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/ Die Rolle von Blockchain-Technologien in der Transformation von Supply Chains in Richtung sozialer und ökologischer Nachhaltigkeit

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Zusammenfassung

Supply Chains sind komplexe Netzwerke von Akteur:innen, die an der Produktion und Lieferung von Waren an Endverbraucher:innen beteiligt sind. Die Komplexität dieser Netzwerke trägt dazu bei, dass die Praktiken entlang der Supply Chains undurchsichtig sind, was Arbeits- und Menschenrechtsverletzungen sowie umweltschädliche Praktiken während des gesamten Produktionsprozesses begünstigt. Vertreter:innen aus dem akademischen und praktischen Bereich interessieren sich zunehmend für den Einsatz von Blockchain-Technologien, um Praktiken und Inputs auf allen Zwischenstufen zu verfolgen und nachzuvollziehen. Der vorliegende Beitrag gibt einen Überblick über das Potenzial von Blockchain-Anwendungen in Supply Chains und analysiert, wie diese zur Transformation in Richtung sozialer und ökologischer Nachhaltigkeit beitragen können. Um sich dem Forschungsziel zu nähern, wird eine Synthese aus akademischen und grauen Literaturquellen durchgeführt. Der Beitrag kommt zu dem Ergebnis, dass Blockchain-Technologien Supply Chain Netzwerke in ihrem Bestreben unterstützen können, nachhaltige Produktionspraktiken zu fördern. Allerdings gibt es auch Einschränkungen, die vor der Technologieeinführung in die Supply Chain eines Produkts zu beachten sind.

Schlagwörter: *Blockchain-Technologie, Supply Chains, soziale und umweltbezogene Nachhaltigkeit, digitale Transformation*

The Role of Blockchain Technologies in Transforming Supply Chains Toward Social and Environmental Sustainability

Abstract

Supply chains are complex networks of actors involved in the production and delivery of goods to a final consumer. The complexity of these networks contributes to the obscurity of practices along supply chains, fostering labor and human rights violations, as well as environmentally damaging practices, throughout the entire production process. Academic and business organizations are increasingly showing interest in the use of blockchain technologies to track and trace practices and inputs at all intermediate steps. This paper provides an overview of the potential of blockchain applications in supply chains and analyzes how they can help a transformation toward social and environmental sustainability. To approach the research goal, academic and gray literary sources were synthesized. This paper finds that blockchain technologies can support supply chain networks in their quest to foster sustainable production practices. Yet, there are also limitations to be considered before introducing blockchain to a product's supply chain.

Keywords: *blockchain technology, supply chains, social-environmental sustainability, digital transformation*

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1 Introduction

In today's economy, supply chain networks are the epitome of globalization, connecting distant parts of the world in the extraction of raw materials, product design and development, manufacturing, and delivery—in short, the entire production process. Advances in communication and information infrastructure have facilitated the spinning of intricate webs that build our supply chains (Min et al. 2019). This same infrastructure also enables access to and the sharing of information about the origins of parts, the conditions of the involved workers, the environmental externalities, and the effects on local economies caused by the production of goods (OECD/KPMG 2019). Reports of damaging practices and inhumane labor conditions in countries contributing to global supply chains are raising public demands for the networks to be disclosed (The Economist 2020). As a regulatory response, the trilogue discussions of the European Union's (EU) legislative bodies recently reached an agreement to adopt the corporate sustainability due diligence directive (European Council 2023), initially proposed by the Commission in February 2022 (European Commission 2022).

Central to due diligence reporting is the availability of trusted and traceable information. However, as supply chains grow increasingly complex and obscure, companies struggle to access information on the origin and circumstances of production at the intermediate steps (Härting et al. 2020), especially beyond the second-tier supplier (Free/Hecimovic 2021; Ganeriwalla et al. 2018; Koberg/Longoni 2019). As Hastig and Sodhi (2020: 15) phrase it "opacity in supply chains enables the exploitation of natural resources as well as human beings." For this reason, a rising interest in blockchain-based technologies, digital tools to store and share information, safeguarding the immutability and forgery-proofness of data, can be detected (Francisco/Swanson 2018; Gurtu/Johny 2019; Min et al. 2019; Saberi et al. 2019).

This paper contributes to the existing body of literature exploring the intersection of blockchain technology, supply chains, and sustainability, and is guided by the following question: How can blockchain technology help to transform global supply chains and contribute to more environmentally and socially sustainable solutions?

To address this question, the paper provides a descriptive overview of the state of the art of blockchain application in supply chains, paying special attention to sustainability effects. To identify current technological practices, both academic and gray literary sources were consulted. In a fast-paced environment the addition of gray literature provides insights into current application trends, although the potential underlying organizational agenda must be acknowledged (Juricek 2009), as must the lack of peer-reviewed scholarly rigor (Paez 2017; Okoroma 2012).

Two broad categories of relevance can be identified. Academically, this paper adds to the fast-changing research area of blockchain technology applications. Constant updates are necessary here to broaden understanding, as rather young fields of research always require more breadth and depth. The societal relevance of this research is underlined by the public demand for supply chain transparency and socially and environmentally sustainable production practices.

The paper is structured as follows. In the first section, the background and related research on blockchain technology, supply chains, and the concept of sustainability are presented. Building on this, the discussion considers the potentials and limits of blockchain application in supply chains and analyzes the implications from a social and environmental sustainability perspective. The paper concludes with a short summary and an outlook for further investigation.

2 Core concepts

2.1 Basics of blockchain technology

As the name suggests, blockchain technology consists of individual digital items of data (blocks) that are linked together in a chronological chain. As a result, the entire blockchain generates a "database of records or a public ledger of all transactions or digital events that have been executed and shared among the participants" (Angelis/Ribeiro da Silva 2019: 308). The individual blocks contain encrypted data, a time stamp, and a reference to the previous block in the chain (hash). The visible hash in the header therefore does not convey information on the contents, but a secure link to the related block. Thus, the stored information is only visible for users with the corresponding key (Francisco/Swanson 2018). The immutability of added blocks underlines the secure character of the technology and the integrity of the stored data (Bender et al 2019; Francisco/Swanson 2018).

All network participants have access to a copy of the common blockchain, can view and, depending on the authorization process, generate data blocks that are in turn validated by a consensus mechanism (Härting et al. 2020). This results in a peer-to-peer organization without the need for a central authority (Batwa et al. 2021). Thus, among the network participants "[e]veryone can read and exchange information without a custom installation of software. This is valuable because it reduces integration needs exponentially" (MH&L 2019: 4). Blockchain solutions are subsumed within the category of distributed ledger technologies (DLTs), which involve a decentralized framework of data storage. DLT forms the "umbrella term for technologies that store, distribute or exchange, publicly or privately, value between entities/users/peers based on shared transaction ledgers" (OECD/KPMG 2019: 7).

Additional key characteristics include the availability of self-executing smart contracts, which describe practical if-then situations that fulfill themselves when initial conditions are met (Laaper et al. 2017). This is particularly beneficial for repetitive and consistent tasks, as the initial if-conditions need to be defined meticulously. Furthermore, blockchain technology enables tokenization. This practice assigns digital and non-digital assets a container to facilitate transfers of value, rights, or other information (Kshetri 2022).

Notwithstanding these valuable characteristics, several inherent weak points deserve some attention. As with any digital storage, blockchains can be subject to hacking attacks affecting the organization's cybersecurity. Furthermore, the inherent traceability of transactions could also lead to the controllability of individuals or organizations that are pseudonymized through their wallet address. If a few data points are known, it would be possible to identify the wallet address and all saved transactions. Finally, there are some data-related weaknesses. Central to this is the argument of "garbage in, garbage out," which implies that the quality of data storage and sharing along the chain is only as valuable as the input data (Bacchetta et al. 2021: 6). Blockchain-based data storage can therefore not replace the monitoring and verification of data inputs.

Initial prominent use cases of blockchain technology are the financial applications of cryptocurrencies and digital assets. In public perception, blockchain is often treated as equivalent to the cryptocurrency Bitcoin and meets with the related criticisms, including its energy intensity (Bacchetta et al. 2021). However, the technology is not limited to these but bears greater potential. Applications such as IBM's Food Trust, Everledger's diamond provenance tracker, and Plastic Bank's Social Recycling exemplify the value of blockchain in supply chain management.

2.2 Supply chains as a source of vulnerability

One commonly accepted definition describes supply chains "as sets of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" (Mentzer et al. 2001: 4). This definition entails four elements. Firstly, at the minimum, a supply chain involves a supplier, a focal organization, and a customer. However, in most cases, reality is more complex and includes multiple suppliers, such as designers and product developers, manufacturers, transporters, marketers and distributers, before a good arrives at its ultimate consumer (Rodrigues et al. 2021). The complexity of a supply chain is subject to variation depending on the type of industry and good. Secondly, both upstream and downstream activities are involved and highlight the bidirectional nature of a supply chain. Thirdly, multiple flow systems characterize the interaction and coordination of activities along a supply chain. Thus, a range of intermediate material, financial, and informational transfers precede the successful delivery of a good or service. Fourthly, the consumer plays an active role in the development and manufacturing of a product according to demand. However, a holistic view of the entire supply chain goes beyond the final consumer to include waste management, recycling, and upcycling options. This extension of the definition by Mentzer and colleagues (2001) then portrays the entire life cycle of a good and recognizes the environmental strain of production and resource extraction.

This definition demonstrates the potentially complex characteristics of supply chain networks. This complexity is heightened by larger market trends in the context of globalization. On the one hand, customer expectations and demand patterns are subject to change. One important trend is the growing demand for mass customization, as consumers call for individualized products (Min et al. 2019). Simultaneously, products are now often subject to "planned obsolescence," meaning that their life cycle is shortened and they are not made to last (Rivera/Lallmahomed 2016: 119; c.f. Christopher 2000); quick consumption and disposal are central to capitalism's success (Martin et al. 2018). On the other hand, the supply side faces a stronger granularization into single, highly specialized production steps. This development is facilitated by exploiting opportunities for economies of scale and varying regulatory frameworks with regard to labor, environmental, and fiscal standards, and making use of advances in infrastructure and telecommunication (Free/Hecimovic 2021).

Considering their centrality to the globalized economy, supply chains face a range of problems that severely complicate the work of their managers. These can roughly be broken down into two large categories. One considers internal problems within the supply chain in question, inherent in the very structure of the supply chain or the supporting network. The other considers external and environmental factors with an impact on the functioning and structure of supply chains. Table 1 summarizes these problems as identified in the literature.

This examination shows that supply chains pose a source of vulnerability. Therefore, resilience has become a central goal of supply chain managers. Resilience strategies respond to both internal and external problems, including diversifying suppliers across regions and maintaining a strategic stock (Ben-Daya et al. 2019; Free/Hecimovic 2021; Kandil et al. 2020). Consequently, regulatory changes have imposed requirements supply chain networks must follow. This is particularly difficult for supply chain regimes that stretch over the globe and must therefore respect legal frameworks in all affected regions. To fulfill this task, they must thus first gain an understanding of all intermediate steps and involved parties.

Table 1: Internal and external problems in supply chains

Internal problems	**Lack of upstream supplier visibility:** Companies rarely know the intermediate steps that precede their first-tier supplier; especially relevant in sectors where processed parts are used as input materials	Gardner et al. 2019; Härting et al. 2020; Free/Hecimovic 2021; Gurzawska 202
	Difficulty to establish trust within network: Building trust requires time and effort, for which fast-paced production is not set up; currently, trust is extended by costly third-party auditors	WEF 2012; Batwa et al. 2021; Ganeriwalla et al. 2018; Casey/Wong 2017; Min et al. 2019
	Insufficient information sharing: Companies are hesitant to share information to protect their competitive advantage; most information is shared in paper format, which makes it difficult to analyze	Biswas/Sen 2016; Hastig/Sodhi 2020; Gurtu/Johny 2019; Cabral et al. 2012; Gurzawska 2020
	Bullwhip effect: Due to information asymmetry, intermediate suppliers often purchase or produce more than is demanded; further downstream, the deviation from actual demand increases; inefficient and wasteful process	Christopher 2000; Ghode et al. 2022; Biswas/Sen 2016
	Liquidity gap: Due to the time lag of transactions, companies may find themselves in the position of having delivered their product without yet receiving the corresponding payment, which hinders their further operation	Jakob et al. 2018; Nelson et al. 2017
	Interoperability within supply chain network: Different tools and IT systems at various firms require legibility and translation to other systems	Cabral et al. 2012; Pawczuk et al. 2020
External problems	**Economic shocks:** Inflation, economic crises	Free/Hecimovic 2021; Gurzawska 2020
	Geopolitical shocks: Sanctions, (trade) wars, social disruptions, (sudden) limits to resource access	WEF 2012; WFP 2022; Free/Hecimovic 2021
	Natural events: Disruption of routes, factories, or sources of raw material, (sudden) limits to resource availabilities	Ben-Daya et al. 2019; Auffhammer 2018
	Changing demand patterns: Shift in consumer preference, change in current needs (potentially sudden, i.e., during the Covid-19 pandemic)	Min et al. 2019; Gurzawska 2020; Kandil et al. 2020

2.3 Social and environmental sustainability in supply chains

To understand a potential transformation of supply chains toward sustainability, it is important to specify how this ambiguous term is understood. In the following, the focus is on social and environmental sustainability.

Social sustainability addresses the labor conditions in the intermediate production steps, such as the extraction of raw materials on farms or in mines, in factories and on assembly lines. Adherence to minimum standards with regard to wages, working hours, and child protection is considered a prerequisite for a healthy and satisfied pool of workers, willing and able to continue to work in the future, contributing to societal well-being (Birkel/Müller 2021). Therefore, social sustainability includes the safety of buildings and infrastructure, as well as the functioning of the health-care sector. In short, everything that contributes to the continuation of the workforce and strengthens foundations of social and human capital. Additionally, social sustainability considers the physical integrity of consumers, and the adherence to safety and health standards in final products. Social sustainability is evaluated on the basis of abidance by social and labor-related standards, as well as the production of safe consumer goods.

Environmental sustainability entails both the availability of natural resources and the effect of externalities on ecosystems (Saberi et al. 2019). Manufacturing requires the input of raw materials, some of which are nonrenewable and depletable whereas others have a cycle of natural renewal, but this takes time. Subject to environmentally intense consumption behavior and short product life cycles (Christopher 2000), the speed of production often does not align with the speed of natural renewal of the resource. Moreover, all production processes have environmental externalities, which are additional effects that are not the main goal of a process. Thus, an environmental sustainability evaluation must consider both resource use and the effects of externalities.

Despite these separate evaluations, there are considerable overlaps between both social and environmental sustainability concerns. Indeed, individuals and society are subsumed within the natural environment and affected by it. For example, environmentally damaging externalities, such as contamination of groundwater, are also detrimental to the safety of workers and the local population.

3 Discussion

3.1 Potentials of blockchain in supply chains

The upstream traceability of supply chains is particularly important to track the provenance of products and facilitate recall processes in the event of shortcomings in the safety or quality of a good (Gambhir et al. 2018). The increased availability and use of information also makes it possible to limit the scope of a recall by tracing the quality impairments directly to the affected products and consumers, without needing to recall the entire shipment. In this context, the immutability of the stored data on the blockchain proves critical. Once data is added to the chain, it cannot be removed or tampered with (Paliwal et al. 2020). This renders the shared information counterfeit-proof. Nevertheless, there still need to be mechanisms to ensure that the input data was correct in the first place. This is sometimes called the need for the "last-mile connection" (Pai et al. 2018: 23).

Being able to trace the product parts, the conditions of its sourcing and manufacturing, as well as its transportation routes, guarantees the authenticity of a product (Pai et al. 2018). A product not being authentic can have serious implications on customers' health, for example in the food or pharmaceutical sectors (Paliwal et al. 2020). Laaper et al. (2017: 6) find that "an estimated 10–30% of medicines sold in developing economies are counterfeits, leading to hundreds of thousands of deaths and billions of dollars in revenue losses globally." Thus, blockchain-based solutions could contribute to a reduction in the circulation of counterfeit goods. In other cases, this may have an effect on the ecological sourcing of goods, such as the authenticity of a wildly caught fish from a certain region (for example Provenance's Indonesian tuna pilot, cf. Leong et al. 2018). Additionally, high-value luxury products carrying a certain prestige due to the brand name can be authenticated (Bender et al. 2019; Saberi et al. 2019). This saves both time and resources and reduces potential reputational damage to the brand.

Intrinsically linked to the traceability aspect is the technology's inherent real-time transparency of transactions. Information can be shared easily with all network members without a time lag and the blockchain network does not rely on a central authority distributing information among the affected stakeholders (Gurtu/Johny 2019). Transparency is relevant for businesses, policymakers, and consumers alike

(Bacchetta et al. 2021). Companies benefit from greater transparency to reduce information asymmetry and effectively disintermediate businesses benefiting from this asymmetry (Bender et al. 2019; Hughes et al. 2019; Roeck et al. 2020; van Engelenburg et al. 2018), and to better communicate the progress of the supply chain functions, inventory levels, and demand data, while "keeping identities anonymized where possible" (Ghode et al. 2022: 100). This is necessary to protect potentially sensitive information about companies (Ganeriwalla et al. 2018).

For end consumers, blockchain-enabled transparency helps to safeguard the promises of a product's marketing, to increase product safety, and to adhere to relevant regulations. For policymakers, transparency is a means to assess adherence to applicable rules, such as the forthcoming due diligence requirements in the EU. What is important to highlight here is that blockchain enables not just transparency, but continuous and real-time transparency, which improves the quality of the shared information (Gardner et al. 2019). Traceability and transparency constitute mechanisms to prevent fraudulent activities along the supply chain (Paliwal et al. 2020). An additional opportunity related to the availability and timely sharing of information is mitigating the bullwhip effect (Helo/Hao 2019). The bullwhip effect is rooted in information asymmetry that, due to greater distance from the final consumer, leads to a deviation of supply from demand and results in inefficiencies and waste as more goods are produced than will realistically be sold. With blockchain-based solutions, and "by collaboration and sharing the end-customer demand with all parties in the chain, each party will be able to make a more realistic planning of the use of their capacity and the orders that will be produced" (van Engelenburg et al. 2018: 70). This enhances operational efficiency within the supply chain network (Gurtu/Johny 2019; Min et al. 2019; Paliwal et al. 2020). The improved collaboration allows for lower inventories and less waste, in line with "lean and green" supply chain paradigms (Alicke et al. 2016). Moreover, "reduced information asymmetry could reduce the rent-seeking behaviour of any of the supply chain players" (Hastig/Sodhi 2020: 17). However, it is necessary to note that businesses might not be willing to share data if doing so may harm their competitive market position (van Engelenburg et al. 2018).

To exploit the full potential of blockchain applications, their combination with other (novel) technologies is suggested. Particularly, tracking devices and the Internet of Things (IoT) enhance the automated processes of smart contract execution to dramatically increase efficiency along the supply chain (Bacchetta et al. 2021; Gambhir et al. 2018; Saberi et al. 2019). Great potential also lies in artificial intelligence (AI) analyses of the vast amount of data collected (Min et al. 2019). As Ben-Daya et al. (2019: 4720) phrase it, "[w]hat was lacking so far is not the availability of information but rather the technologies for collecting and processing big data and the lag between data collection and action." Thus, the combination of the data collected by IoT tracking on a shared blockchain and the data processing mechanisms of AI opens up opportunities to adapt supply chain processes according to the real circumstances of changing demand patterns (Gurzawska 2020). These mechanisms can help identify potential weak links in the network, enabling management to redefine action plans. This improves operational efficiency and the effectiveness of the supply chain (Gambhir et al. 2018; Laaper et al. 2017). Here it is crucial to highlight the potentials inherent in the instalment of self-executing smart contracts, which eliminate oversight authorities to approve standardized transactions and reduce accruing time lags (Saberi et al. 2019).

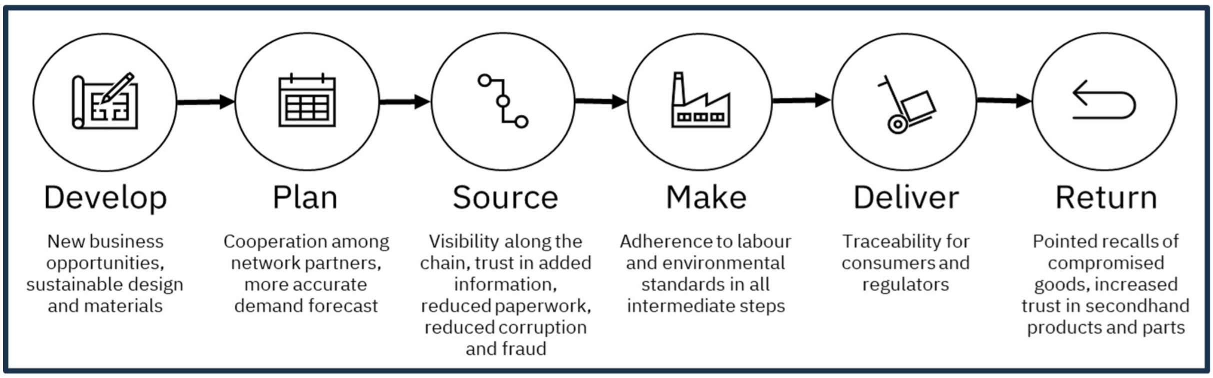

Figure 1: Blockchain's potential in supply chain management (author's own illustration, based on Pai et al. 2018: 10)

To sum up, blockchain-based solutions have the ability to address inefficiencies in all steps of supply chain management, from the planning and development stages, through sourcing and manufacturing, to delivery and returns (see figure 1 above). What is critical is the availability and quality of the shared information, the ability to oversee supply chain processes in real time, and to share risks among members of the entire network.

3.2 Limits to blockchain's application in supply chains

Despite these potentials, the research indicates there are limits to blockchain's applications. These limits can be categorized as technical or operational.

Technical limitations refer to challenges inherent in the structure of the blockchain technology, but their severity may differ according to type or structure. Common to all types is the "fundamental conflict between data accessibility and data protection" (van Engelenburg et al. 2018: 80). The open and transparent character of blockchain technology conflicts with commercial or regulatory reasons for privacy. Commercially, businesses might refrain from sharing information that is crucial to their competitive advantage. Legal regulations protect some (private) data from disclosure. For example, the EU's General Data Protection Regulation safeguards individuals' right to be forgotten, which is technically at odds with the immutable permanent data storage in a blockchain network (Bacchetta et al. 2021; Hughes et al. 2019).

Another technical challenge is connected to the size of the blockchain network and its inherent redundancy of shared data. As records are duplicated among all network participants, increasing the number of blocks also affects the performance of the blockchain in terms of scalability, information transfer rate, and processing latency (Esmaeilian et al. 2020; Paliwal et al. 2020). Yet, in the supply context, more potentials are attributed to permissioned blockchain types (Saberi et al. 2019) and smaller networks, which do not have these limitations.

The second category of shortcomings relates to the operational challenges of blockchain applications. These issues challenge the operational efficiency and effectiveness of the anticipated results of blockchain adoption. Although the immutability of stored data can be guaranteed by blockchain technology, there is no indication of the quality and verity of the input data. This leads to the common criticism of "garbage in, garbage out" (Bacchetta et al. 2021: 6), as mentioned above. However, in the same context, these authors argue that the blockchain architecture facilitates the fact-checking of input data in that it allows for greater time flexibility concerning when the verification should take place, to allow for authentication at a later date (Bacchetta et al. 2021: 6). This is accompanied by the challenge of adding a digital token to a non-digital asset (Kshetri 2022). Decisions on the granularity and timing of adding a digital token to a physical good must consider the "trade-off between risks, inferred trust and value added" (Laaper et al. 2017: 20). Furthermore, it needs to be clarified how tokens cope with changes to the material or part later in the supply chain.

Additional challenges that cause supply chain managers to hesitate about adopting blockchain concern interoperability issues. It remains unclear how the blockchain architecture fits into the established supply chain network and how it interacts with prevailing structures (Weking et al. 2020). As "[o]rganisations do not want to find themselves on a blockchain platform that may limit their options for external collaboration in the future" (Warren et al. 2019: 9), interoperability addresses current business frameworks, their information technology systems, and the interaction between various blockchain solutions. The lack of industry standards and clear indications about return on investment further delay its widespread adoption, which is technically at odds with the immutable, permanent data storage

3.3 Social sustainability and blockchain's potential contributions

Social sustainability encompasses actions and activities that affect human and community life. In the long term, social sustainability is concerned with the preservation of society across generations, ensuring the livability and livelihoods of communities. Thus, conditions to sustain life and to reproduce must be met. The social sustainability considerations above address the minimum requirements to meet basic needs and provide safe and just living conditions to safeguard social capital. In a supply chain context, social sustainability addresses two main groups: the workers along the supply network and the consumers of the final product.

In the functioning of a supply chain, many actors are involved. Especially in the early stages of the production cycle, such as the extraction of raw materials, initial processing, and manufacturing, the adherence to working conditions in line with international labor standards is deficient. By way of example, investigative journalists have made public the child labor involved in the artisanal mining of metals, safety hazards in factories, and forced labor on farms (cf. Amnesty International 2016; Burke 2013; Chohan 2018; The Economist 2020). Although companies and countries claim to be committed to the prevailing labor standards, these malpractices continue to exist. Blockchain technology-facilitated traceability can support the use of product inputs from certified and tested mines, factories, or farms, to support claims of social sustainability and contribute to the fulfillment of the United Nation's Sustainable Development Goal (SDG) 8 on decent work, and SDG 3 on good health and well-being. This would increase the trustworthiness of responsibly sourced products and allow consumers to oversee the practices involved in the production of the consumed good (Kühne 2021). Moreover, this translates into companies having increased accountability (Chohan 2018). Importantly, this "needs to be backed by an offline verification process that gives credibility to the information that is being shared" (European Parliament, Directorate General for Parliamentary Research Services 2020: 49). Thus, certification and auditing continue to constitute necessary aspects of sustainability claims.

While blockchain technology can, in theory, track and trace all material inputs and intermediate production and distribution steps, complex supply chain networks face an operational problem. In order to impose a blockchain along all network participants, the instituting party first requires a complete, gapless overview starting at the first step. Yet, in reality, many supply chains are characterized by obscurity due to their complexity or mixing of material inputs. Hence, subsequent to melting metal ores it becomes nearly impossible to prove the origin of the raw material. The transparency and traceability of the supply chain should start at the earliest possible instance, i.e., the extraction of the natural resource, in order to truly guarantee claims of forced labor-free products. Hence, to enjoy the traceability of blockchain, traceability must already be available in the supply chain: blockchain does not create traceability data but only records it, rendering it transparent and accessible. The lack of traceability in many supply chains is something that their managers currently lament. This is further complicated by the operationalization of adding a digital token (Kshetri 2022), especially when the material is subject to further processing. For example, if a container of metal ores from a certified mine is delivered to a smelter that processes multiple materials, the same certification cannot be guaranteed of the melted, possibly multiple-source outcome. Some industry experts have hence proposed a mass-balance approach, where minimum shares of certified inputs are guaranteed in mixes with noncertified resources, as is the case in fair-trade cocoa (Batwa et al. 2021; Chohan 2018).

Remaining on the production and supply side of social sustainability, blockchain technology presents opportunities for small suppliers in third countries, which would otherwise rarely have access to global markets (Jakob et al. 2018; Min et al. 2019). It has been discussed above that in current supply chain structures the receipt of shipments is a lengthy process, which has to be completed before the suppliers can be paid. This results in a liquidity gap, where suppliers advance their deliveries without having yet received financial compensation. Particularly small companies, with limited financial resources, struggle with this time lag. Blockchain-enabled smart contract execution can trigger immediate payments to suppliers, circumventing intermediaries and time lags (European Parliament, Directorate General for Parliamentary Research Services 2020). Moreover, the transparency and traceability of records allows companies to trace payments upstream to ensure that they arrive where intended. Thus, blockchain technology has the potential to reduce corruptibility in both directions. Yet, the technological setup and necessary prerequisites to participate on the blockchain, usually the availability of a smartphone and stable internet connection, also need to be considered here (Bacchetta et al. 2021).

For consumers, social sustainability means that the product adheres to health standards and is safe to consume or use. In the above description, the health considerations of food and pharmaceutical products were mentioned. In these industry sectors, blockchain technology has found initial applications and exhibits great potential to safeguard the authenticity of e.g., the medicine, and the correct handling of the product in terms of temperature and transport (Leong et al. 2018). This reduces the need for costly recalls of faulty or damaged goods and the associated reparations claims and avoids a brand suffering reputational damage. On a societal level, this increases consumer safety and reduces sickness-related costs. Further sectors and industries require considerations of social sustainability for their consumers. For example, the supply chains forming the construction of a building must ensure that no potentially hazardous materials can be released, such as asbestos. A permanent record of materials and tasks is important here to facilitate later reparations and renovations. Digital solutions, possibly on a blockchain, can prove useful in this regard, also contributing to SDG 3 on health and well-being.

3.4 Environmental sustainability and blockchain solutions

The second aspect of sustainability considers the environmental effects of supply chain practices and goes beyond consumption to include the entire life cycle of a product and its parts. A common argument against widespread blockchain adoption lies in the energy intensity of the technology (Biswas/Gupta 2019; Cole et al. 2019; Hughes et al. 2019). The largest share of energy demand in blockchain technology originates in the proof-of-work consensus mechanism (Paliwal et al. 2020), where computational "work" allows the addition of new blocks to a chain. This is, thus, energy-intensive by design. However, newer generations of blockchain mostly rely on alternative consensus mechanisms that allow the addition of new blocks without the corresponding computational effort (Sedlmeir et al. 2020).

Additional energy requirements are due to the inherent data redundancy, with each piece of (encrypted) information being shared and saved across all participants in the blockchain. The technology imposes a higher strain on data storage, thus energy, than non-blockchain centralized digital solutions (Schütte et al. 2017; Sedlmeir et al. 2020). Therefore, to consider blockchain-based solutions environmentally sustainable, the energy savings they enable must offset their energy requirements (Birkel/Müller 2021). Energy savings can originate from "reduc[ing] the amount of paperwork and transport, including air-freight, or allow[ing] for more targeted recalls, leveraging many opportunities to reduce carbon emissions" (Sedlmeir et al. 2020: 607).

Assuming that knowledge and transparency about misdemeanors and damages is central to enable the mitigation of such unwanted effects, blockchain technology has the ability to "revolutionise life cycle assessments and carbon footprints" (Kühne 2021: 92), thereby strengthening environmental sustainability. These assessments are crucial to evaluate the true costs of products and their preceding production processes. Moreover, they assist in the discovery of damaging practices and provide more targeted mitigation. Indirectly, they can therefore assist in the protection of natural capital.

Determining products' carbon footprints relies heavily on tracking the intermediate steps in the production process. Blockchain-enabled traceability and trust in its immutable, permanent records can support these calculations by enabling greater accuracy and transparency of the supply chain process, and inputs of e.g., recycled materials. Moreover, in line with the underpinnings of the IoT, information about the use and performance of products after their consumption can support life cycle assessments in their entirety, thus, including (anonymized) data on the product's use and reuse or recycling after its natural product cycle (Saberi et al. 2019). The availability of this information could significantly improve confidence in buying authentic, well-functioning secondhand products, such as machinery, technology, or luxury goods (Schwab 2022). This also addresses the aims incorporated in SDG 12 on responsible consumption and production and allows more targeted climate action (SDG 13) on mitigating adverse effects along the downstream supply chain.

In addition, information shared on the blockchain could contribute to a circular economy, where resources are used and reused consciously (Saberi et al. 2019). This significantly limits waste and reduces the need for raw materials. The circular economy is in stark contrast to the current economic setup, where enormous amounts of used goods end up in landfills, garbage patches, or in waste incineration plants (cf. Brand/Wissen 2011). In a circular economy, the focus is on repairing products, reusing them for different purposes, or recycling their parts and materials. In this system, raw material extraction is limited, as is the consumption of new products. Yet, one must keep in mind that the extraction of recyclable parts and the reprocessing of used materials is also energy-intensive. Blockchain technology could support the shift toward a circular economy by providing a permanent, immutable, and ideally complete record of the product cycle, including the use phase. In this, "valuable information could be gained for the downstream disposal phase or future product developments" (Kühne 2021: 93).

To sum up, blockchain technology has the potential to assist in advancing environmental sustainability by providing transparent information on the circumstances of production, the negative externalities involved, and the raw or recycled material inputs. Yet, as with any digital technology solution, energy consumption with regard to data storage and dissemination needs to be considered as well.

4 Conclusion

This article set out to investigate the prevailing challenges supply chains continue to face, and the role blockchain technologies can play in addressing these issues. There are strong use cases where blockchain offers additional benefits. However, the results also show the limitations of the technology. As factors such as complexity, length, industry, and geographic circumstances influence the need to reform current supply chain practices, it can be expected that the corresponding digital technology solution will vary. Furthermore, it remains to be seen how companies will cope with the additional hurdles of the EU's recent agreement on the corporate sustainability due diligence directive and the corresponding reporting requirements.

This article considered supply chains as an aggregation, falling short of addressing the concrete issues of, as well as the applicability of blockchain in, specific industry sectors and contexts. With respect to the great variations in supply chain networks, additional research should consider specific products and the respective characteristics and expectations of their supply chains. Additionally, more research focused on the implementation phase of blockchain applications is needed. Despite the vast theoretical and technical interest in blockchain technology, the availability of applied cases is still limited. Research on initial applications could advance solutions and address the specific challenges that arise during implementation to enable a better understanding of the learning processes involved in blockchain adoption.

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