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ScienceDirect

Procedia Computer Science 200 (2022) 638–647

Procedia Computer Science

www.elsevier.com/locate/procedia

3rd International Conference on Industry 4.0 and Smart Manufacturing

Blockchain technology needs for sustainable mineral supply chains: A framework for responsible sourcing of Cobalt.

Godfrey Mugurusi[a]* and Emmanuel Ahishakiye[b]

[a]*Department of Industrial Economics & Technology Management, Norwegian University of Science & Technology, Norway.*
[b]*Department of computer science, Kyambogo University, Kampala, Uganda*

Abstract

Blockchain technology has recently become the go-to solution for companies and industries that seek to enhance value chain traceability of their products, and transparency in their supply chains. Because of these benefits, it's been proposed for monitoring environmental, social, and governance (ESG) performance and compliance in industries that have weak regulatory and formal structures. The cobalt mining industry especially in the Democratic Republic of Congo, the world's biggest producer of cobalt ore used in the manufacturing of lithium-ion batteries, is one such environment that's characterized by conflict, and serious human rights abuses. The key actors in the cobalt supply chain, therefore, face the tradeoff involving maintaining long-term supply versus reducing the risks associated with cobalt sourced from locations with poor environmental and human rights records. Most of such problems emerge from Artisanal and small-scale mining. This paper presents an attempt to tightly link existing blockchain technology frameworks in the cobalt industry with ESG performance of companies to enable them to audit the chain of custody journeys for their components and ultimately sustainability performance. We present a responsible sourcing framework to connect blockchain source data needs to ESG metrics to help companies build interoperable but understandable blockchain architectures.

Keywords: Responsible sourcing; Blockchain technology; Cobalt supply chains; sustainable supply chain management; Environmental, Social and Governance

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* Corresponding author. *E-mail address:* godfrey.mugurusi@ntnu.no

10.1016/j.procs.2022.01.262

1. Introduction

The rapid transition to electric mobility and low carbon energy ecosystems globally has placed a significant amount of pressure on critical metals not just for the mobility solutions but also for aerospace, defense, energy, electronics industries which compete for these same resources. The critical metals in these industries that include tantalum, indium, rare earths, cobalt, nickel, manganese, tellurium, aluminum, graphite, and many others, have hit a peak as demand for cell phones, laptops, cameras, power tools, electric vehicles (EVs), etc. grows exponentially [1]. The soaring production and sales of EVs especially in Europe and North America has put pressure on the mining of lithium, graphite, and cobalt, which raises so many questions on sustainability in these supply chains [2] [3]. This paper focuses on the mining of cobalt especially from the Democratic Republic of Congo (DRC) which accounts for 60% of the world's total cobalt reserves and supply [3] [4].

Sustainability in cobalt mining has become a key issue mainly because cobalt has become a key component in the manufacture of lithium-ion batteries, yet its supply chain is rather opaque [2]. Also, because large EV carmakers are increasingly trying to secure long-term supply especially from supply chains that value human and workers' rights, social and environmental welfare as well as lower greenhouse gas (GHG) emissions [5]. Yet most cobalt production in DRC comes from the conflict-ridden Katanga Copperbelt which is presently policed by the United Nations Organization Stabilization Mission in the Democratic Republic of the Congo – MONUSCO [6]. In addition, both [4,7] show that cobalt mining in this region is largely dominated by artisanal or small-scale mining (ASM) using rudimentary tools in very hazardous environments. According to [5], there are about 255000 artisanal miners for cobalt in the DRC, "35000 of whom are children working in exceedingly harsh, hazardous, and toxic conditions". Both [4,6] cite an extremely high cobalt load in the environment and among ASM miners hence possible oxidative DNA damage. In spite the need to secure long-term supply, no company wants to be involved in financing conflict in mineral production areas. This supply chain problem affects investor confidence and breaches several laws, regulations, and global industry standards, including the EU's conflict minerals regulations, International Council on Mining and Metals (ICMM) standards, and OECD's due diligence guidance for the supply of minerals in conflict and high-risk areas (OECD DDG) [2,3]. The mining industry especially the regulators, certification organizations, and the large-scale and industrial mining companies (LSMs) propose blockchain technology to address some of these challenges [8]. Three well-publicized cases of blockchain technology in the mining industry includes Australia's Everledger blockchain system to track dirty diamonds and reduce document fraud in the diamond mineral value chain [9], UKs Provenance to track environmental certification data along the supply chain, and the French company Stratumn's cryptography-based system for end-to-end traceability for chemical supply chains [1]. Two LSMs BHP Billiton and De beers are heavily investing in BcT to increase transparency and increase environmental, social, and governance (ESG) in their operations.

Blockchain Technology (BcT) is a form of distributed ledger technology used to record information in a database in a way that makes it difficult to change or hack into since the system creates a permanent record of all of the transactions that ever took place among the participants [28]. The potential strengths of using BcT in the mining industry would include: enhanced security, flexible and efficient, robust and therefore can recover from attacks or failure, independence from the third party which improves on the trust of the system, allows multiple access, reliability of the system, less redundant due to peer-to-peer collaboration, offers low transaction cost, and its auditable and verifiable. However, BcT has several pitfalls which include the following: latency where BcT requires a minimum of 10 minutes to ensure sufficient security for each transaction, complicated usability, lack of legislation and regulation, the challenge of identity crisis during the transaction, anonymous transactions that may be difficult for the government to regulate, less throughput during transactions, the transactions are non-erasable which could be an issue in case of an error, and also there are higher chances of cyber-attack in BcT [29]. In addition, the absence of use cases of BcT in the mining sector could be explained by misunderstanding of the data requirements such block chains shall need [41]

Thus, the purpose of this paper is to identify the data sources for the environmental, social, and governance reporting in the mining of cobalt and then examine where blockchain technology can facilitate responsible sourcing of cobalt focusing on ASM in DRC. There exists a plethora of studies on the application of BcT for traceability in agriculture [10], food waste management [11], and the mining industry itself [8, 12]. Perhaps the most important application for this study to benchmark is the mine-to-market blockchain visualization by [1] to help companies' pilot how the chain of custody (CoC) for cobalt production should work. The challenge of the framework in [1] and many applications is the inherent assumption that traceability and provenance translate to better ecological, economic, and social outcomes, especially in the cobalt mining industry. Traceability is just a mechanism to monitor and analyze different sustainability aspects but does not guarantee better ESG outcomes [13]. Moreover, the nuanced link between traceability and sustainability makes the environmental impacts of cobalt extraction and processing seem underrepresented. Therefore, a BcT framework that embeds environmental sustainability in the cobalt supply chain is needed taking into consideration the following aspects:

- That 20% of 60% of the world's cobalt production is ASM [4]
- That current literature on the sustainability of cobalt mining is significantly skewed to consumption and not production and is largely dominated by LSMs who control over 70% of the cobalt market globally [2,5].

As such, the following research question will be answered:

RQ: *Where and how can sustainability considerations be embedded in a blockchain-based system to enable responsible sourcing of cobalt from ASMs?*

The paper presents the state of the art, the methodological approach follows, and then the analysis and discussion follow. In the end, the conclusion and outlook for future research are presented.

2. The state of the art

To answer RQ in section 1, it is important to first understand the significance of sustainable supply chain management (SSCM), and from which shall define and focus on the concept "responsible sourcing".

Sauer and Seuring [30] adopt a definition of [31] to define SSCM as "the creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term". Sauer and Seuring [30] cite several benefits of SSCM in the mining sector, including reduced risk especially associated with reputational damage, better governance which reduces environmental impact and ensures continuity of supply, but most importantly SSCM enables better integration which reduces costs and ensures primary supply stability.

It appears that responsible sourcing not only upholds the benefits of SSCM but also provides the mechanism of implementing SSCM. The international chamber of commerce [14], and [2] among others, have argued that "responsible sourcing" enables companies to promote environmental stewardship and the respect of human rights in the supply chain. [15] defined "responsible sourcing" is 'the management of social, environmental and/or economic sustainability in the supply chain through production data". This definition infers that environmental sustainability risks emerge from several pain points in the supply chain. We shall review those risks going forward and tease out how the literature considers ESG aspects in the cobalt supply chain.

The study by [1] mapped the entire cobalt from source to battery supply chain to illustrate the key actors, their interactions, and the processes. The adapted version shown in Fig. 1 will help us identify and outline the sustainability risks from which we shall argue, can be addressed by a conceptually grounded BcT framework for responsible sourcing.

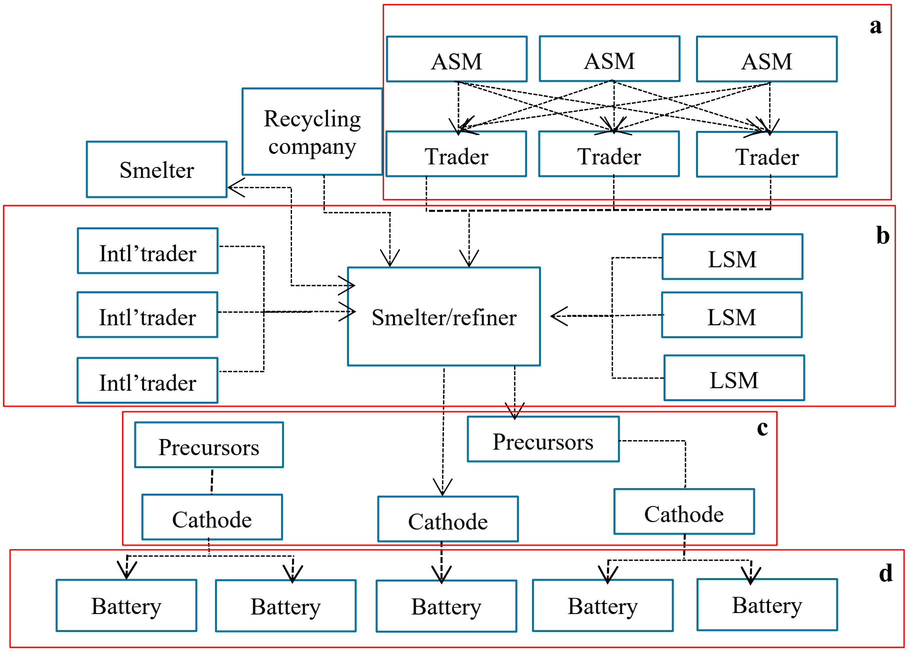

Fig. 1. An adapted figure of the cobalt supply chain [1]

In Fig.1, **Four** categorizations have been identified to highlight the sustainability bottlenecks for some of the key actors in the cobalt supply chain drawing examples from the DRC.

- Mining and extraction processes including grinding, crushing, and compaction occur in category **a**) [3,16]. In this category, the interactions between ASMs and traders is one which [4] describes as in "precarious" because of the balance of power skewed against artisanal miners who work in very risky conditions. The ASMs sell their ore to predominantly Chinese trading centers ("*comptoirs*") who have stronger negotiating power because of their contracts with the LSMs and the DRC government in this case [4]. [5] cites serious human rights abuses, poor working conditions, and as well a high potential for conflict. [6] found reports grave health concerns in water in the Katanga region. [3] cites child labor and air pollution from drilling and dust blasting which affects people.
- Pre-trade processing and smelting largely for export occur in category **b)** [1, 16]. This category involves smelters, international traders, and LSMs that generally work closely with regulators and draw operational licenses from governments [16]. [4] cites deep-rooted corruption in commercial bargaining between governments and mining companies which leaves ASM disadvantaged. In addition, [8] cite the outsourcing of responsibility by global and LSMs in order to reduce operational and labor costs but this shifts risks to works and ASMs and fuels insecurity.
- Cathode production occurs in category **c**) [1,16]. This category involves actors in the cathode and precursor materials market. The preparation of precursors and manufacturing of active cathode materials is a chemical process that is energy-intensive and depending on the cobalt grade, is associated with high GHG emissions [17]. According to [2], lithium-ion batteries are recyclable primarily for the valuable cobalt and nickel which is also an energy-intensive process and produces toxic byproducts that are harmful to the environment. The [3] cites long-lasting impact on biodiversity, and reports about toxic waters due to high levels of lead in drinking water for people.
- Batteries and industrial components production occurs in category **d**) [1]. In this category, the focus is on the end-use of the final product by OEMs and other component manufacturers. The exponential demand for cobalt

has put a lot of pressure on fragile ecosystems. [5] cites the case of Chile where mining activities in parts of the Atacama Desert have been drained of water which has affected local farmers. Due to pressure, the study [3] on cobalt mining has cited human rights abuses including the emergence of violent armed groups due to land conflicts and disagreements with government concessions to LSMs.

So, to develop a BcT based framework that shall help companies characterize responsible sourcing practices, one needs an outline of what responsible sourcing is. The study [17] presents six steps that companies can take to influence and monitor ESG performance of their supply chains. A closer look suggests that these six steps are primarily the interface between the firm and its suppliers and tend to focus on supplier compliance with the firm's internal processes as well as suppliers and the firm's compliance with stakeholders' requirements such as third-party certifications shown in Fig.2.

In Fig.2, responsible procurement processes focus on monitoring relations with suppliers and ensuring that suppliers meet the firm's environmental and social obligations [14,15]. Supplier selection decisions ensure that buyers conduct environmental and source risk analysis in the cost-benefit analyses [14]. Managing stakeholder relationships includes among other things building consumer trust and ensuring compliance with regulatory requirements in the markets the firm operates.

All the 3 sub-processes a), b) and c) in Fig. 2 can be digitized using the BcT. To check for compliance (a), [18] show that BcT enables transparency which eases supplier compliance checks. [19] argue that suppliers too can keep track of their social sustainability performance using BcT. To ensure trust and monitor compliance (b), [20] show the value in the characteristics of BcT to allow different stakeholders to negotiate and find consensus on trust, transparency, security, and accountability. To ease tracking (c), [21] show that BcT can provide full tracking capabilities of material and energy traceability enabling ease of predictions for material recycling and reuse.

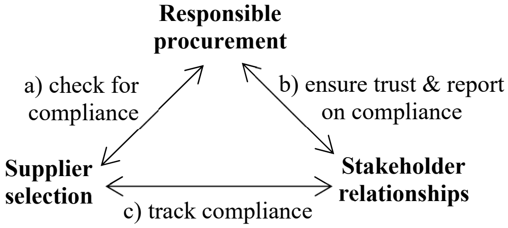

Fig. 2. framework to illustrate key responsible sourcing tenets [14]

In sum, this state of the art demonstrates using different sustainability frameworks that BcT has the potential to enable responsible sourcing of cobalt from ASMs.

3. Methods and Materials

This paper is based on the document analysis method. [22] defines document analysis as a systematic procedure for reviewing or evaluating documents of any type especially those that have been recorded without a researcher’s intervention to elicit meaning, gain understanding, and develop empirical knowledge. We adopted a two-pronged approach. Firstly, we reviewed and synthesized a number of cobalt mining industry documents and standards that address “BcT applications in the mining industry”. These reviewed are sustainability standards and schemas are shown in Table 1 that were identified by the [3] as the most relevant for cobalt production in the DRC. These standards were assessed by [3] for *comprehensives* **(c)** i.e., the depth in the environmental criteria they considered, *level of detail* **(d)** i.e., prescriptiveness of the standards, *accountability* **(a)** i.e., how the standards assure compliance, *transparency* **(t)** i.e., how the mineral origin is certified, *governance* **(g)** i.e. who is involved in drafting the standards, and *scale* **(s)** i.e. the scope of adaptability of the standard to other industries.

Table 1. Sustainability standards [3]

Standards	**(c)**	**(d)**	**(a)**	**(t)**	**(g)**	**(s)**
Global reporting initiative (GRI) G4 standard	O	∅	⊗	⊗	O	∅
International Finance Corporation (IFC) Universal standard	O	O	⊕	⊗	O	∅
Initiative for Responsible Mining Assurance (IRMA) standard	O	O	∅	⊕	∅	O
Mining Association of Canada (MAC) Towards Sustainable Mining (MAC TSM)	⊕	O	∅	⊗	O	⊕
International Council on Mining & Minerals Sustainable Development Framework	∅	⊕	∅	⊕	⊕	∅
Certified Trading Chains (CTC) BGR scheme	∅	⊗	O	∅	⊕	O

Key: O *for very good:* ∅ *for good:* ⊕ *for fair:* ⊗ *for poor*

Secondly, we triangulated the documents in Table 1. with articles sourced from mainly the Web of Science core collection, a comprehensive online subscription-based scientific citation and indexing database. To conduct a replicable document analysis, it is very important to review articles from high-quality data sources [32]. A method similar to the PRISMA (the Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was used for the identification of the relevant research articles [33]. This approach involves four steps which include (i) Identification Phase, this phase involved acquiring articles from various sources; (ii) the screening process. During this phase, article duplicates were excluded, and also inadequate articles were removed. (iii) Eligibility phase. We analyzed articles to determine their eligibility for further review. Ineligible articles were excluded. (iv) The final phase is called the included phase. Studies that presented BcT applications in the mining industry were considered during this study.

2.2 Process description and Inclusion criteria

The process started with a dummy run based on keyword-based searches in three of the biggest databases: Google Scholar, Scopus, and Web of Science (WoS) for publications related to "blockchain technology applications in sustainable supply chains". This search generated a total of 23747 hits where most articles were cross-listed in all the three databases, with google scholar generating even more non-peer-reviewed literature that was not relevant for this paper. So, we focused our attention on the WoS collection, which compares very well with Scopus [34]. According to [34], WoS citation data often shows better reproducible results and is seen as the standard for bibliometric and meta-analysis studies. We re-run a refined within WoS core collection using the following search key: "*(TOPIC: (Sustainability) AND TOPIC: (blockchain technology)"*. We refined the search by: DOCUMENT TYPES: (ARTICLE) and the timespan: 2010-2021. The following indexes were considered: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, and ESCI. The results were **141 hits**, which we screened for "English language only articles".

2.3 Exclusion criteria

We then individually read the 141 articles and manually excluded articles that did not address the "Supply chain" context and whose keywords/abstract excluded the terms "blockchain" and "sustainability". We also excluded articles that focused on "sustainable microgrids design using blockchain technology", "broad technologies like IoT, big data analytics", "crypto-economics", "use of blockchain for the sustainability of smart cities". In the end, **44 articles** that were included in this study were analyzed during the next phase.

4. Analysis and discussion

The analysis in this section confirms that sustainability considerations — which in this case are the ESG dimensions drawn from the industry standards in Table 1 can be embedded in a blockchain-based system to enable responsible sourcing of cobalt from ASMs in the DRC. BcT continues to remain a big force for ESG implementation in supply chains, despite firm-specific constraints such as its immaturity, technology inaccessibility and the absence of real-world applications that have been associated with the technology (see: [35, 36]. Generally speaking, [37] suggest that BcT properties of traceability, transparency and reliability of decentralized data enable access to real-time quality information that (i) facilitates the process of reproducing and recalling products in sustainable supply chains; (ii) encourages better ways of monitoring and storing data-related activities responsible for pollution and environmental degradation, (iii) and allows real-time collection and analysis of green or low carbon data for timely decision making. That way producers and manufacturers can easily monitor and measure the carbon footprint of each of their products and processes by sharing accurate and authentic information and enhancing traceability.

The Table 2, with data from the literature reviewed, shows the linkages between the ESG dimensions and the data source metrics that emerge from the mine-to-market BcT pilot framework in [1]. What we demonstrate in this paper is the possibility of linking the existing BcT source data with the ESG measures which companies can use to monitor, track and trace internal compliance as well as supplier compliance. To the best of our knowledge, the absence of scalable and interoperable but understandable BcT architecture has been the main challenge for key actors in this industry to audit their sustainability and CoC journeys of their components [21, 24, 26].

Both [21, 23] show that BcT can indeed provide comprehensive information regarding each product and its supply chain to enable sustainability assessment and reporting. [25] show that BcT can be a very useful tool for corporate reporting, traceability, and sustainability reporting as it provides a trustable and transparent way to track and trace products from their origins as basic raw materials to the final customer hence mitigating the risk of counterfeit or illegal goods and products. [26] show that BcT based technologies can reduce verification costs by substituting data-verified practices for human-verified practices. Moreso, it was revealed from the literature that integrating BcT with other technologies like Enterprise Resource Planning systems (ERP) [38], Internet of Things (IoT) [39] and Artificial Intelligence (AI) [40] may result in a powerful tool to improve supply chain operations.

Besides facilitating monitoring ESG compliance among suppliers and providing the history of compliance, we see that BcTs also improves collaborative efficiency by replacing intermediaries and reducing informal practices [27]. This is arguably the other biggest challenge for ASM in the DRC, and thus the inability for companies to see through the environmental blackbox of ASM.

Table 2. A BcT-based framework for responsible cobalt sourcing practices

RESPONSIBLE SOURCING TENETS	**Supplier selection decisions** [14]		**Responsible procurement** [14, 15]		**Stakeholder relations management** [14]	
KEY COBALT SUPPLY CHAIN PROCESSES (a to d)	ESG dimensions	blockchain source data	ESG dimensions	blockchain source data	ESG dimensions	blockchain source data
(a) Mining and extraction processes	〉Human rights 〉 OHS 〉 Land use 〉 Water use 〉 Waste management 〉 Fair business practices	〈 mineral source 〈 mineral provenance	〉 Human rights 〉 OHS 〉 Land use 〉 Water use 〉 Waste management 〉 Fair business practices	〈 mineral source 〈 mineral provenance 〈 mineral grade	〉 Noise & air pollution 〉 Human rights 〉 Biodiversity 〉 Land use 〉 Water use 〉 Fair business practices	〈 mineral source 〈 mineral provenance
(b) Pre-trade processing & smelting	〉 Local value addition 〉 OHS 〉 Waste management 〉 Fair business practices	〈 mineral source 〈 mineral provenance	〉 Local value addition 〉 OHS 〉 Waste management 〉 Fair business practices	〈 mineral source 〈 mineral provenance 〈 mineral grade	〉 OHS 〉 Land use 〉 Water use 〉 Fair business practices 〉 GHG emissions	〈 mineral source 〈 mineral provenance
(c) Cathode production	〉 Water use 〉 Energy use 〉 Waste management	〈 mineral source 〈 mineral provenance 〈 Mass balance	〉 Water use 〉 Energy use 〉 Waste management	〈 mineral source 〈 mineral provenance 〈 Mass balance	〉 Energy use 〉 GHG emissions	〈 mineral source 〈 mineral provenance 〈 Mass balance
(d) Batteries & industrial components manufacturing	〉 Energy use 〉 GHG 〉 Recycling 〉 Governance 〉 Waste management	〈 mineral source 〈 mineral provenance 〈 Mass balance	〉 Energy use 〉 GHG 〉 Recycling 〉 Governance 〉 Waste management	〈 mineral source 〈 mineral provenance 〈 Mass balance	〉 Governance 〉 Waste management 〉 Fair business practices	〈 mineral source 〈 mineral provenance 〈 Mass balance

5. Conclusion and Outlook

This paper sought to find out where and how sustainability considerations can be embedded in a blockchain-based system to enable responsible sourcing of cobalt from ASMs. The study focused on the significance of ASM to the global cobalt feedstocks and ASM in the DRC where social conflict and environmental risks have been cited following the surge in demand for cobalt driven by the demand for clean, green technologies and mobility solutions. We focus on the end-to-end supply chain of cobalt as a key component of lithium-ion battery production.

Our findings show that the ASM industry in the DRC has weak formal structures which makes it difficult for miners, LSMs, regulatory institutions, and the global cobalt certification industry to maintain end-to-end visibility in these circumstances. The lack of transparency has significant implications for the environmental, social, and governance (ESG) impacts of this industry. We agree with several industry studies and company reports that blockchain technology (BcT), even if not a panacea to this problem, offers solutions to overcome the challenges associated with ESG monitoring and compliance at different levels of the supply chain. However, the strong focus of BcT today in the cobalt supply chain is on traceability and governance of the chain of custody but not necessarily on ESG considerations.

This paper argued that traceability and transparency are just one aspect where BcT can be useful. The other we have proposed in this paper is to piggyback ESG metrics to existing BcT source data which we show in Table 2. This way existing BcTs can directly facilitate responsible sourcing of cobalt from ASM activities. Through BcT based architecture firms can responsibly source, monitor, measure and report their environmental and social performance in their supply chains to their stakeholders and shareholders.

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