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Blockchain for the future of sustainable supply chain management in Industry 4.0

Behzad Esmaeilian Conceptualization; Writing - original draft [a], Joe Sarkis [b], Kemper Lewis [c], Sara Behdad Supervision; Writing - review & editing [d,*]

[a] Western New England University
[b] Worcester Polytechnic Institute
[c] University at Buffalo
[d] University of Florida

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ABSTRACT

The objective of this study is to provide an overview of Blockchain technology and Industry 4.0 for advancing supply chains towards sustainability. First, extracted from the existing literature, we evaluate the capabilities of Industry 4.0 for sustainability under three main topics of (1) Internet of things (IoT)-enabled energy management in smart factories; (2) smart logistics and transportation; and (3) smart business models. We expand beyond Industry 4.0 with unfolding the capabilities that Blockchain offers for increasing sustainability, under four main areas: (1) design of incentive mechanisms and tokenization to promote consumer green behavior; (2) enhance visibility across the entire product lifecycle; (3) increase systems efficiency while decreasing development and operational costs; and (4) foster sustainability monitoring and reporting performance across supply chain networks. Furthermore, Blockchain technology capabilities for contributing to social and environmental sustainability, research gaps, adversary effects of Blockchain, and future research directions are discussed.

1. Introduction

Novel technologies emerging under the umbrella of Industry 4.0 are creating new business and financial opportunities for supply chain networks. According to the Computing Technology Industry Association (CompTIA), the Internet of Thing (IoT), artificial intelligence, 5/6G networks, serverless computing, Blockchain, Robotics, Biometrics, 3D printing, Augmented Reality/Virtual Reality, and Drones are the top ten emerging technologies in 2019 (Rayome, 2019). Although these technologies are Industry 4.0 processes enablers, some of them – Blockchain, 6G network technologies, and wireless communication – are emerging and well-positioned for innovative business models. For instance, shifting trust from organizations to analytics, automated smart contracts, and facilitating sharing economy applications without a central entity, are examples of Blockchain's potential for changing business models (Nowiński and Kozma, 2017).

The contribution of technology to fundamentally change both business and society has been acknowledged by scholars. However, minimal attention has focused on how these emergent technologies address sustainability challenges; especially helping organizations move towards a circular economy (CE).

There are also potentially detrimental outcomes. Applications of technology in different industries – ranging from agriculture to transportation and energy systems – have imposed threats to nature and global ecosystems. Understanding the complex integrated system of technology, society, and business is necessary for identifying and addressing sustainability challenges.

This study contributes to sustainable development and CE literature by offering a set of guidelines on how technology plays a role in a sustainable society. The extent by which adverse environmental effects of these emergent technologies can be offset by new sustainability-related opportunities they offer is a central tension and theme. There is a lack of scientific research on the impact of Industry 4.0 on solving industrial symbiosis and sustainability problems (Stock and Seliger, 2016).

We review the current state of the art of Industry 4.0 and Blockchain technology with a focus on sustainability relationships to these concepts. The opportunities offered by Industry 4.0 and Blockchain technology, as well as the adverse sustainability consequences in the manufacturing and CE context, are addressed. The capabilities of Blockchain technology for promoting green behavior among consumers and decreasing the operational costs of systems appear in the remainder of the paper. A summary of research directions and concerns concludes the paper.

The remainder of this paper is organized as follows. Section 2 provides brief descriptions of sustainability, industry 4.0, and Blockchain. Section 3 introduces the research method for collecting and analyz-

* Corresponding author.
E-mail address: sara.behdad@essie.ufl.edu (S. Behdad)

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ing the literature. Section 4 reviews the research work on the sustainability of Industry 4.0, and Section 5 discusses the capabilities of Blockchain for addressing sustainability issues. Section 6 discusses the Blockchain adverse effects. Section 7 summarizes research gaps, and finally, Section 8 concludes the paper.

2. Background

Before reviewing the literature on the sustainability of Industry 4.0 and the impact of Blockchain on sustainable supply chains, we will briefly review three concepts of sustainable development, Industry 4.0, and Blockchain in this section.

2.1. Sustainable development

Before introducing Industry 4.0 and Blockchain as enablers for sustainable development, a brief discussion on sustainability is provided. The focus will be on the circular economy concept to acknowledge the importance of economic sustainability and the role of industry in implementing sustainability principles.

The circular economy concept has originated from both industrial ecology and environmental economics. There is no consensus on the exact definition of the circular economy (Korhonen et al., 2018). Practitioners often consider it as a way to overcome the limitations of linear production and consumption models for increasing resource use efficiency. The circular economy has been introduced to achieve a better balance between the economic aspect and the environmental and social aspects of sustainability. Countries such as China promote CE as a cleaner production strategy that supports resource use efficiency. Other regions, such as the European Union, Japan, and the USA also consider it as a waste management strategy (Ghisellini et al., 2016).

Economic system circularity was introduced with the law of thermodynamics as its foundation (Pearce and Turner, 1990). It initially was to describe matter and energy degradation to maintain the sustainability of Earth's resources. In these initial CE descriptions, the environment has three main functions: supply resources, provide a life support system, and offer a sink for emissions and waste. Unlike other economic functions with explicit pricing, sometimes no direct price or market for environmental goods exists (what is the price of air and water quality?), although recent Life Cycle Assessment (LCA) methods have tried to monetize environmental prices, indicating the loss of economic welfare as a result of environmental emissions (De Bruyn et al., 2018; Weidema, 2015). Environmental policies, consumer and producer responsibilities have been employed to mitigate the high consumption of resources (Ghisellini et al., 2016).

CE has several value drivers: 1) extending an asset's usage cycle, 2) enhancing asset utilization through sharing or resource productivity, 3) asset looping and cascading through reuse, remanufacture, recycling, or moving to a secondary usage, and 4) regenerating and preserving natural resources by returning biological elements to their original ecosystem and avoid nutrients leakage from one system to another (Ellen MacArthur Foundation, 2016). To implement these value drivers, a framework named ReSOLVE – Regenerate, Share, Optimize, Loop, Virtualize, and Exchange has been introduced by the Ellen Macarthur foundation (Prendeville et al., 2017).

CE is not without its criticism (Prendeville et al., 2017): (1) First is the definition of CE. Practitioners are often unclear about the actual principles of CE. Some consider it as a macro-level activity and while others view it as a micro-level intervention. (2) Second, some of the principles may not necessarily be beneficial for the environment. For instance, infinite recycling of materials and energy will not be without efficiency loss, or reuse of old technologies may result in higher energy consumption or sharing economy initiatives that may not be as environmentally viable as promoted. (3) Third, very few businesses adopt CE-related strategies. Also, CE models often give more authority to businesses than consumers and social communities.

While CE can companies realize business outcomes of implementing sustainable operations, the scope and scale of CE efforts implementation are currently limited. As new technologies emerge, novel business models can orient organizations toward enhancing sustainability outcomes through CE principles.

2.2. Industry 4.0

Industry 4.0 – derived from the German word Industrie 4.0 – is defined as a set of connected cyber-physical objects capable of using big data analytics within the manufacturing and production domains (Vogel-Heuser and Hess, 2016). Industry 4.0 is part of smart city initiatives due to cyber-physical systems (CPSs) applications and the Industrial Internet of Things (IIoT) (Lom et al., 2016). Researchers often use these terms interchangeably. For instance, industry 4.0 is commonly used as a synonym for CPS. Different characteristics have been assigned to Industry 4.0 with the aim of not only equipping manufacturing systems with advanced data acquisition technologies but also value generation and services innovation (Kagermann, 2015).

Germany has developed a four-step strategic plan for transforming industries of information-age to Industry 4.0: (1) building a network of CPSs, (2) researching the 'smart factory' and 'intelligent production' concepts, (3) integrating the elements of value chains on three levels of horizontal integration, vertical integration, and end-to-end integration, and finally (4) achieving eight planning objectives. The eight planning objectives include standardization, efficient management, a reliable industrial infrastructure, safety and security, organization and work design, workforce training, creating a regulatory framework, and improving the efficiency of resources (Zhou et al., 2015).

Short development time, mass customization, flexibility in product design and production, decentralization of production systems, and resource efficiency are among several capability goals of Industry 4.0 (Lasi et al., 2014). Table 1 provides a brief description of several technological advancements that power Industry 4.0.

Many studies have reviewed Industry 4.0 and the opportunities offered by the latest industrial revolution. Figs. 1 and 2 provide reports of the number of recent publications with Industry 4.0 or Industrie 4.0 terms in their titles and the geographical locations, respectively. As seen in Fig. 2, Germany is leading Industry 4.0 research.

Table 1.
Examples of Industry 4.0 technologies.

Technology	Description
Artificial Intelligence	Using computer systems to simulate human intelligence
Robo-Advisory	Digital experts systems, mathematical rules, and algorithms that provide financial advice with minimal human intervention
VR/AR	Virtual Reality/Augmented Reality
Additive Manufacturing	The use of computer control to manufacture objects by adding materials together layer by layer
Industrial Internet of Things	Connecting and monitoring industrial objects and physical devices through the internet
6G network	The 6th generation of mobile networks that interconnects not only people but also devices and objects
Serverless computing	A new resource allocation model for cloud-computing execution in which cloud providers match demand and capacity
Biometrics	Technology for body measurement and calculation for an individual's identity identification and surveillance control
Cybersecurity	Protection of computer systems from malfunctioning
Blockchain	A decentralized, distributed data structure and public digital ledger

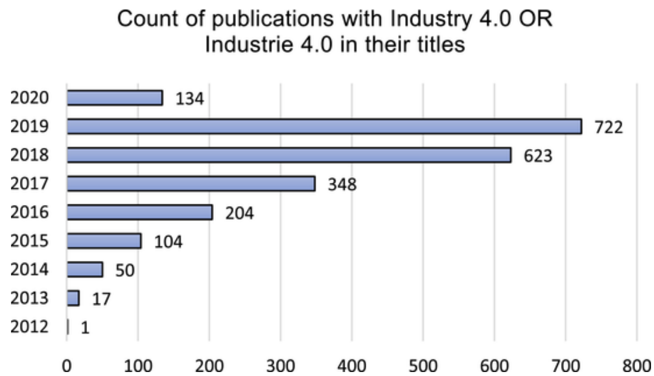

Fig. 1. The number of publications with the term “Industry 4.0” or “Industrie 4.0” in their titles (extracted from Compendex database on 03/31/2020).

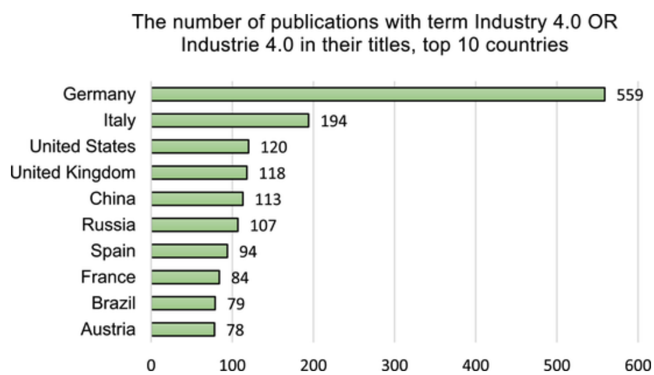

Fig. 2. The number of publications with the term “Industry 4.0” or “Industrie 4.0” in their titles based on the principal place of publication (extracted from Compendex database on 03/31/2020).

Given that Industry 4.0 is such a broad topic, to show its potential one of the most recent elements, blockchain technology is evaluated. The importance of blockchain resides in its abilities in enhancing the level of information integration across supply chains and between various actors, one of the main agendas of industry 4.0.

While in Section 4 of this paper, we review current research in Industry 4.0 for fostering sustainability efforts, the main focus of the paper will be on the impact of Blockchain and the potential of this technology for enhancing sustainable operations.

2.3. Blockchain technology

A blockchain is a distributed data structure – a distributed ledger – in which the data is shared on a peer-to-peer network. The network members – nodes – communicate and validate the data following a pre-defined protocol without a central authority. Distributed ledgers can be either decentralized, giving equal rights to all users or centralized, providing specific users with special rights. Fig. 3 shows the evolution of computer networks from decentralized to decentralized and distributed systems. Blockchain is, by nature, a distributed ledger since each node of the network has a copy of the ledger. Depending on the right of the users, Blockchain can be designed as a centralized or decentralized ledger. If Blockchain is designed such that the decision-making is shared among multiple users, it is decentralized; if one central entity is the primary decision-maker, then it is centralized.

Blockchain technology was popularized with the Bitcoin cryptocurrency peer-to-peer network. Blockchains are created using cryptography in which each block –transaction, file of data – has a cryptographic hash and is linked to a previous block. Once a block is verified by a certain percentage of the network nodes, it is added to previous blocks and forms a blockchain – also known as a public ledger of transactions (Casado-Vara et al., 2018).

Blockchain technology alters how administrative control is digitally regulated and maintained. In blockchains, data are converted to digital codes, are stored in shared databases, have higher transparency, and limited risk of deletion and revision – immutability. Blockchain potential lies with every agreement, payment, and transactional activity having a digital record. These records may be validated and shared among individuals, machines, algorithms, and organizations. Intermediaries such as brokers, bankers, and lawyers are needed less often (Lansiti and Lakhani, 2017). Intermediaries are entities that act as middlemen and handle the accuracy and verification of transactions in different industries. With blockchain, trust is shifted from human and traditional agents for verifying transactions to computer codes.

As an example, in the Bitcoin market, an individual has full control over their Bitcoin balance. Unlike a bank balance, an individual's Bitcoin balance cannot be manipulated or viewed digitally. If the individual has the proper passcode, they can authorize entry on the blockchain ledger and transfer it to another individual's address (Athey et al., 2016). Transparency, less risk of fraud, instantaneous transactions, privacy and security, financial data assurance, and no exchange costs are among blockchain technology benefits (Sharma et al., 2017) (Crosby et al., 2016).

Blockchain typically includes the following capabilities, which may be dependent on the platform used (Barton, 2018):

- *Shared ledger:* a data structure that is distributed locally and shared between different participants;
- *Permissioning:* secure and authenticated transactions that ensure privacy and transparency of data;
- *Smart contracts:* business terms are embedded in a database and are implemented with transactions; and

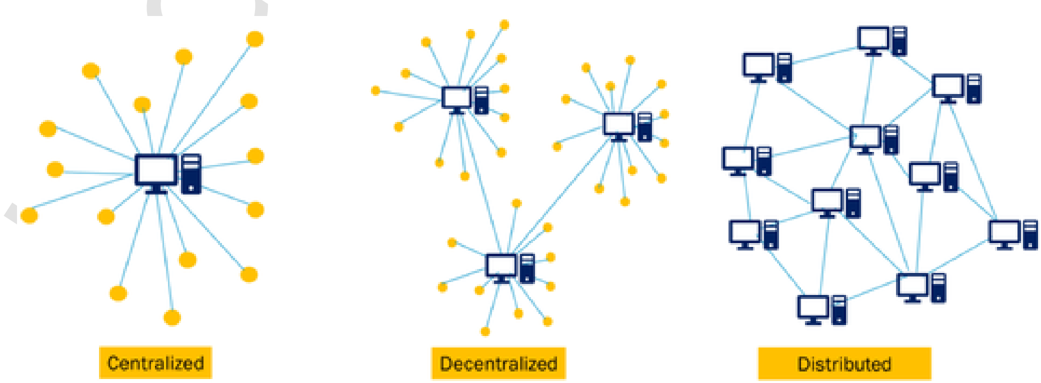

Fig. 3. Blockchain is a distributed ledger (Three stages of computer network evolution, source: Daxx.com).

- *Consensus:* transactions are endorsed by relevant users that ensure immutability and traceability of data.

Most of the existing blockchain studies focus on Bitcoin and cryptocurrency applications (Yli-Huumo et al., 2016). However, the technology can be employed in different industries ranging from healthcare to real estate and energy markets (Athey et al., 2016). Although blockchain is in its relative infancy, some consider it a general-purpose technology (GPT) with several key features of GPTs (Kane, 2017). GPTs such as the steam engine, electricity, and the internet result in innovation and productivity gains among multiple industries and lead to economic growth for multiple years (Catalini and Gans, 2016). This outcome is part of the blockchain promise; whether it comes to fruition is an open question.

Blockchain has numerous current limitations before broad adoption and implementation. Scalability, regulatory challenges, security risks, and energy consumption are major limitations. In the smart contract world, underlying rules that govern the system are defined by software engineers and coders as they decide about the architecture, applications, and structure of the network. Determining the content and scope of smart contracts by coders brings many difficulties in implementing compliance with regulations. It is challenging to write all possible scenarios that may happen in complex business scenarios as computer codes in smart contracts, and smart contracts will still have to rely on courts and traditional legislators in the matter of doubts. Besides the inflexibility of smart contracts to adapt to the changing preferences of parties and unique uncertain scenarios, the insufficiency of smart contracts in connecting to the physical world and verifying information recorded on the ledger (e.g., verifying the person claiming to have the title of the land) are among other legal challenges facing blockchain platforms (von Haller Gronbaek, 2016).

The rise of permissioned or private Blockchains for industrial applications also has critics. Permissioned blockchain is very different from public blockchain; its emergence has hidden blockchain platforms' advantages. Some believe that permissioned blockchain is just a shared database (Narayanan, 2015). Due to this confusion, some contend that blockchain technology is not an innovative technology.

Blockchain undergoes several scalability issues such as communication malfunctions among users, data storage, and linear transaction record (Barber et al., 2012). The scalability issues originate from growing the number of transactions, and difficulty of the consensus protocols (Conoscenti et al., 2016). To address scalability issues, different scaling approaches have been developed in computer science literature. The idea behind scalable networks is to enable information transfer among intermediaries without recording every transaction on the blockchain (Xie et al., 2019).

Other blockchain criticisms exist. While Blockchain helps with reducing the needs for an intermediary and assists with the automatic verification of transactions due to capabilities such as the tamper-proof nature of Blockchain and the use of cryptography hash functions, it is almost impossible to alter information once it is recorded on the ledger. Therefore, the correct information must be entered into the Blockchain system. This challenge is known as the last-mile problem or endpoint vulnerability. The verification of data uploaded on digital platforms still requires intermediaries. Mechanisms are needed to ensure that the link between digital records and physical entities are correctly established, and the information uploaded on digital platforms is accurate. Mechanisms such as IoT sensors and certified inspectors can be used to ensure the accuracy of information uploaded on the network (Gopalakrishnan and Behdad, 2019).

Although the current development of blockchain supports the anonymity of users' identity via digital signature, data protection via immutable ledger, and confidentiality of transactions via cryptography, the security of consensus algorithms is still a problem. More secure consensus algorithms are needed for enhancing security and system resistance to attacks (Zhang et al., 2019). Besides human-related security issues, 51% vulnerability, double spending, and the lack of a proper mechanism for protecting private keys are among other security issues. Public blockchains are exposed to 51% attacks, in which a group of users control most of the network's computing power and can control the ledger.

Although blockchain has its share of criticism, it is gradually becoming integrated into the industry, with new user applications continuously identified. Existing large technology companies are investing in this technology, and various efforts on developing socially open-sourced platforms are underway. These activities exhibit blockchain technology potential; and its integration with Industry 4.0. Fig. 4 summarizes the capabilities and criticisms of blockchain and the cur-

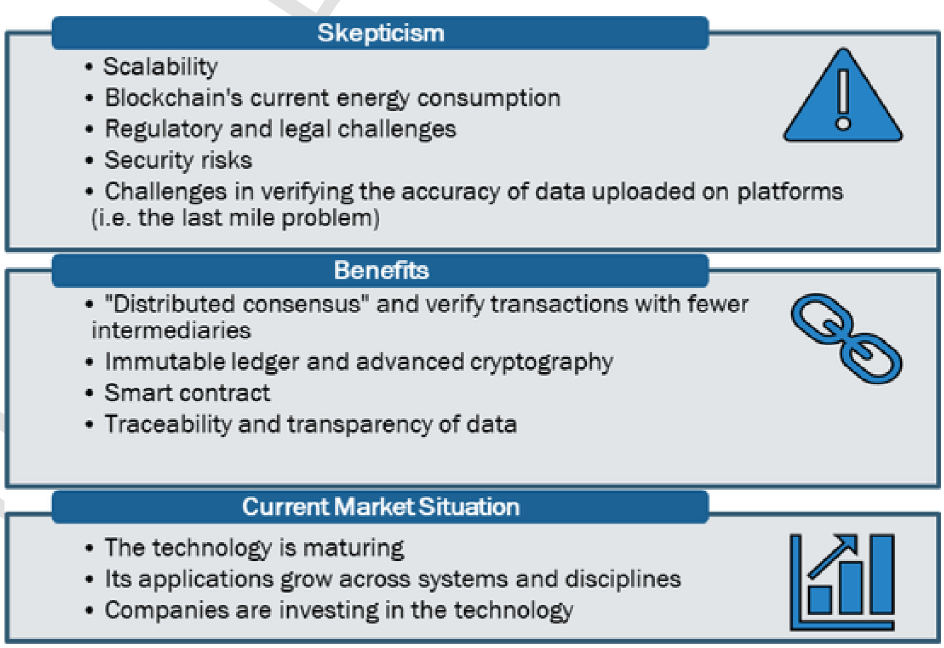

Fig. 4. The capabilities, criticisms, and current situation of Blockchain technology.

rent market situation. Figs. 5 and 6 show the number of scholarly publications using the word Blockchain in their titles and the principal place of the publications.

3. Research method

To identify the progress of research on the sustainability of Industry 4.0 and Blockchain, we have employed the standard four-step literature review method used in Srivastava (2007). The literature review method consists of (1) defining the unit of analysis, (2) defining the classification context based on methodology and problem context, (3) collecting the literature, and (4) evaluating and interpreting the collected publications.

A journal, full conference paper, or book is considered as the unit of analysis. Engineering Village, Inspec, Compendex, Knovel, NTIS & GeoRef databases have been used to collect the published work from 1990 to 2019. A set of keywords, including Industry 4.0, sustainability, circular economy, cyber-physical systems, smart manufacturing, and Blockchain, as well as a combination of AND/OR operators, have been used to filter the relevant publications. Finally, the materials obtained through databases were analyzed and categorized into different sections of this paper. The above-mentioned databases enabled us to refine the results of our search based on the publication year, the country, document type, and keywords. In addition, the use of Engineering Village helps generate data analytics reports and relevant statistics.

4. Current Industry 4.0 research for enhancing sustainability of supply chains

The importance of considering sustainability is highlighted in smart manufacturing literature. Studies pointed out that intelligent manufacturing systems should consider sustainability to be competitive in the long-run (Erol, 2020), where future products, processes, and industrial systems should be designed with keeping the 3S' smart, sustainability and safety into consideration (Trentesaux et al., 2016). Supply chain sustainability is a highly complex process, where the specifications

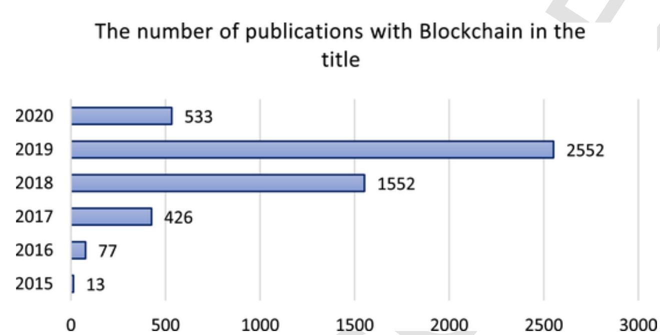

Fig. 5. Statistics on the number of publications with Blockchain in the title (extracted from Compendex database on 3/31/20).

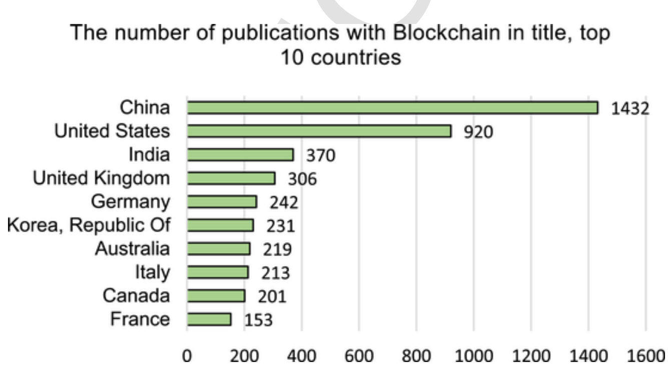

Fig. 6. Statistics on the number of publications with Blockchain in the title based on the principal place of publication (extracted from Compendex database on 03/31/20).

and needs required from sustainable systems are often ill-defined. An effective industrial revolution that helps businesses create a balance between the economic viability of their decisions and environmental and social consequences requires efficient knowledge representation schemes on sustainability.

Kiel et al. (2017) interviewed 46 managers from German companies to extract the impact of Industry 4.0 on three pillars of sustainability and concluded that Industry 4.0 influences the ecological aspect of sustainability mainly in terms of resource efficiency. The resource and energy use can also be optimized in Industry 4.0 due to the detailed information available on the production process (Gabriel and Pessl, 2016). In addition to waste reduction and energy consumption, Industry 4.0 has an impact on reducing overproduction where smart factories often use the pull principle in which products are manufactured upon demand, and raw materials are ordered when needed (Waibel et al., 2017). Pacis et al. (2020) provided a review of three environmental challenges in manufacturing systems, including waste generation, energy consumption, and emissions, and highlighted the role of IoT capabilities in predictive maintenance, overall management system, and enhanced production control on solving those issues. Duarte and Cruz-Machado (Duarte and Cruz-Machado, 2020) discussed the connection between Industry 4.0 and green supply chain and commented that industry 4.0 is based on the characteristics that already have been the focus of lean and green concepts.

As mentioned earlier, most of the prior studies have only generally discussed the importance of industry 4.0 for solving sustainability-related needs, with minimum guidelines on the ways that Industry 4.0 characteristics influence sustainability. Also, the analyses have not fully critically examined the influences of Industry 4.0 on total resource consumption – for example, energy consumption can increase greatly for some of the algorithms used in some technologies. The examination may also be limiting in terms of social issues, especially related to concerns in job loss and social unsustainability.

Besides general discussion on the role of smart initiatives in solving sustainability issues, other studies that have provided insights on connecting IoT-enabled infrastructure, ICT, and smart factories within a *Manufacturing context* can be categorized under the following three main groups – also depicted in Fig. 7:

- IoT-enabled energy management in smart factories
- Smart logistics and transportation
- New business models

A brief discussion of each three major categories is provided in this section. In addition to the above-mentioned three categories, other studies cover a wide range of topics from sustainability education to design innovation and business strategies that have been beyond the scope of this study. There are even some closely related topics such as IoT-enabled water pipeline monitoring and IoT-enabled condition-based maintenance that are among the capabilities of Industry 4.0.

4.1. IoT-enabled energy management in manufacturing systems

Previous industry 4.0 studies on energy management have suggested a three-step methodology for employing IoT capabilities in energy management – data collection, data analysis, and integration of collected data into decision-making processes (Shrouf, 2016; Shrouf and Miragliotta, 2015). According to May et al. (2017) Information technology studies that support optimization of manufacturing systems toward energy efficiency can be categorized under four groups of studies: (1) process automation for reducing energy consumption; (2) development of production control tools and algorithms towards reducing energy use and resources consumption; (3) development of monitoring and decision-making tools for monitoring the real-

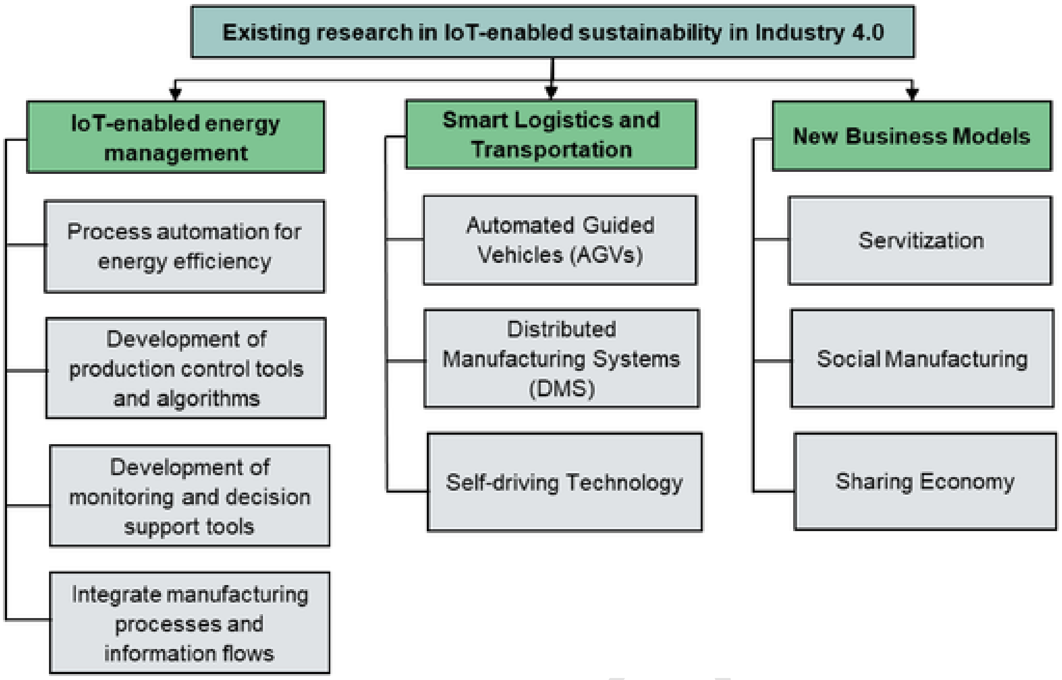

Fig. 7. The three main current research areas in IoT-enabled sustainability in smart manufacturing.

time energy consumption of machine tools; and (4) studies which are focused on integrating manufacturing processes and information flows to facilitate resource savings.

Other studies exist in evaluating IoT in an energy management environment. Shrouf et al. (2014) discussed the capabilities that IoT offers for collecting energy consumption data from the shop floor and offering real-time information to decision-makers towards managing energy-efficient production practices. Wei et al. (2016) designed an information model for an integrated energy management platform for industrial applications to provide interconnectivity and interoperability between devices, equipment, and machines to reduce the energy costs of industrial facilities. Tan et al. (2017) developed a software application for real-time monitoring of energy consumption on shop floors and further applied a data envelopment analysis (DEA) technique for identifying abnormal energy consumption patterns. Qin et al. (2017) also suggested an IoT framework for collecting energy consumption data from Additive Manufacturing processes and decreasing the power consumption during production. Bevilacqua et al. (2017) showed the application of IoT-based energy management systems through a case study conducted in an Italian manufacturing company where smart meters have been installed on machine equipment to collect real-time energy consumption data; the data have been analyzed to help decision-makers integrate them in their production planning decisions.

To better quantify the environmental impacts of processes, Ballarino et al. (2017) discussed the potential of Life Cycle Assessment (LCA) tools integration with cyber-physical systems (CPS). The appropriate use of sensors for collecting the right data and protocol development for data integration are among the key factors for the successful integration of LCA and CPS. CPS applications in a smart grid can be used to optimize energy consumption.

Estevez and Wu (2017) have discussed the ways that CPS influences the environment and emphasized that at present ICT infrastructure is the consumer of 2–5% of the world's energy, and this percentage is increasing as CPS becomes ubiquitous. Enhancing machine-to-machine (M2M) communications, the utilization of large-scale-equipment architectures, and the use of small resource-constrained devices with pervasive computing capabilities are among suggested methods for power savings in Industry 4.0.

4.2. Logistics and transportation in Industry 4.0

Industry 4.0 generates new perspectives on logistics. In Europe, a considerable number of programs have been initiated for greening freight logistics. For example, green transport corridors for transshipments between major hubs and with a long distance of transport has been initiated to address environmental issues and climate effects (Prause, 2015). In manufacturing logistics, the role of automated guided vehicles (AGVs) in efficient materials handling operations improve environmental and social sustainability (Bechtsis et al., 2017). Studies have discussed the type of decisions that should be made on the strategic, tactical, and operational levels to integrate AGVs to supply chain activities considering sustainability objectives (Bechtsis et al., 2017). Overall, the available stream of literature on smart transportation and logistics can be categorized into three groups – AGVs, distributed manufacturing systems, and self-driving technologies.

Industry 4.0 has transformed centralized production systems to decentralized smart entities connected through IT systems (Almada-Lobo, 2016). Automated distributed manufacturing systems (DMS) facilitate sustainability in manufacturing through the reduction of transportation and democratization of the design and development of local communities (Rauch et al., 2015). Siemens, as part of its digitalization initiative, has started developing *Plant-in-the-Box*, in which additive manufacturing machines are fitted to a container to be transported to the demand node (Sidenvall, 2016). Moveable milling machines for grinding billboard banners and signage – recycling them locally rather than transporting them to recycling plants (Fox and Richardson, 2017). Care should be taken since centralized manufacturing can have better sustainability outcomes than some forms of distributed production (Fox and Alptekin, 2018).

4.3. Green Industry 4.0 business models

Business models are integral to manufacturing systems and define how resources should be used for value creation. IoT platforms with data collection and analysis capabilities can better support corporate value-generation processes. Industry 4.0 is distinguished from previous concepts by making the production process transparent and traceable (Prause, 2015). We focus on servitization, social manufacturing, and sharing economy business models and discuss their smart manufacturing sustainability potential.

Servitization is defined as offering an integrated product-service experience rather than just selling products. Product Service-Systems (PSS) are an example of businesses developing and offering customers products with value-added services (Lee et al., 2014). Customer-driven instead of product-oriented innovation, the use of monetization innovation such as pay-per-use, and innovations in reaching new customers are examples of value creation innovations in Industry 4.0 settings (Müller et al., 2018). Another dimension of servitization emerging from smart manufacturing is the concept of "Manufacturing-as-a-Service," where manufacturing is offered as a service to users. The concept opens the opportunities for manufacturing collaboration and large-scale smart applications (Tao and Qi, 2017). Industry 4.0 enables traditional service providers to offer new services throughout the product lifecycle. For example, CPSs can enable service organizations to improve internal service efficiency and provide innovations in repair and preventive maintenance services (Herterich et al., 2015).

Social manufacturing is another business model in which open design platforms allow broad participation in designing and producing products. They use capabilities embedded in online community platforms to co-manufacture products (Steenkamp et al., 2016). There is also the ability to transform the mind directly into products through crowdsourcing platforms and social media. Anyone can participate throughout design and manufacturing processes (Xiong et al., 2018).

Sharing economy, sharing or collaborative consumption is another business trend. Sharing can include collaborative consumption as peer-to-peer exchanging, giving or sharing consumption of services and goods, enabled through community-based online platforms (Hamari et al., 2016). Example platforms include accommodation sharing in the tourism industry (e.g., Airbnb, Couchsurfing), ridesharing for mobility (e.g., Zipcar, Uber), peer-to-peer employment markets (e.g., TaskRabbit, PeoplePerHour), resource sharing in waste disposal, and production-consumption and the ICT industry (Martin, 2016) (e.g., Freecycle, Peerby). There is a significant potential of the sharing economy for more sustainable consumption and production (Cohen and Muñoz, 2016).

5. Blockchain technology for sustainability

Assuming that a core sustainability objective is closing the product lifecycle, Industry 4.0 and blockchain technology can reduce barriers towards realizing this objective. Technology capabilities can be categorized into three main groups – (1) data collection, (2) data analytics, and (3) decision making. Industry 4.0 provides data collection through sensor technologies and opens the way for software tools that analyze data in real-time with decision support systems that interpret the data streams and facilitate decision-making across multiple levels of analysis. Industry 4.0 increases the level of information sharing over the entire supply chain, makes the product lifecycle more transparent, facilitates the collection of new data types, and enhances timely decision making.

In the current IoT-enabled world, there is an explosion data available for businesses. Insufficient capabilities of current decision-making techniques limit the abilities of businesses to fully utilize big data. New software tools and techniques should be integrated with smart factories and CPS to enable real-time quantification of the ecological impacts of production processes from ubiquitous sources. Sensors can help collect appropriate data, and protocol development for data integration are key factors for the successful integration of sustainability principles within smart factories.

Smart Manufacturing Execution Systems (MES) equipped with data acquisition, analysis, and decision making features compatible with sustainable development goals have been structured (Larreina et al., 2013). Blunck and Multiple Industry 4.0 elements enable the implementation of a CE (Blunck and Werthmann, 2017). Using resources and optimizing processes, utilization of assets, labor productivity, management of inventories, quality improvement, reducing time to market, match of supply and demand, and efficient offering of service and aftersales are examples areas that Industry 4.0 eases implementation of CE. We should highlight that data collection and analysis capabilities enabled by industry 4.0 improve not only addressing sustainability issues but also advance our understanding of such problems. Fig. 8 summarizes the capabilities of Industry 4.0 and the ways it may influence sustainability

Blockchain plays a particularly important sustainability role. Four main Blockchain capabilities can support sustainable supply chains: (1) they help reduce the product recall and rework due to its tracking capabilities; (2) they make it easy to trace the actual footprint of products and determine the accurate amount of carbon tax that each company should be charged; (3) they facilitate recycling behavior by incentivizing individuals to participate in deposit-based recycling programs; (4) they improve the efficiency of emission trading schemes by reducing fraud and improving the fidelity of the system (Saberi et al., 2018).

We further discuss the potential of Blockchain for implementing sustainable lifecycle engineering principles. While Blockchain has its limitations, it has the potential to mitigate some sustainability-related challenges and advance circular economy realization (Kouhizadeh et al., 2019). We discuss four main Blockchain capabilities for (1) promoting green behavior; (2) enhancing product lifecycle visibility; (3) improving operations and systems efficiency; and (4) improving sustainability reporting and monitoring.

5.1. Incentivizing green behavior through tokenization

Consumer green behavior is a vital sustainability sub-field. Consumer green behaviors include behaviors such as recycling behavior, waste reduction, local consumption, purchasing refurbished products, purchasing energy-efficient products, energy conservation, reuse, repair, maintenance, and sharing (Esmaeilian et al., 2018). We categorize eco-behavior under three main categories – purchase behavior, usage behavior, and end-of-use behavior. Table 2 overviews eco-behavior under each category.

Coin or token offerings can be used as a mechanism for financing sustainability-related behaviors. Entrepreneurs who are creating new peer-to-peer networks using Blockchain have widely adopted the token sales and Initial Coin Offering (ICO) as mechanisms for financing their start-up costs. They use ICO to raise funds for their open-source or private blockchain platforms by preselling access to future products and services (Li and Mann, 2018). Although no commitment is made by a venture about the price of future services, the venture offers crypto-tokens with a promise that those tokens will perform the role as the medium of exchange (payment) when accessing services on the Blockchain digital platform (Catalini and Gans, 2018).

Local tokens on digital platforms can be designed to promote green behavior among consumers and other players involved during the product lifespan. Through offering local tokens, a company or initiative offers incentives or stock of specialized crypto tokens for exchange of any eco-behavior or eco-service provided by the users on the network.

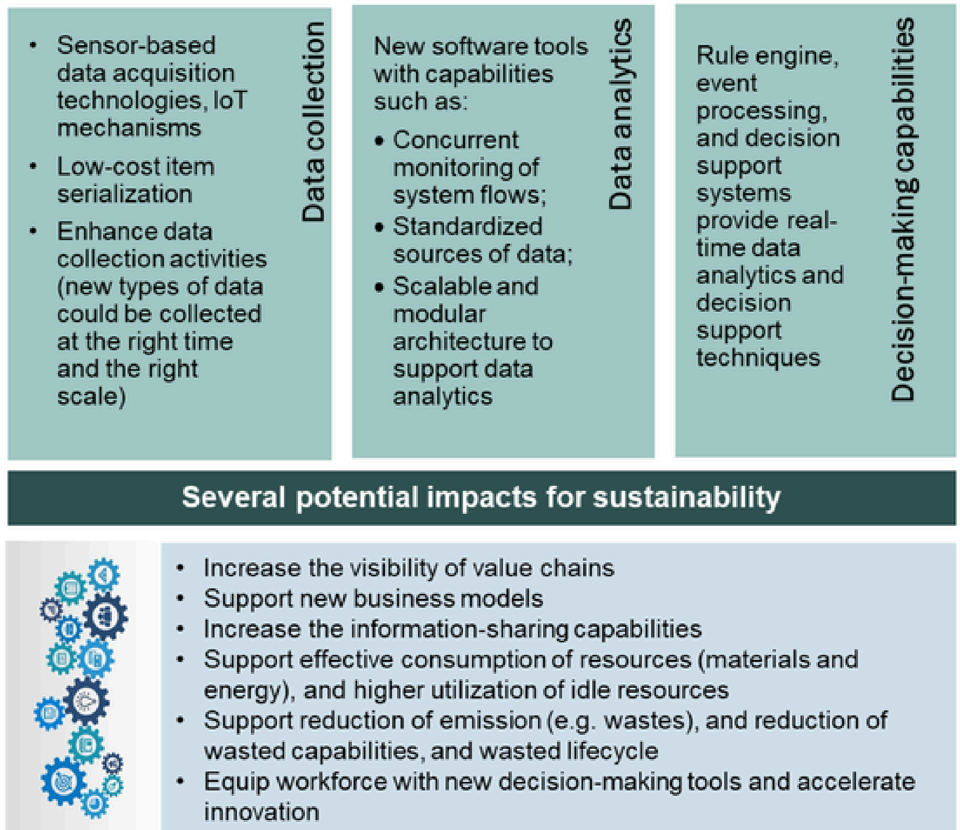

Fig. 8. Capabilities of Industry 4.0 and their potential impacts for sustainability (Blunck and Werthmann, 2017; Ellen MacArthur Foundation, 2013; Pfeiffer and Suphan, 2015).

Table 2
Examples of consumer eco-behavior over the product lifecycle.

Purchase behavior	Consumption behavior	End-of-Life behavior
• Purchase refurbished, used, remanufactured products	• Energy conservation	• Repair, Maintenance
	• Sharing	• Recycle
• Purchase green (e.g., energy-efficient, emissions-free) products	• Green consumption	• Reuse
	• Waste avoidance	• Use trade-in programs
• Purchase local services	• Consume less	• Discard properly
	• Consume locally	• Donate used items

The crypto tokens act as the medium of exchange when users access services on digital platforms offered by the company or initiatives.

Several startups and digital platforms incentivize sustainable behavior. CarbonX assesses products and services based on their carbon footprint and reward consumers who purchase carbon-neutral products with GOODcoins. RecycleToCoin is a digital platform that rewards consumers with coins for recycling plastic, aluminum, and steel cans. Once consumers return their recyclable items to local collection sites, they will be provided with unique Quick Response (QR) codes that can be exchanged for a reward. EcoCoin rewards users for their sustainable behavior, such as purchasing green products or bike to work. Mechanisms such as certified vendors, inspectors, and IoT sensors are used to verify the eco-behavior of individuals (Andoni et al., 2019).

Caveats exist. Blockchain developers should define their token policy carefully, such as tokens either serve as investment mechanisms or medium of exchange – but not both (Catalini and Gans, 2019). Token value is a function of platform size, the token supply, and the product or service value. Token economics should be considered when adopting a token policy.

To design an incentive system for rewarding sustainable behavior, systems should answer questions on what behaviors to award, how much to award, and what to include in smart contracts. User actions taken on the platform should be based on sustainable behavior and benefit business economic aspects. However, it is critical to address any misalignment between the business objectives of blockchain platforms and the final sustainability outcomes of rewarding eco-behavior.

One example is the potential "rebound effect" which is exemplified by improving the efficiency of energy services resulting in increased demand for energy services and an overall increase in consumption (Greening et al., 2000). Thus, the benefits of encouraging consumers to use blockchain platforms designed to incentivize eco-behavior may be offset depending on the extent of the behaviors and actions taken by participants to receive further incentives.

Other aspects to consider when designing a blockchain platform are deciding on the type of users who have access to the platform (clients and miners) and the type of blockchain platform to develop (permissioned versus public). For instance, public blockchain platforms such as cryptocurrencies are open to both clients, who join the network to trade cryptocurrencies, and verifiers or miners, who contribute to verifying transactions and receive reward for their contribution in executing consensus protocols. On the other hand, most private and permissioned blockchains do not require miners to verify information since consensus protocols are different in them and they do not call for public participation to verify transactions. Overall, some believe that permissioned blockchains are just shared databases.

Token generation is also different on permissioned blockchains, since tokens are just medium of exchange and can be used to trade goods or services. Innovative approaches can be used as well to create a system of exchange where users directly exchange goods or services for other services or goods with no need of any medium of exchange, such as token or money. This all depends on how the platform is programmed. For example, one can imagine a blockchain for trading emissions "permit" or "credit" in Cap-and-Trade (CAT) programs in which permits are viewed as the medium of exchange (e.g., local money) for trading on such platforms. For any clean alternatives that companies adapt, they are rewarded by credits where they can sell or trade their unused credits to other members.

In cryptocurrency blockchains, the crypto generation policy varies from one platform to another. For example, Bitcoin protocol is written such that Bitcoin is a nonrenewable source, and there is a total of 21 million bitcoins to mine, but Ethereum does not have any upper limits on the total coin supply. The cap for ether is 18 million per year. Overall, designing a digital platform and the economic models behind them requires exploring token economy models to investigate the value of each token and how to reward consumer behavior.

Consumer behavior is complex. User reaction to digital platforms requires further research. While designing tokens to incentivize eco-behaviors is a potential solution, many questions and challenges still exist. Monetizing digital platforms, the business models implemented in such platforms, and the degree of sustainability of such efforts are all concerns. While consumers are rewarded through tokenization for their sustainable behaviors, tokens earned should also be spent sustainably. For example, if individuals bike to work – a sustainable behavior – and receive tokens, then they can spend tokens on purchasing products unsustainably.

To design a blockchain platform to reward green behavior, several steps are necessary – see Fig. 9. The objectives of the platform should be defined, the behavior to reward should be determined, and the terms to include in a smart contract should be specified. Besides, the amount of incentive to offer users should be precisely calculated with effective business models, token economics, and sustainability consequences.

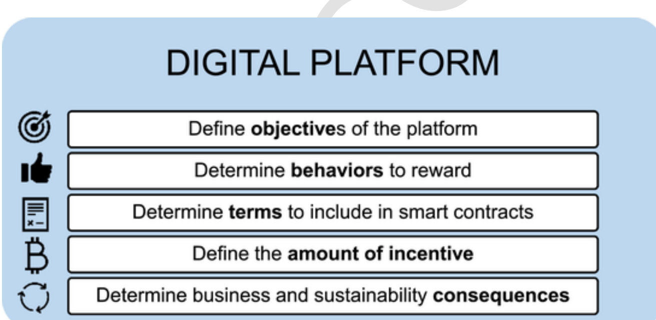

Fig. 9. The five steps to design incentive systems for rewarding green behaviors.

5.2. Enhance the visibility of the product lifecycle

The capabilities of Blockchain as distributed and decentralized databases are not limited to, reducing the need for central authorities and mediators. The decentralized and immutable nature of Blockchain, along with its identity protection feature, provides opportunities for different nodes of the network to record, use, and verify information on this public ledger while keeping their identity protected. Blockchain can enable manufacturers to monitor products during their entire lifespan and collect necessary data for better design, manufacture, sale, usage, and recovery of products. Traditionally, sharing data across a product's lifecycle was forbidden or infeasible. Blockchain can change the way the product lifecycle is captured, processed, and used. Different stakeholders or nodes of the network can participate in the collection, verification, and usage of the product lifecycle data. The smart contract behind the system defines when the data should be collected, who should collect the data, who uses the data, and what the amount of transaction fee and the incentive is. Blockchain has provided a way to improve the feasibility of shared product lifecycle data; the problem is the foreboding barriers. Sharing can help corporations integrate sustainability principles into their business models. A transparent and traceable product lifecycle can further close product lifecycle loops, decrease waste generation, decrease emissions, and engage governments, stakeholders, and users. Fig. 10 shows the integration of information flows throughout the product lifespan possible with blockchain.

Blockchain technology can manage shared product-centric information management platforms that facilitate the use of product lifecycle data by different stakeholders, especially for durable and capital goods industry sectors (Mattila et al., 2016). Blockchain can help manage public healthcare, user-oriented medical research, and drug counterfeiting in the pharmaceutical sector (Mettler, 2016). Blockchain technology can contribute to the development of smart cities through sharing devices (Sun et al., 2016). Blockchain can also: (1) facilitate paperwork processing in global container shipping; (2) identify counterfeit products in pharmacy supply chains; (3) facilitate origin tracking in the food supply chain for solving foodborne outbreak challenges, and (4) facilitate checking the status of sensor-equipped shipments in IoT-enabled supply chains (Hackius and Petersen, 2017). These actions can all contribute to environmental and social sustainability.

The auto industry can utilize blockchain vehicle identity (VID) that can be used for vehicle communication, traffic management, reducing carbon emissions, facilitating vehicle maintenance, and sharing self-driving car data, among other applications of VIDs (Ledger Insights, 2019).

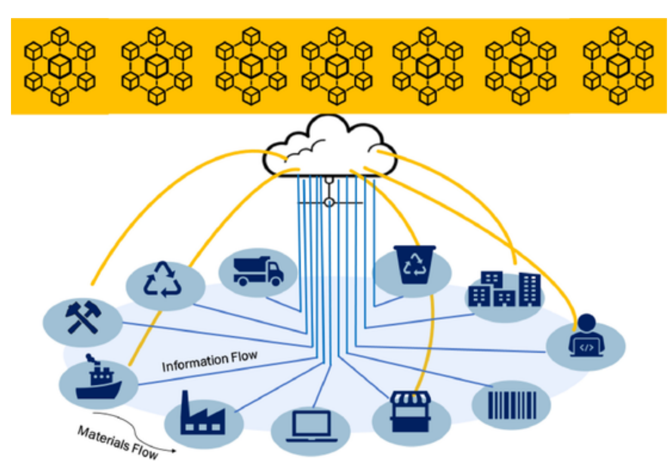

Fig. 10. Integration of information flow and material flow possible by blockchain (modified from (Moller, 2018)).

To clarify the value of information, we discuss several cases that a transparent product lifespan can support efficient operations planning and thus, sustainability.

Example 1: Bullwhip effect reduction: The "Bullwhip effect" causes significant supply chain inefficiencies and costs. It is typically due to each entity in the supply chain seeking to optimize their positions (Rabe et al., 2006). There are several remedies for eliminating bullwhip effect ranging from channel alignment and price stabilization to information sharing. Information sharing includes supply chain parties sharing point-of-sale data and basing their market forecast on these data. Blockchain can support information sharing. The smart contract can be employed to prohibit over-ordering of inventories, with the accurate, traceable and transparent transaction and inventory information. Fig. 11 summarizes the supply chain policies influenced by blockchain technology.

Unlike traditional centralized databases, Blockchain has several unique characteristics that help supply chain entities share data previously less comfortable putting on the cloud. First, the distributed design of blockchain facilitates multi-organizational business networks to communicate and share data with authorized parties. Permissioned or private Blockchains allow network initiators to define a set of rules to determine the level of authority of each participant. Second, smart contracts allow making agreements between participants on the type of information and credible transactions without the need for third-party interventions. Third, the digital signature allows establishing a cryptographically digital identity for network users and addresses data integrity and authentication. Fourth, the use of cryptographic hash functions helps encrypting transactions and makes Blockchain a tamper-proof ledger. Imagine a ledger with encrypted data recorded on it, where different users have access to information based on a set of predefined rules in a smart contract that defines the level and authority of each user in accessing, recording, retrieving, and evaluating data.

Example 2: Extended Producer Responsibility: Blockchain can aid extended producer responsibility (EPR). EPR is a type of product stewardship that forces original equipment manufacturers (OEMs) to take responsibility for their products even at the end of life phase and pay for the cost of product collection and recycling. Most EPR efforts have not been successful, particularly since it has been tough to track and monitor discarded and recycled products by brand category.

Currently, OEMs pay a fee to governments based on their market share. Once used products are discarded by end-users and recovered by a chain of remanufacturers and recyclers, the final processor or recycler who recover the materials will submit the paperwork to the government and receive payment based on the weight of materials recycled. The current EPR system has several deficiencies, mainly due to the missing connection between the actual product sold by OEMs in the market and the product recovered by the final processor. Designing a digital platform based on Blockchain technology that can incentivize proper recycling would mitigate existing EPR limitations.

Example 3: Efficient Transportation and Shipment Tracking

Blockchain implementation efforts are underway in logistics and transportation. Walmart is working with IBM and Tsinghua University to track the movement of pork in China using the blockchain concept. Maersk and IBM have addressed the problem of costly document processing of container shipments by developing a distributed permission platform accessible by different layers of the supply chain to manage document workflows, exchange information between different parties, and track shipments end-to-end (Sadouskaya, 2017).

SmartLog is a proof of concept project for IoT Blockchain in logistics and supply chain. The motivation behind SmartLog is to facilitate data flows associated with cargo, which are currently slower than the physical cargo movements. It is part of an industry-wide open-source platform for enabling different companies to find relevant logistics information in real-time. The information is gathered from information management systems of different companies, is filtered and sufficiently anonymized, and then added to a public transaction ledger for all parties and nodes of the network (SmartLog 2017; Sadouskaya, 2017).

Example 4: Food Safety, Food Recalls, and Traceability: Retailers and food companies have started using Blockchain for increasing the safety and traceability of the food supply chain. In addition to food safety, reduction of document workflow and creating an auto-

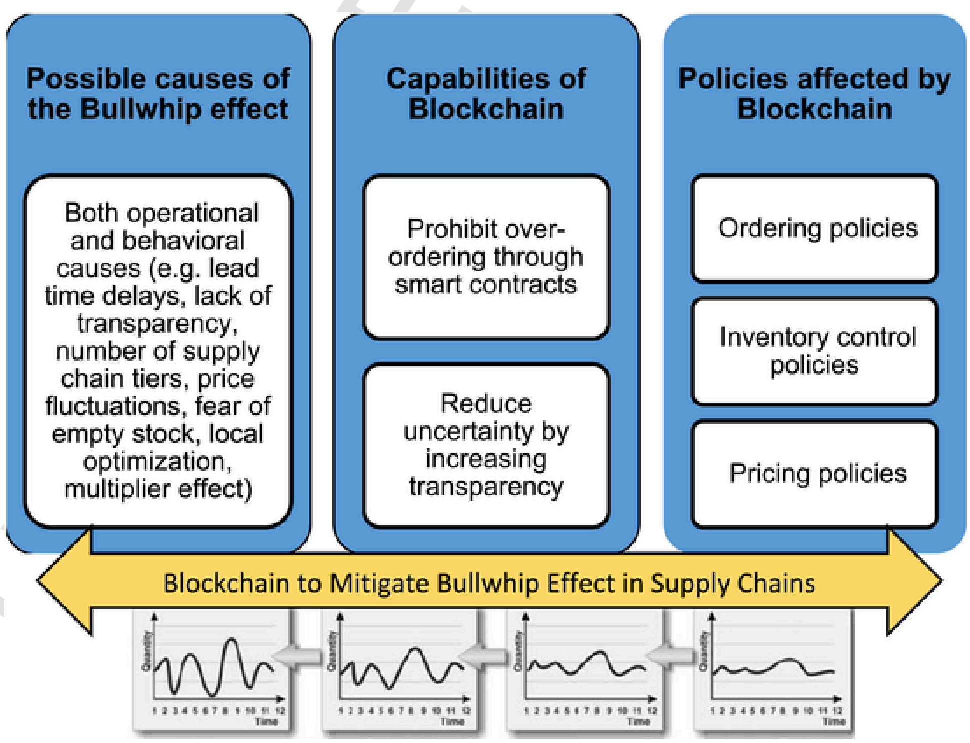

Fig. 11. Several causes of the Bullwhip effect and the capabilities of Blockchain.

mated billing and invoicing system is another motive behind using Blockchain in the food supply chain. A collaborative project between IBM and Brooklyn Roasting Company has shown the capabilities of Blockchain for tracking the bags of coffee through the supply chain to provide consumers with the product's journey over the entire supply chain. The BeefChain platform facilitates the tracking of “grass-fed” beef in Wyoming to offer trustworthy meat to consumers who already have paid a premium for grass-fed beef and ensuring that ranchers receive the payoff for diligently raised cows on open range condition.

5.3. Increase systems efficiency and decreasing development and operational costs

Two key cost elements are affected by Blockchain technology: (1) the cost of verification, and (2) the cost of networking (Catalini and Gans, 2016). The cost of verification is important in the exchange of goods and services between sellers and buyers. For transactions to happen, participants engaged in the transaction should be able to verify and audit the attributes of the transaction, including the credentials of the entities involved in the market transaction, the features of the goods and services exchanged between parties and any other contractual clauses. Blockchain reduces the cost of verification by reducing the need for intermediaries and facilitating the verification of transaction attributes.

Blockchain also reduces the cost of networking. In the case of developing a new platform, often entrepreneurs and developers use ICO or selling native or specialized tokens to crowdfund the cost of developing a new platform. The capabilities of Blockchain in reducing costs are particularly important given the point that traditionally intermediaries would gain more market power as a result of offering their intermediary services. However, in the case of Blockchain, the market power is distributed among different players in the network, social sustainability. Fig. 12 summarizes the cost efficiency of Blockchain-based platforms.

We should acknowledge that Blockchain is not free and is not sufficiently fast due to scalability issues; however, compared to traditional systems, Blockchain is faster and cost-effective. For example, in the case of the financial industry, money can be transferred anywhere in the world faster and cheaper than current inter-banking transactions that can take days and be quite expensive. The transaction fee on such networks goes as rewards to those nodes or users who serve as mediators or miners. Different types of incentive mechanisms such as Pay-Per-Share (PPS), Pay-Per-Last-N-Shares (PPLNS), and Proportional methods (Schrijvers et al., 2016) are designed to determine the amount of incentive for each miner based on their contribution and computational resources they spend to verify transactions.

Efficiencies also exist in trading markets. One example we discuss here is the energy trading market, which has direct and strong relationships with sustainability concerns.

Blockchain for energy trading market: several studies have discussed the capabilities of blockchain in the energy market. There have been proofs-of-concept for two electricity producers and one consumer connected over a blockchain to facilitate electricity trading (Sikorski et al., 2017). Mengelkamp et al. (2018) also applied the concept of a distributed decentralized information system, a private blockchain, to simulate a local energy market with 100 residential households. Li et al. (2018) described the application of blockchain in improving security in a peer-to-peer energy trading market, where the need for a central trusted entity is removed and transactions are confirmed by users on the network. Aitzhan and Svetinovic (2018) developed a multi-signature and anonymous encrypted messaging stream based on the blockchain concept that enables users to anonymously negotiate prices on a peer-to-peer energy market and securely perform trading transactions. Zhao et al. (2018) developed a transaction mechanism based on blockchain in which a two-phase trading process is followed: the call auction phase, and the continuous auction phase. For more information about the role of blockchain in the energy market, we refer readers to the review paper by Andoni et al. (2019).

While trading energy on peer-to-peer electricity networks has benefits such as reducing peak demand, minimizing the need for energy storage, and having a more reliable power system (Tushar et al., 2020), it does not necessarily reduce environmental footprints. Comprehensive lifecycle assessment methods are needed to investigate the scale and impact of peer-to-peer energy trading fully.

5.4. Enhance corporate performance reporting and sustainability monitoring capabilities

Blockchain helps corporations improve their sustainability reporting systems by assisting them to monitor, manage and report their activities properly. These capabilities not only help companies improve their performance but also increases consumer and stakeholders awareness of corporate sustainability practices (PWC 2018). In industry 4.0, the existing and future tracking technologies will enable businesses to mon-

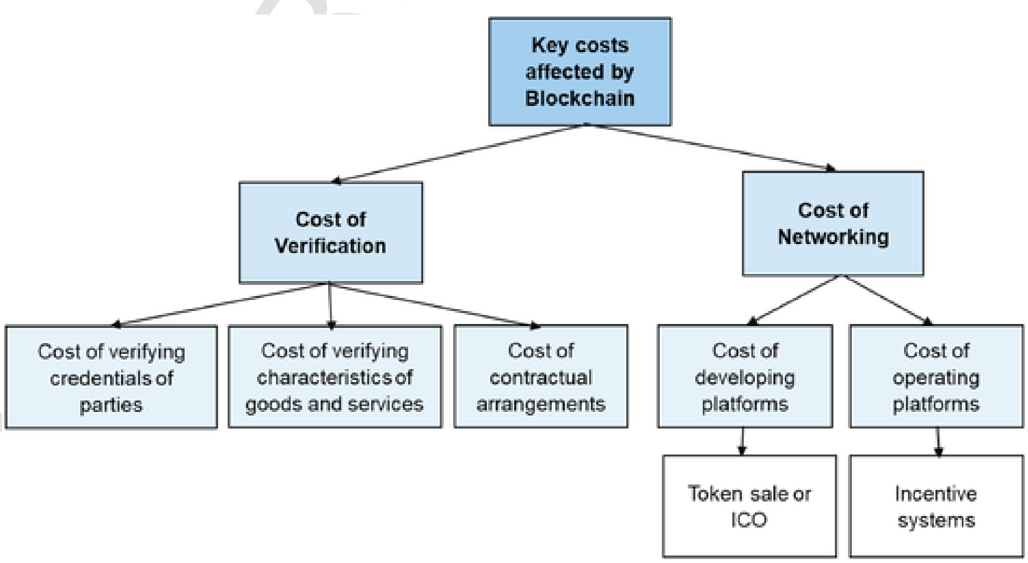

Fig. 12. Summary of the key costs affected by Blockchain technology.

itor products during their entire life span and collect datasets that require the development of more accurate allocation procedures for defining proportional shares of environmental burdens among different products and industries. This is valuable information for sustainability reporting from digital monitoring.

We should clarify that the potentials of Blockchain are not limited to only the above-mentioned categories, a wide range of use cases and pilots are underway ranging from social media platforms to protect individual data to systems for tracking the life of wild animals and protecting intellectual property. Table 3 provides examples of Blockchain ideas available in the market and the pillars of sustainability targeted by each use case.

A look at the progress of blockchain over time reveals the potential of this technology for reducing operational costs and increasing efficiency. Bitcoin, the first public blockchain originated in 2008, is extremely energy-intensive due to the consensus protocol behind the network. After bitcoin, other cryptocurrencies came to the market to solve Bitcoin's scalability issues. In 2014, the evolution of technology went beyond just cryptocurrencies, and the concept of Blockchain 2.0 received attention when the application of blockchain in other sectors as a solution to business issues has been promoted. The rise of permissioned blockchain platforms and new algorithms with lower computational power facilitate the adaption of the technology for solving business problems. As large tech companies are considering offering blockchain as a service (BaaS) and more computationally efficient private blockchains come to the market, companies are considering using this technology. A study by McKinsey identified over 90 use cases of blockchain in business applications, mainly for reducing operational costs of existing processes by applying blockchain for facilitating the exchange of transaction records among entities and removing intermediaries (Batra et al., 2019).

Table 3
Examples of Blockchain use cases and the sustainability pillars they affect.

Purpose	Examples	Sustainability Pillar		
		Economic	Social	Environment
Social media platforms to reward content creators and allow each user to control their data	Steemit, Indorse,	X	X	
Digital platforms for tracking the flows of goods, information, data, and documents	3IPK, BoxBit, IBM Supply Chain, Provenance	X	X	
Platforms to protect content ownership, intellectual property, and rights	Mycelia, Resonate,	X	X	
Platforms to reward green behavior (e.g. purchase and usage of energy-efficient, carbon-free products, use of low emissions transportation)	Energi Mine, CarbonX, RecycleToCoin	X		X
Tracking the life of wild animals and plants	Care for the Uncared (CfU)			X
Platforms for tracking charity projects, making the activities of aid agencies more transparent to increase trust	Alice, Aidcoin		X	

6. Adverse effects of Blockchain

While distributed ledger technologies have tremendous potentials to deliver benefits to society, they also raise certain social and environmental concerns. Like any technology, Blockchain is just a tool for enhancing system efficiency. Inspired by the natural capitalism dialogue by Hawken et al. (2013), a fundamental rethinking of the structure of commerce is needed to ensure that the use of technology is focused on getting the right things done beyond just doing something in the right way. Without linking Blockchain to a value-driven business model, focusing on only eco-efficiency would be disastrous for the environment by facilitating resource-saving in wrong business models, where materials are extracted faster and wrong products get to the market with lower cost. For example, consider a digital platform that connects consumers to vendors who reward consumers with coins for their sustainable behavior and consumers can spend their coins to purchase non-green products from vendors. Another example is a digital platform that facilitates shipments tracking and increases the efficiency of a geographically-dispersed supply chain with higher CO_2 emissions than local supply chains.

Another challenge is the computational-intensive nature of current Blockchain protocols. For example, the Bitcoin network suffers from several scalability challenges ranging from communication failures among users, data retention to linear transaction history (Barber et al., 2012), and miners competition on verifying transactions, which results in significant energy loss.

Several studies have estimated the energy footprint of Bitcoin. Mora et al. (2018) discussed that if Bitcoin follows the same rate of adoption of other broadly adopted technologies, then the CO2 emissions from Bitcoin alone is sufficient to push global warming above 2 °C. Krause and Tolaymat (2018) provided an estimate for the energy required to generate one US$ through mining cryptocurrencies and compared it with the energy required to mine one US$ from conventional mining of minerals (aluminum, copper, gold) and concluded that crypto mining consumes more energy to generate the same market value. Stoll et al. discussed that the information about the geographical regions and IP addresses of miners available through mining pools and websites that report the compositions of their mining pools will help in converting the energy consumption information to the greenhouse gas emissions metrics (Stoll et al., 2018).

As the technology matures, there will be ways to mitigate some of the environmental sustainability issues. For example, the Bitcoin scalability issue can be mitigated by avoiding broadcasting all the data to all nodes of the network using a subscription-based filtering service offered by a third-party cloud service provider. The Bitcoin users can be divided into two groups of verifiers or miners and clients. Verifiers are those users who verify transactions and create blocks and, as a result, mine coins, while clients are users who do not mine codes and only need to receive transactions payable to their accounts (Barber et al., 2012). Other consensus algorithms are coming to the market such as Proof-of-Stake (PoS) created by Ethereum in which miners validate the next block based on a chance proportional to their stake or Delegated Proof of Stake (DPoS) which limits the number of block creators (Konstantopoulos, 2018). However, often they sacrifice security for throughput, and they do not have full decentralization capabilities as Bitcoin's Proof-of-Work (PoW) protocol yet.

In addition to the scalability issue, the complexity of Blockchain, the need for a decentralized network of users, and immutable human errors are among the current limitations of the technology. Due to the immutable nature of Blockchain, verification of the initial information uploaded on Blockchain platforms is essential, since data recorded on the platforms are irreversible, and there should be mechanisms for preventing human errors.

Besides the limitations of technology, factors such as the lack of government regulations and the lack of trust among stakeholders are listed in the literature as barriers for Blockchain implementation (Yadav et al., 2020). Also, data safety, quality, accessibility, and documentation are other success factors for Blockchain in the supply chain (Yadav and Singh, 2020).

7. Discussion and research needs

Blockchain is in its early stage, and to achieve its full potential several forces should be at work to overcome the limitations of this technology. For example, the shortcomings related to the scalability of Blockchain should be addressed as the number of users and the size of Blockchain platforms increases, the privacy and security within the Blockchain networks should be enhanced, the computational efficiency and the energy consumption of Blockchain networks should be improved, more efficient consensus models and smart contracts should be designed, the future workforce should be educated on this technology, and its social and human dimensions should be better understood. In this section, however, we would like to elaborate on the research gaps in the sustainability area, given the opportunities offered by Blockchain and Industry 4.0.

Our review of the literature reveals the lack of scientific research on the important topic of sustainability of Industry 4.0 and Blockchain. While various concepts and principles can be developed to solve the aforementioned research gap, we have categorized the way that the scientific community can create conditions for emerging Industry 4.0 to benefit sustainability objectives under five main streams of research needs: (1) development of new performance indicators and life cycle assessment methods, (2) development of new data-driven decision-making techniques, (3) explore new case studies and best practices, (4) explore the role of product design, and (5) analyze the human-machine interaction.

The need for new performance indicators and life cycle assessment methods: The capabilities of Industry 4.0 enables businesses to monitor the entire product lifespan efficiently and collect previously inaccessible data that would benefit quantifying the actual environmental and social footprints of the product lifecycle. While the data collection capabilities have become advanced, the current LCA methods do not fully capture the opportunities created by these advancements. There is a mismatch between the advancement in Industry 4.0 and the environmental assessment fields. The traditional LCA method consists of four main phases of defining goals, inventory analysis, impact assessment, and interpretation of the results. While there is less argument on the way that Blockchain and Industry 4.0 would assist inventory analysis and data collection phase (Zhang et al., 2020), there is no evidence of advanced impact assessment methods developed in the literature to employ the value created in the inventory analysis phase. Therefore, new LCA methods are needed to address the existing gap in the literature.

The new impact assessment methods should be capable of uncertainty quantification to accommodate the heterogeneous nature of the product lifecycle representing the uncertain behavior of different users. In addition, new allocation models are needed to assign impacts to different impact categories accurately. Besides, the functional unit should be redefined as a product-service hybrid, which demands a new set of assessment methods that considers the impacts of both service and product. For example, integration of agent-based simulation and LCA models facilitates the collection and analysis of individual consumer data than traditional aggregate modeling of consumer behavior (Raihanian Mashhadi and Behdad, 2020; Davis et al., 2009).

The need for novel data-driven decision-making architecture: As new data acquisition technologies are emerging to the market, new software tools and data reasoning techniques are needed to analyze the collected data effectively, interpret results, and extract real-time decisions (Lee et al., 2015). There is a need for future data analytics infrastructure with at least the following capabilities: a uniform standard for data collection, exchange, and integration (Ćwikła, 2014), scalable architecture for analyzing a large volume of data (Wan et al., 2016), and a real-time platform for data processing and reasoning (Sheth et al., 2013).

The need for more case studies and best practices: Although a considerable number of studies have discussed the concept of Industry 4.0 and blockchain, the number of studies that have addressed the practical implementation of Industry 4.0's concept is very limited. Besides, the real case studies that have tackled sustainability issues, as well as benefits of Industry 4.0, are even more limited. The gap particularly exists in the context of manufacturing and supply chain, where future research is needed on the ways that IoT initiatives create sustainability outcomes for the entire supply chain entities.

The need for empirical evidence of the sustainability gains of Industry 4.0 efforts, data-driven decision-making and optimization techniques in circular economy practices, and the need for defining universally applicable metrics for evaluating integrated industrial symbiosis are examples of research needs that require immediate attention (Tseng et al., 2018).

The need for exploring the role of product design: The concept of manufacturing has grown beyond just manufacturing processes, and it covers the entire product lifecycle, including the entire spectrum of business activities. The best practice in improving the supply chain is to design the supply chain simultaneously at the time of designing products (Fixson, 2005) (Ellen MacArthur Foundation, 2013). Most of the sustainability-related issues of the product lifecycle should be tackled upstream at the early stage of the design. Therefore, it is particularly important to embed the design features compatible with the requirement of industry 4.0. For example, designing smart products and quality control systems would enable companies to offer mass customization capabilities in Industry 4.0 (Zawadzki and Żywicki, 2016). Smart products help companies have more control over their products, collect more transparent data about consumer usage behavior, and finally offer lifecycle oriented business models that assist them in monitoring a product during its lifecycle, closing product lifecycle loop and providing sustainable end-of-use collection and recovery options.

The need for analyzing human-machine interactions: Hawken and Lovins (Hawken et al., 2013) have extended the traditional definition of capital to include not only physical (goods) and financial capital (money) but also human (people) and natural capital (nature). They emphasized that businesses should fully value their human and natural capital without scarifying them, making trade-offs, or monetizing them. This is particularly important in the context of Industry 4.0, where new needs and opportunities are provided for workforce development (Gorecky et al., 2014). More research is needed on the way new technologies impact the workforce and the way human-machine interactions should be investigated (Schirner et al., 2013). The needs of Industry 4.0's operating force are different from traditional manufacturing settings in various forms, such as skill sets, flexibility, decision-making capabilities, and even the location of their service where most of the centralized physical factories are replacing with more cloud-based decentralized locations.

In addition to the above-mentioned research gaps, more research is needed in other areas ranging from workforce development to new business models based on value generation.

8. Conclusion

The paper summarizes the previous studies on Industry 4.0 for sustainable supply chains under three main groups of (1) IoT-enabled energy management, (2) green logistics and transportation, and (3) new business models such as servitization, sharing economy, and social manufacturing. Further, it reviews the capabilities of Blockchain, an emerging distributed ledger technology, as an enabler for the successful implementation of sustainability and circular economy concepts under four main categories of (1) promoting green behavior through designing specialized tokens, (2) enhancing the visibility of product lifecycle, (3) increasing systems efficiency and decreasing development and operational costs, and (4) enhancing corporate performance reporting and sustainability monitoring capabilities. The above-mentioned capabilities drive circular economy promises such as extending product lifespan, maximizing resource usage, and reducing emissions. The transparency on the type of materials used, traded, and reported opens new opportunities for implementing circular economy concepts with the help of both economic and regulatory forces.

The paper concludes with summarizing the research gaps and the ways that the scientific community can participate in creating conditions for Industry 4.0 to assist sustainability objectives. Five directions for future research have been discussed, including the development of new performance indicators and LCA methods, development of new data processing and reasoning techniques, development of novel design strategies, implementation of industry-scale case studies and best practices, and finally, analyzing the needs of the future workforce.

Future studies are needed to enhance the current paper. First, the lack of available successful implementations of blockchains in practice limits the full validity of the discussions provided in the paper. Blockchain is still in its growing phase, and many shortcomings should be overcome before its sustainability consequences are observed in practice. Second, our discussion was mainly focused on environmental sustainability; therefore, the social and economic aspects of Blockchain require further analyses and discussions. Third, as businesses are adapting other technological advancements possible through artificial intelligence and machine learning infrastructure, more discussion is needed on the proper connection of Blockchain with other complementary IT infrastructure in place towards sustainability. Fourth, Blockchain is just a tool, and sustainability consequences of it mainly depend on the underlying vision and strategies that businesses select to govern their daily operations. Therefore, further studies are needed to optimize the set of business strategies along with the choice of technology towards sustainable development goals. Future analyses should consider the complexity of multi-layer supply chains and the needs of multiple stakeholders. Finally, as the concept of distributed ledger technologies or better say computer networks evolve over time, new sustainability discussions arise that require opinions of both researchers and practitioners.

CRediT authorship contribution statement

Joe Sarkis: Writing - review & editing. **Kemper Lewis:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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