperature, humidity etc.) significantly safer. Machine-chain communication is also what SKYFChain [67] focuses on, creating a platform between unmanned autonomous vehicles and businesses. Finally, Malik et al. [44] argues that blockchain alone cannot support the trust and reliability of data stored on chain regarding the quality of physical commodities and the trustworthiness of supply chain entities. They aim to provide an automated framework to associate a trust value to each supply chain event based on the trust value of the participant and the quality of the commodity.

1) Design Decisions

A popular approach in incorporating distributed ledger technology in the supply chain is to build on top of an established blockchain platform. Even though the argument behind the choice of a specific implementation is usually not discussed in detail by the resources examined, the different use cases will be reviewed around recurring patterns in design decisions. The platform choice, very often, dictates by design the permission rights of the used blockchain system. For example, the systems implemented on the Hyperledger Fabric are primarily private, in the sense that only parties with granted permission can enter and audit data on the chain. Although such system design choices are counterintuitive for a blockchain technology, they allow the different partners involved in a supply chain to comply with agreed rules, establish transparency in their transactions and increase a sense of trust among them for their businesses. Public, or permissionless, systems, on the other hand, permit every

[3]https://guardtime.com/portfolio
[4]https://www.ey.com/en_gl/blockchain

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Platform Configuration	Ethereum	Hyperledger Fabric	Platform Agnostic	Stellar	Unspecified
Permissioned	[50]	[43], [44], [46], [48], [49], [56], [67], [69]	[51]	-	[70]
Permissionless	[15], [39], [59]	-	[47]	-	-
Hybrid	[41], [54]	-	-	-	[40]
Unspecified	[57], [58], [62]–[64]	[68]	[42], [45], [52], [55], [60], [61], [65]	[66]	[53]

TABLE 3. Platforms and permission rights for the implemented applications and use cases (Group G1)

entity, either it is part of the supply chain or not, to interact with the blockchain entries. In the middle of these two design choices, some applications choose a hybrid system, where the data entry part is private to the partners involved in the supply chain interactions whereas all data and information on the chain is then available for auditing by the greater public. We summarize these choices in Table 3.

Hyperledger Fabric and Permissioned systems Supply chains involve high volume of commercially sensitive data of different stakeholders. [71] argues that permissionless blockchains are unlikely to become a good basis of GDPR compliant systems. They discuss several ways of incorporating privacy, out of which the two most frequently used are the recording of off-chain data hashes and role based access control – the latter being the major reason why permissioned ledgers gained popularity in the commercial scene. The widespread implementation Hyperledger Fabric is used by various industries from tracking food [48] to diamonds [49]. Fabric has two main features supporting the storage of data privately, both of which being extensively used by TradeLens [46]. Firstly, channels provide a separation between different ocean carriers, while authorities and other stakeholders can join multiple channels. Secondly access control lists (ACL) add granular data access rights based on the role of the specific participant in the system. Also built on Hyperledger Fabric, [44] propose an additional so called reputation and trust module to the supply chain. It updates trust profiles of supply chain entities and commodities upon each chain event across their lifetime.

Ethereum and Permissionless systems Multiple projects opted to develop on the Ethereum network. [15] presents a popular architecture with the clear separation of blockchain and application layers. The client is connected to a web service that is responsible for caching transactions, for performing queries and maintaining an up to date state of the distributed ledger. It is connected to local Geth[5] node, which serves as a bridge between the application and the rest of the nodes. Some projects [57], [58], [62]–[64] take an extra step in the integration with Ethereum, and offer an ERC-20 / ERC-223 compatible token, that is not only useful for value transfer, but also for covering transaction costs on the public blockchain. [41] argues that a purely permissionless system is incapable of preventing counterfeiters to impersonate any company. They claim it requires a centralized, trusted third party to enroll a manufacturer, resulting in a hybrid approach regarding the openness of the system. Others integrate with cloud services in order to solve the off-chain data storage, e.g [39] runs on the Azure Blockchain Workbench, while [46] is backed by IBM cloud services.

Blockchain agnostic systems With the rapid development of distributed ledger technologies, some projects [42], [52], [60] decided to remain blockchain agnostic. Staying agnostic brings the advantage of avoiding vendor lock-in, the possibility to upgrade to a better implementation, and the flexibility to integrate with multiple networks in the fragmented landscape of distributed ledger technologies. Skuchain [51] claims to achieve reliable access control on various blockchains, from Hyperledger Fabric to Ethereum or Corda. Ambrosus [54] built their own protocol on Ethereum and IPFS, with an ERC-20 token AMBER. The tokens are so called data-bonded, meaning that they are reserved with each batch of products and follow them along the production chain. They split and merge with the materials and components until they reach the end of the supply chain. End customers can claim these tokens which incentivizes the purchase of Ambrosus tracked products and tokens to be recycled. They claim initially all data is private, and no entity can view these records. However it can be shared with different peers, or can be made public for all users of the AMB-NET network. OriginTrail [47] states that there is no standalone decentralized solution - distributed file storage (IPFS), distributed database (BigchainDB), blockchains (Ethereum, IOTA) - suitable for interconnected supply chains at the time of writing. At least not one that satisfies the performance, scalability, cost-effectiveness and trust requirements. They propose creating a distributed network of entities, where the dynamic data of transactions are stored off-chain on the different stakeholders' own servers. When they transact, they agree on the dynamic content via zero knowledge proofs. External auditors can also participate in this agreement and provide their own confirmation. Then the confirmed transaction's hash is stored on the blockchain, for data integrity. The network and the protocol stays the same regardless which implementation is integrated. For storage they use graph databases and replicate parts of the graph across different so-called data holders, increasing resiliency against single point of failure. The data storage, the consensus and replication checks consume processing power, thus participation needs to be incentivized by introducing a token to the system.

Multi-chain architectures Another way of tackling the scalability and privacy challenges is to utilize multi-chain archi-

[5]https://geth.ethereum.org/

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tectures. [40] creates private sub-ledgers for each shipment involving the trading partners. They are connected via a public ledger containing the private event hashes as well as tracking information of all trucks associated. ShipChain [59] follows a similar approach, incorporating a side chain that stores transport information as encrypted, owner controlled data. SKYFChain [67] has a three layered architecture. A permissioned ledger (Hyperledger Fabric) operates as a top level trusted environment storing platform related data (i.e, device, licensing, operator, authority and financial). The secondary network runs on the Ethereum platform with an ERC-20 compatible token, while the tertiary network is necessary to store and process device telemetry and in-flight information. Scalability and privacy are not the only concern when working with distributed ledgers. [43], in order to overcome the latency issues of current Proof of Work based blockchains, it applies a two step block generation approach. It maintains two ledgers, one for storing actual supply chain records, and one for reserving the blocks necessary for it. By doing this, they shift the latency of adding a new block to the reservation process. Waltonchain [55] brought customization one step further. In their setup the parent chain is a mod of Ethereum with a new consensus protocol called Proof of Contribution. It connects different child chains (e.g Ethereum or Hyperledger Fabric) creating inter-ledger consensus and making it possible to work across chains. They claim theoretically endless scalability, since the number of child chain hierarchies are not limited. While the main net is a public chain open to everyone, child chains are implemented according to industry requirements, and are not necessarily public. Their development depends on the desires of the data rights' holders.

Solution scope The majority of the listed projects is aiming to only extend the current supply chain technology and not to replace the entire software stack. The common idea is to provide a shared platform bridging isolated data silos. The main difference is on what abstraction level the connection happens. For example, the TradeLens platform [46] does not directly comply to any current system's interface, but provides an open API that can be easily integrated by implementing a connector for the already in-use modern supply chain management software. Others [50], [51], [56] aim to directly extend current ERP solutions, adding just an additional layer on top in order to join the network. Waltonchain [55] takes this idea one step further, and bridges different blockchain platforms to create a shared indexing framework where blocks can refer to any other blocks in the system. Some projects also extend the platform with user facing web or mobile clients to provide a fully fledged end-to-end solution. This usually requires some sort of application service, as described in [15].

There are a few use cases that are not attempting to ship a widely scoped product for the entire supply chain but focus on one element of it. [44] proposes the previously mentioned trust framework that is in theory applicable to various blockchain implementations. Gao et al's two-step block generation protocol [43] aims to solve latency issues specific to recent blockchain implementations. Multiple projects have also developed hardware products. Modum [52] built a temperature measurement device that operates offline and syncs up to a blockchain network when the transportation is complete. Waltonchain [55] developed a technology which claims to make RFIDs tamper proof.

Project scope	Papers
End-to-end software	[15], [39], [46], [51], [52], [54], [57]–[59], [62]–[65], [65], [66]
Platform	[40], [41], [47], [50], [55], [56], [69], [70]
Concept technology	[43], [44]
Unknown	[42], [45], [48], [49], [60], [67], [68]

TABLE 4. Scope of blockchain projects in supply chain.

State of the projects Most of the use cases we encountered in the academic literature are proof of concept works that have been tested in lab, ranking those as *non-mature* use cases. Some of these works often disclose a performance metric based on which they run their lab tests. For instance, in [40] the authors identify scaling issues caused by block collisions and forks. In another instance, [41] analyzes gas costs required by every transaction. Even though the gas price increases with each transaction, it stays under 1 USD for six transactions, which is deemed tolerable for medium priced items. The benchmarks proposed in [42] result in Sawtooth outperforming Ethereum in all measured metrics. It is also noted that Ethereum's Proof of Work does not go well with low power IoT devices and edge gateways. In [44], the authors note that the extra layer of computing reputation for different parties adds a minimal overhead to each event, which affects the latency significantly when transaction rate is approaching 100 tps. An increase of the chain throughput by means of decreasing the latency of the block generation is addressed in [43]. Since the block reservation step is not considered in the test measurements, the authors claim to achieve higher throughput than other PoW chains with 40 transactions per second for 100 nodes.

Adoption of new technologies in the industry usually starts with a pilot project involving only a fragment of the complete set of stakeholders. Chronicled [50] is finishing Mediledger's first pilot as of writing, with over 25 companies. They report having a sub 300 ms lookup time among geographically diverse nodes within the network. If the item is not found in the system, it connects to external validation providers with increased response time of around one second.

Finally, there are several companies utilizing distributed ledger technology in production. From this pool of initiatives, one that distinguishes itself as the most mature implementation, is the IBM projects in collaboration with Walmart and Maersk. Walmart's [48] food traceability endeavor first piloted in 2017, and is in production since 2018. They claim to reduce 7 days of back-tracing the source to approx 2 seconds. TradeLens [46] now involve the four largest global

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carriers. They claim the system handles 10M events and 100k documents each week.

Project maturity	Papers
Production	[46]–[48], [51], [52], [55]–[59], [62], [70]
Pilot	[39], [50], [54], [55], [60], [69]
Proof of Concept	[15], [40]–[45], [63]–[68]

TABLE 5. Maturity of blockchain projects in supply chain.

C. ADOPTION REQUIREMENTS AND CHALLENGES (G1C)

It is undoubtedly a long and uncertain process the adoption of a new technology in the industrial and financial world. No matter the nature of the organization, such entities are creatures of habit, and attempting to learn an old dog new tricks takes significant effort. Likewise, for the industrial world to change their current status quo for their supply chain implementation, significant effort needs to be made for the necessary requirements to be met and the adoption difficulties to be addressed and overcome. Thankfully, this issue is tackled in more and more works that are considering the application of blockchains in supply chains [20], [22], [23], [26], [34].

The adoption challenges discussed in these works can be divided in two categories: those that are technical and native to the limitations caused by the current state of the blockchain technology, and those that are related to the industry perspective and policy making (Table 6).

With regards to the technical challenges and requirements, a key issue is data security and user privacy. This, along with the limitations of IT infrastructure, especially for small and medium enterprises, are the main technical reasons causing reluctance among industry partners and making them hesitant in applying blockchain technology to their use cases. Specific to the integration of supply chains, mainly between businesses, the authors in [24], are investigating the functionalities and requirements of their potential blockchain-based systems. They point out the inefficiency of the current status quo among businesses and banks and how most of the expected requirements and functionalities for their transactions and supply chains, are already offered by the blockchain technology, at lower costs and faster speeds.

Another main issue is the known scalability problem of blockchains, which limits the amount of transactions and information that can be stored and processed in a short amount of time, with the current available infrastructure. Given that most industries form part of large and complex networks, the current state of the blockchain technology creates uncertainty with regards to the size and complexity of use cases that can be *currently* implemented. However, as we discussed in the previous section, real-world attempts to adopt the technology in the industrial world (e.g., [46], [48]) are working towards faster transactions and higher throughput. In [22], the need for in system implementation of the smart contracts and the constant updates of the digital profiles, have been identified as technical issues that impede the application of blockchains in manufacturing supply chains. A key issue, especially in the food industry, is the linkage between a physical product and its digital record [34] and the technological tools that can help overcome this problem (such as paired RFID tags).

Moving to barriers and requirements from the perspective of the industry partners and policy making, one of the key issues is the reluctance from the industry and finance parties to adopt the technology, partly due to the technical limitations we sketched in the previous paragraph and partly due to the declining reputation of the technology which is linked to cryptocurrencies. Because of the distributed nature of the technology, its success heavily depends on compliance and general agreement between the different parties involved with the supply chain. More than often, this implies a heavy dependence on blockchain operators, as well, and a strong requirement of trust between the different parties and between the industry and the technology itself. Even though, from a scientific point of view, such issues are reasonable requirements rather than challenges, it is understandable that the industry and financial sector are concerned with all these dependencies.

Lack of regulations, unclear benefits as well as the communication barriers between technical experts and policy makers are key issues that do not facilitate the adoption of the technology. Significant barriers exist because of the lack of sufficient educational and training platforms, for non technical experts to familiarize themselves with the operations and benefits of blockchains, as well as because of the digital divide between developed and developing worlds, where already different standards exist in most aspects of modern life. In the intersection of technical and non technical barriers, we highlight that the lack of standardization of traceability and certification processes as well as of quality requirements, in the digital world, coupled with the aforementioned lack of regulations and related policies, are stressful barriers that slow down the acceptance and adoption of blockchains in supply chain instances.

D. USER PERSPECTIVE (G1D)

A different approach is taken in works such as [37], [38], where the perspective of the users is sketched. In [37], the authors use the Unified Theory of Acceptance and Use of Technology (UTAUT) to assess the acceptance of users of blockchain technologies in supply chain traceability applications, and find that this depends on the technology's performance expectancy, the expectations regarding the users' own efforts, the facilitating conditions, the social influence as well as the users' own behavioural intention. In [38], after surveying about 180 practitioners of the supply chains in India, additional concerns were found regarding discomfort about understanding and learning how to use the blockchain technology, insecurity in terms of the transactions and the different parties of the network that have access to it, the users' perceived (non) ease of use (obviously stemming from

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Technical	Data security & Privacy Issues	[20], [24], [26], [36]
	Lack of technical maturity	[20], [22], [24], [26]
	Flexibility in design decision for complicated supply chains	[26], [34], [36]
	Storage & Latency of transactions	[26], [34]
	Performance capability	[22], [26]
	Digital Integration	[24], [36]
	Link between physical product and digital record	[34]
	In system implementation of smart contracts	[22]
	Constant updates of digital profiles	[22]
Industry & Policy making	Reluctance from industry and finance partners	[20], [22], [26]
	Compliance between different parties	[20], [34], [35]
	Lack of regulations	[20], [26]
	Lack of understanding between policy makers and technical experts	[24], [26]
	Standardization of quality requirements	[23], [26]
	Unclear benefits	[20]
	Dependance on blockchain operators	[20]
	Standardization of traceability processes	[23]
	Limited educational and training platforms	[26]
	Digital divide between developed & developing countries	[26]

TABLE 6. Summary of adoption challenges

the lack of education) and how useful they consider the technology (again, due to limited information on the subject and declining reputation of blockchain-based cryptocurrencies).

E. ADOPTION FACILITATORS AND BENEFITS (G1E)

The adoption of blockchain technology in supply chains has a number of benefits, summarized next. Two very important, well-known and obvious benefits concern the ease of managing the vast amount of paperwork and tracing of products origins offered by the automated and transparent nature of the technology (we remind the reader here the increased throughput and improvement in transactions in the case of TradeLens [46]). Beyond these two advantages, the authors in [20] discuss how the technology can assist in identifying fraud cases and counterfeit products, but also the facilitation of using the Internet of Things, by allowing the connection of sensors and digital devices that take part in the various stages of a supply chain. The technological benefits of the integration are well discussed in [24], highlighting the track of changes on the chain, the interoperability of the systems, the monitoring and control of the various services along the chain, cloud security and secure real time connectivity, real time sharing of information with partners, control of user identification etc. We include all these under the umbrella term "Benefits stemming from blockchain functionalities", in our summary of benefits:

- Benefits stemming from blockchain functionalities
- Consumer awareness
- Decrease of paperwork processing cost and time
- Facilitate IoT
- Facilitation of transactions in developing countries
- Fairer pricing
- Identify fraud and counterfeit cases
- Platform for emission reduction
- Support and Insurance to SMEs
- Tracing product origins
- Waste management

A number of conceptual papers are proposing systems, discuss use cases or address issues regarding the adoption of blockchains in supply chains with a focus on assessing one or more blockchain properties and functionalities. Apart from the already mentioned ones, in Table 7 we summarize what are the properties and functionalities most researches focus their assessment on. The possibility to trace the products, especially food, and the quality management from the production of the items to their delivery, storage and sale, are the key properties that encourage the adoption of the technology in supply chains. The potential to publish all information regarding the products, their production processes etc. both between the parties involved in the different stages of the supply chain, but also between the industry partners and the consumers, has the power to create a secure and comfortable relationship between consumers, producers and manufacturers. Blockchain technology allows for different types of trust to be satisfied. Fraud and counterfeit cases can be detected, any attempts to temper with the ledger can be identified and all transactions are transparent, by default. The case of double marginalization is also discussed in literature as one of the key reasons that blockchains can improve manufacturing supply chains.

Property	Papers
Quality Management	[25], [28], [30], [31], [35]
Traceability	[23], [30], [31], [35], [37]
Information Sharing	[28], [32]
Trust	[35]
Transaction Transparency	[36]
Double Marginalization	[32]

TABLE 7. Blockchain properties and funcionalities that supply chains can take advantage from

A number of additional adoption opportunities and benefits are outlined in [26], including: (i) public access and

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control of the supply chain, as well as the reduction of the cost of maintenance of the current supply chains, can lead to fairer prices of products across the market, (ii) small enterprises, farmers and producers will feel more secure and well supported, (iii) facilitation of transactions and fair trading in developing countries.

Finally, a couple of works are considering the environmental benefits of the technology, such as waste management. In [21], the authors discuss opportunities for greening supply chains and enumerate the various use cases that facilitate it. In [27], the decrease of carbon emissions are considered as one of the goals for using blockchain technology for a textile supply chain.

V. DISCUSSION

From the analysis conducted in the previous paragraphs, we summarize the following key findings with regards to the research questions posed in Section III concerning the applicability and application of blockchain technology in supply chains. Those are highlighted as well in Table 8.

RQ1[6] From the papers we mined for our review, we conclude that the existing literature (with the broader sense of the term, in order to include project descriptions) can be classified in three large groups: (a) theoretical analyses that address the benefits, the challenges and/or the limitations of the technology being applied on supply chains (c.20% of the reviewed literature), (b) conceptual systems for case studies or to showcase the applicability of the technology (c.38% of the reviewed literature) and (c) implemented systems for industrial case studies (c.41% of the reviewed literature). Although it is undoubtedly necessary to conduct abstract analyses of new technologies and their applications in real life scenarios, there is an obvious lack in technical works on the subject. That is either because the industries applying the technologies are being silent with regards to the technical details, or because the scientific community researching the subject is mainly coming from the business and financial sector and have limited interest or knowledge on the technical details of the system.

RQ2[7] As shown in Tables 2 and 9, distributed ledgers can be applied to a large variety of industrial supply chains but also to business-to-business networks. In terms of industrial supply chains, the food, pharmaceutical and shipment sectors are the dominating use cases. The reason for this is twofold: firstly, it is the sensitivity of the products that requires advanced and secure means of production and transfer and secondly, blockchain technology facilitates the traceability of the products, which is even more vital nowadays for edible products, due to the increased attempts of fraud.

RQ3[8] There are nowadays tenths of use cases or implemented blockchain-based systems in industry to learn from, although only a part of them have published their technical choices and implementations. As discussed in our analysis and shown in Tables 3, 4, 5 and 9, many implemented systems utilise the Ethereum or Hyperledger Fabric platforms for their systems, however a large number chooses to be platform agnostic so that multiple and various technologies can be incorporated in the system. In terms of permission rights, most implementations leave that technical detail unspecified, even though it is a crucial one. We next found that most implemented systems use the blockchain technology for an end-to-end implementation of their supply chain. Another promising finding is that, although there are many works at the level of proof of concept, the number of systems at production stage are not negligible – here we should again highlight that the actual number of implemented systems is larger than the reviewed one, due to the large number of industries that do not share their technical details and are therefore excluded from studies such as ours.

RQ4[9] The benefits from adopting distributed ledger technologies to supply chains are various and numerous, as discussed in our analysis and summarized in Subsection IV-E. The benefits span from decreasing management and transactional costs, to tracing fast and accurately frauds and counterfeit cases and from supporting and insuring SMEs to environmental benefits.

RQ5[10] The adoption challenges and limitations of the technology, at the current state, as they result from our analysis, are shown in Table 6. As we show there, those belong to two categories, the technical ones and the ones coming from the industry and policy making. We feel that in either case, such challenges should not be received by the research and industrial communities as obstacles, rather as opportunities to improve the technology (by solving the scalability problem for example, irrespective of the application of the blockchain technology) and to standardise procedures and increase education and awareness to a broader audience. Such awareness need not be just technical but also to increase understanding of business procedures, policy making and the opportunities offered in the new digital era.

RQ6[11] Incorporating new technologies is one of the modern ways used by companies and organizations to increase both their capital and their popularity. The blockchain technology, for reasons highlighted in this document, has gained a lot of attention in this respect, as its properties and innate characteristics find direct application to manufacturing supply chains.

From the analysis presented in this survey, we sketched a number of issues that are yet to be solved. We group such issues in two categories: firstly, technical limitations of the distributed ledger technologies (and especially of the blockchain) that need to be addressed irrespective of the ap-

[6] What are the existing research approaches on the subject of blockchains for supply chains?

[7] What type of supply chains can be implemented on a distributed ledger?

[8] What are the existing blockchain-based supply chain implemented systems? What are their design choices and technical characteristics?

[9] What are the benefits from the adoption of blockchain technology on supply chains?

[10] What are the challenges to be addressed?

[11] What are the current research gaps and open problems?

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Research Questions	Key findings
RQ1: Existing research approaches	(a) Theoretical analyses (20%) (b) Conceptual systems for case studies (38%) (c) Implemented systems for case studies (41%) Observation : there is obvious shortage of comprehensive technical works on the subject
RQ2: Types of supply chains	Variety of industrial supply chains (e.g., food, pharmaceuticals, shipment) and business-to-business networks See Tables 2 and 9
RQ3: Existing implemented systems and their design choices	Proof of Concept (42%) Production (38%) Pilot (19%) Ethereum platform (33%) Hyperledger Fabric (27%) Agnostic (27%) Unspecified permission rights (45%) Permissioned (33%) Permissionless (12%) See Tables 3, 4, 5 and 9
RQ4: Adoption benefits	Blockchain functionalities Facilitate IoT Identify fraud and counterfeit cases Platform for emission reduction Support and Insurance to SMEs Decrease of paperwork processing cost and time Facilitation of transactions in developing countries Consumer awareness Fairer pricing Tracing product origins Waste management
RQ5: Challenges to be addressed	(a) Technical challenges (e.g., blockchain scalability issue) (b) Industry and policy making (e.g., procedure standardization) See Table 6
RQ6: Open problems	(a) Technical limitations of distributed ledger technologies: - Scalability issue - Interoperability between various platforms - Integration of IoT - Immutability and control of off-the-chain tasks (b) Digitalization of supply chains: - Formulation of regulations and policies - Link between physical and digital product - Standardization of traceability and quality certification

TABLE 8. Summary of the key findings to the research questions RQ1-RQ6

plication of the technology and secondly, issues arising from the digitalization of supply chains and their implementation on a distributed ledger. These issues are potential research directions so that the field can advance significantly in the near future.

The main technical limitation of the current state of blockchains is the scalability issue, severely affecting cryptocurrency applications. As shown earlier, in a supply chain applications there are instances where new systems with high throughput and low latency are implemented (e.g., [46]). This is a promising attempt to make the blockchain technology flexible and even more efficient for real life applications. We believe that such limitations and preliminary results should be viewed as opportunities for further research and not discouraging factors. Moreover, the interoperability between the various platforms needs to be addressed, as this would allow companies with existing blockchain-based systems and implementations of different platforms to cooperate without neither party having to change their status quo. The integration of IoT and formulation of regulations and policies are issues that need to be addressed widely for all applications of blockchains so that the technology is not viewed merely as a hype by the non-experts but as a standard choice for future industrial, governmental and financial transactions.

Specific to the supply chain application, the most crucial challenge to be addressed is the link between a physical product with its digital record so that the quality and origin of the product can be authenticated on the chain. As discussed in the previous sections, a lot of implementations choose to leave certain data sharing tasks off-the-chain. It is necessary, therefore to make the design details of this choice controlled and immutable. The standardization of processes, and especially of the traceability and certification of quality at the various stages of food supply chains, are issues that need to be addressed in manufacturing supply chains, irrespective of the implementation. It is however noted that distributed implementations through the use of technologies such as blockchain would facilitate and speed up the procedures towards standardization.

VI. CONCLUSIVE REMARKS

A decade after the publication of Bitcoin [1], the blockchain technology is starting to hesitantly enter the industrial domain with the goal to take over manufacturing supply chains. In this paper, we survey existing literature from academia, but more importantly from industrial practices and use cases, in order to assess the applicability and existing applications of blockchains in the supply chain domain, the stage of research and the maturity of the projects. More importantly, our goal was to summarize the benefits and the challenges from the adoption, in order to provide a foundation for practitioners and researchers to direct their future projects towards improving the technology and its applicability. In terms of the actual implementations, we set forth to discuss the limitations of such projects and their technical characteristics. An overview of all existing use cases, whose technical details we could

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access (at least partly) can be seen in Table 9.

Overall, the application of blockchain technology in supply chains offers noumerous opportunities for researchers to address innate issues of the technology (such as scalability) and of practitioners (and the scientific communitiy in general) to bring the technology in our everyday lives and closer to the understanding and acceptance of the general public. The silence kept by most industries applying the technology with regards to the technical details of their systems is a problematic issue that only impedes the progress of the technology. As a result, most industries are hesitant towards blockchains and consider it a hype for the elit companies. Our vision is that more and more implementations will reveal their systems to the community, so that more and more companies will be persuaded to use it and governments and unions will be therefore forced to standardize its involved procedures and issue relevant policies.

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Name / Reference	Industry/ Academic	Product Type	Focus	Access Rights	Platform	Status
AgriBlockIoT [42]	Academic	Food	Traceability	Unknown	Agnostic	PoC
Ambrosus [54]	Industry	Generic	Traceability	Hybrid	Ethereum	Pilot
Aquachain [45]	Academic	Food	Traceability	Unknown	Agnostic	PoC
CargoCoin [64]	Industry	Shipping	Transparency	Unknown	Ethereum	PoC
CargoX [58]	Industry	Shipping	Not applicable	Unknown	Ethereum	Production
CoC [43]	Academic	Generic	Traceability	Permissioned	H. Fabric	PoC
Everledger [49]	Industry	Diamonds	Anti-counterfeit	Permissioned	H. Fabric	Production
Fr8 [65]	Industry	Transport	Transparency	Unknown	Agnostic	PoC
Guardtime HSX [61]	Industry	Pharma	Anti-counterfeit	Unknown	Unknown	Production
Helo et al. [15]	Academic	Generic	Traceability	Permissionless	Ethereum	PoC
Insurwave [60]	Industry	Insurance	Transparency	Unknown	Unknown	Pilot
Mediledger [50]	Industry	Pharma	Traceability	Permissioned	Ethereum	Pilot
Modum [52]	Industry	Pharma	Traceability	Unknown	Agnostic	Production
Morpheus.Network [57]	Industry	Trade finance	Not applicable	Unknown	Ethereum	Production
NextPakk [66]	Industry	Transport	Transparency	Unknown	Stellar	PoC
OpenPort [62]	Industry	Shipping	Traceability	Unknown	Ethereum	Production
OriginTrail [47]	Industry	Generic	Generic	Permissionless	Agnostic	Production
PDV [40]	Academic	Transport	Traceability	Hybrid	Unknown	PoC
PeerLedger [56]	Industry	Generic	Traceability	Permissioned	H. Fabric	Production
PharmaTrace [68]	Industry	Pharma	Traceability	Unknown	H. Fabric	PoC
POMS [41]	Academic	Generic	Anti-counterfeit	Hybrid	Ethereum	PoC
Provenance [70]	Industry	Generic	Traceability	Permissioned	Unknown	Production
Riddle & Code [53]	Industry	Generic	Not applicable	Unknown	Unknown	Production
ShipChain [59]	Industry	Shipping	Traceability	Permissionless	Ethereum	Production
Skuchain [51]	Industry	Generic	Generic	Permissioned	Agnostic	Production
SKYFChain [67]	Industry	Transport	Not applicable	Hybrid	H. Fabric	PoC
SmartLog [69]	Industry	Generic	Traceability	Permissioned	H. Fabric	Pilot
SyncFab [63]	Industry	Manufacturing	Transparency	Unknown	Ethereum	PoC
Traceability of Wood [39]	Academic	Wood	Traceability	Permissionless	Ethereum	Pilot
TradeLens [46]	Industry	Shipping	Traceability	Permissioned	H. Fabric	Production
TrustChain [44]	Academic	Generic	Trust management	Permissioned	H. Fabric	PoC
Walmart [48]	Industry	Food	Traceability	Permissioned	H. Fabric	Production
Waltonchain [55]	Industry	Generic	Generic	Unknown	Agnostic	Pilot

TABLE 9. All use cases categorized in alphabetic order

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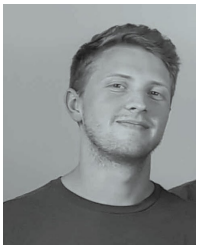

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