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Integration of Blockchain Technology in the Sustainable Supply Chain Management

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Zayed Khalifa

Faculty of Information Technology
University of Zawia
m.zayed@zu.edu.ly

Imen Rahal

Faculty of Economics and Management of Sfax
University of Sfax, Tunisia
imenerahal96@gmail.com

Abstract

Supply chain sustainability (SCS) aims to create long-term economic, social, and environmental value. Blockchain Technology (BT), as a foundational technology, represents a significant development in the advancement of sustainability in the Supply Chain (SC). Research on the potential impact of BT on SCS is still limited, despite its growing role in improving SC efficiency and societal changes. The main objective of this study is to fill this knowledge Gap by synthesizing existing literature. Most studies focus on the economic implications of blockchains, highlighting their transformative potential, including the creation of new economic models, increased operational efficiency, economic advantages, and opportunities for value creation. However, BT also offers social benefits, fostering trust among partners, enhancing food safety, supporting humanitarian logistics, and promoting social equity. Additionally, it can contribute to environmental efforts by reducing pressure on energy and natural resources and enabling the creation of environmentally friendly products. In conclusion, BT has the potential to bring about significant changes in .the economic, social, and environmental dimensions of SCS.

Keywords: Supply Chain, Blockchain Technology, Supply Chain Sustainability.

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زايد العربي خليقة
كلية تقنية المعلومات
جامعة الزاوية
m.zayed@zu.edu.ly

إيمان رحال
كلية العلوم الإقتصادية و التصرف
بصفاقس، تونس
imenerahal96@gmail.com

الملخص:

تهدف استدامة سلسلة التوريد إلى خلق قيم اقتصادية واجتماعية وبيئية طويلة الأمد. تعتبر تقنية البلوكتشين تقنية أساسية وتطورًا هامًا في تقدم استدامة سلسلة التوريد. لا تزال الأبحاث حول التأثير المحتمل لتقنية البلوكتشين على استدامة سلسلة التوريد محدودة، على الرغم من دورها المتزايد في تحسين كفاءة سلسلة التوريد والتغييرات في المجتمع. الهدف الرئيسي لهذه الدراسة هو سد هذه الفجوة المعرفية من خلال تجميع الدراسات السابقة. تركز معظم الدراسات على الآثار الاقتصادية لتقنيات البلوكتشين، مبرزة إمكانياتها التحولية، مثل إنشاء نماذج اقتصادية جديدة، وزيادة الكفاءة التشغيلية، والمزايا الاقتصادية، والفرص لإيجاد القيمة. ومع ذلك، تقدم تقنية البلوكتشين أيضًا فوائد اجتماعية، مثل تعزيز الثقة بين الشركاء، وتعزيز سلامة الطعام، ودعم اللوجستيات الإنسانية، وتعزيز العدالة الاجتماعية. بالإضافة إلى ذلك، يمكن أن تسهم في الجهود البيئية من خلال تقليل الضغط على الطاقة والموارد الطبيعية وتمكين إنتاج منتجات صديقة للبيئة. في الختام، تحمل تقنية البلوكتشين الإمكانات لإحداث تغييرات كبيرة في الأبعاد الاقتصادية والاجتماعية والبيئية لاستدامة سلسلة التوريد.

الكلمات الرئيسية: سلسلة التوريد، تقنية البلوكتشين، استدامة سلسلة التوريد .

1. Introduction

Supply chain sustainability (SCS), with its overarching goal of establishing enduring economic, social, and environmental value, has emerged as a pivotal pursuit in contemporary business practices. A key catalyst in this pursuit is the advent of BT, signifying a noteworthy stride in advancing sustainability within the supply chain domain. Despite the increasing prominence of BT in enhancing SC efficiency and driving societal changes, the exploration of its potential impact on SCS remains relatively limited.

This study endeavors to address this knowledge gap by synthesizing existing literature and shedding light on the multifaceted implications of BT on SCS. While numerous studies have predominantly focused on the economic dimensions of BT, underscoring its transformative potential through the creation of novel economic models, heightened operational efficiency, economic advantages, and avenues for value creation, it is crucial to recognize that BT extends beyond mere economic considerations.

Notably, BT also unfolds a spectrum of social benefits, playing a pivotal role in nurturing trust among supply chain partners, bolstering food safety protocols, supporting humanitarian Logistics endeavors, and championing the cause of social equity. Furthermore, the environmental dimension is not overlooked, as blockchain technology emerges as a valuable ally in reducing the strain on energy and natural resources, thereby facilitating the production of environmentally friendly products.

In essence, this study contends that BT, with its diverse applications, possesses the potential to instigate substantial transformations across the economic, social, and environmental facets of SCS. Through a comprehensive examination of the existing literature, we aim to contribute to a more holistic understanding of the role BT plays in shaping the sustainable future of S C.

2. Literature review

2.1. Blockchain Technology (BT)

The BT functions as a decentralized digital ledger capable of distributing and storing data. It is also recognized as a distributed ledger, operate on peer-to-peer (P 2P), or decentralized network, comprising a continuous sequence of blocks.

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Deshpande et al., (2017) indicates that the terms blockchains and digital ledgers are generally interchangeable.
Within a blockchain network, all participants can simultaneously share and record blocks, which require verification and validation from every user in the network. Blocks are interconnected through a cryptographic hash function. Each .transaction is traceable by examining the block information connected through hash keys (Fu et al., 2020; Kim and Kim, 2024). Advocates of blockchain asserts transparency, speed, accessibility, and non-falsifiability as the fundamental principles of this innovative paradigm (Wang et al., 2020). Yadav et al., (2023) propose that blockchain is a decentralized database containing sequential, cryptographically linked blocks of digitally signed asset transactions, governed by a consensus model.
Every ledger is encrypted and sent to the block network with a timestamp, resulting in the integration of all blocks in a chronological sequence, much like a comprehensive book. Essentially, if a user intends to modify a record, they must amend the entire set of book records. This is because blockchain relies on a distributed database that stores all data, emphasizing distributed computing rather than centralization. To put it differently, hackers won't succeed by altering information in just one block.
Distributed computing not only reduces the cost of computation but also addresses data security concerns, as all participants share the same book. Furthermore, in a blockchain, each node uses a peer-to-peer (P2P) approach to transfer data, minimizing the expenses associated with achieving decentralization. With no centralized server, all data is distributed and stored on individual computers, preventing any organization from altering data without consensus across the entire blockchain network. Conversely, when a new transaction occurs throughout the network, every participant will verify and incorporate it into their respective (books) (Surjandari et al., 2021).
Even though blockchain technology is relatively recent, it has undergone three generations of development. This includes

Blockchain 1.0, the foundational technology behind cryptocurrencies like Bitcoin and Litecoin, which emerged in 2009 as an incorruptible digital ledger for economic transactions within Bitcoin. In 2015, Ethereum introduced an enhanced Blockchain 2.0 for validating transactions.

Blockchain 2.0 stems from the decentralized digital ledger concept, encompassing diverse categories such as Blockchain 2.0 protocols, smart contracts, and decentralized applications. With advancing computer technology, Blockchain 2.0 protocols have expanded their use beyond financial transactions to manage practically anything of value. Despite ongoing development, Blockchain 2.0 projects are mainly focused on transferring various assets beyond currency using the blockchain (Swan, 2015).

The primary justification for transactions in Blockchain 1.0 and 2.0 lies in the economic efficiency and cost savings derived from trustless interactions within decentralized network models. The evolution to Blockchain 3.0 is still in progress, with unclear future research directions, as argued by (Wang et al. 2020). One could perceive blockchain as a novel paradigm a decentralized network facilitating supply chain integration and collaboration that extends beyond currency, payment, and traditional economics.

2.2. Supply Chain Management

Supply chain management involves the coordination of material, information, and financial flows within a network of companies or organizations (Rahal, 2024). Collaboration among multiple partners in the supply chain is essential to produce and deliver products and services to consumers. The Concept of supply chain management fundamentally transforms the nature of a firm, shifting control from direct management of internal processes to integration across member organizations in the SC. (Roy et al., 2020).

SC collaboration is regarded as a crucial factor in achieving a mutually beneficial outcome for various stakeholders within a supply chain (Baah et al., 2022). Additionally, Ahmad et al., (2024) emphasize that collaboration extends beyond mere integration, encompassing long-term commitments to technology sharing

and closely integrated planning and control systems. Various forms of SC collaboration exist, including collaborative planning, collaborative decision-making, and collaborative execution (Yin et al., 2024 ; Rahal and Elloumi, 2024). Successful supply chain collaboration demands a high level of commitment, trust, joint decision-making, and information sharing (Paluri and Mishal, 2020).
SC integration involves internal, external, supplier, and customer integration (Tiwari, 2021). A high level of both SC integration and collaboration leads to elevated levels of SC performance (Saragih et al., 2020; Munir et al., 2020 ; Rahal, 2024).

2.3. Linking Blockchain Technology and Supply Chain Management

BT introduces four essential features that can improve integration and coordination among the members of a supply chain (Kamble et al., 2023) : transparency, validation, automation, and tokenization. Transparency involves a shared ledger of information aggregated from various sources and participants within the BT . The immutability of records and consensus-based verification ensure the validation of information (Sharma and Dwivedi, 2024). Automation refers to the ability to execute smart contracts based on verified information on the blockchain. BT enables the creation of tokens representing specific claims on valuable assets and their exchange between blockchain members (tokenization) (Prabhu et al., 2024). Leveraging these four key features of BT, one can identify corresponding clusters of use cases in supply chain management that complement each other.
SC Integrity **:** With a shared ledger of transparent and immutable records, BT provides the opportunity to trace assets back to their origin (Brandin and Abrishami, 2021). Provenance information certifying authenticity ensures the integrity of assets, encompassing both products and technical equipment. This capability could strengthen responsible sourcing and enable the detection or even prevention of product counterfeiting and other fraudulent actions (Machado et al., 2018). Applications may involve tracking asset ownership post-sale for warranty purposes. Furthermore, BT

streamlines paperwork in global trade by ensuring the validity of freight documents, such as in customs clearance (Huy et al., 2021).

SC Orchestration**:** By combining transparency and validation with automation through smart contracts, one can envision supply chains (SCs) that operate highly autonomously based on pre-specified rules (Zinovyeva et al., 2023). This enhances speed and simplifies coordination, as information and corresponding decisions or actions are disseminated throughout the supply chain. In the case of a machine failure, for example, the machine could autonomously order the necessary spare part from the supplier, request maintenance service, and notify downstream parties about anticipated delays. Another advantage of automation is the ex-post enforceability of contracts, meaning contractual parties cannot reverse their commitments (Gallone, 2020). Consequently, BT provides the essential foundation to extend the smart factory paradigm of Industry 4.0 to inter-company supply chains (Veile et al., 2022).

SC Visibility**:** One of the primary contributors to supply chain inefficiencies is a lack of end-to-end transparency, which can also result in the so-called bullwhip effect (Rahal and Elloumi, 2022). BT enables the real-time sharing of information regarding the location and status of an object among multiple supply chain members (Han and Fang, 2023). Leveraging sensor technology and the Internet of Things (Zubaydi et al., 2023), any measurable condition, such as product temperature in a cold chain or the availability of technical equipment within the supply chain, can be monitored. This enhances data accuracy, thereby improving collaborative planning and execution, as well as the implementation of preventive and reactive risk management measures.

SC Virtualization**:** Virtualization is a well-established approach in IT infrastructure management aimed at enhancing the utilization and flexibility of IT assets by creating a logical representation of physical hardware in software (Attarha et al., 2020). The tokenization of physical SC assets, such as technical equipment and inventories, follows a similar concept. This goes beyond merely shifting the acquisition/sale of SC assets to the blockchain. Claims on capacities or ordering options could be represented as tokens and circulated outside the typical (bilateral) contractual relationships. Similar to the virtualization of IT hardware, this approach would facilitate improved capacity utilization of SC assets, allowing the monetization of excess capacities. Additionally, virtualization would enhance contract flexibility and enable the redistribution of corresponding risks within supply chains in general (Bekrar et al., 2021).

***SC Finance*:** Applications supporting financial supply chain management (SCM) naturally align with BT due to its close association with cryptocurrencies and the significant role of financial intermediaries in global trade (Paliwal et al., 2020). Consequently, two types of applications emerge: firstly, BT facilitates the settlement of multi-party and multi-tier financial transactions within supply chains, arising from the collaborative value creation of blockchain members (Cao et al., 2022). Secondly, transparent and validated records, along with automated transactions and tokenized financial claims, streamline the financing of working capital (including inventories and accounts receivable net of accounts payable (Sriraman et al., 2023)) among blockchain members, consequently reducing financing costs (Nguyen et al., 2021). To achieve this, SC assets could be collateralized by issuing corresponding financial claims using tokens (Schar, 2021).

In this article, we view blockchain as a foundational technology (Paliwal et al., 2020 ; Mukherjee et al., 2022) that brings about a transformative shift in the advancement of S CS. From this perspective, our goal is to explore the connection between blockchain technology and the triple bottom line (T BL) approach to sustainability, covering the economic, social, and environmental of SCs. Despite the continuous growth in scholarly interest in the blockchain phenomenon, there remains a gap in research that delves into the application of this technology for achieving sustainability in supply chains. The majority of academics studying blockchain in the context of supply chain management and logistics have predominantly focused on its economic implications, with minimal attention to the nonquantifiable benefits (social values, human and environmental sustainability) that arise from integrating BT into S C networks. To address this knowledge gap, this paper seeks to analyze and consolidate the existing literature on blockchain and sustainable supply chain practices. The research is structured to respond to the following research question: How can blockchain technology contribute to advancing supply chain sustainability? To uncover this important inter linkage of key trends, we conducted a systematic literature review (SLR) to identify and analyze relevant publications. To the .best of our knowledge, no other researchers have investigated and synthesized the existing body of knowledge from the lens of sustainability, making this study one of the earliest attempts to explore the sustainability-induced .changes generated by leveraging blockchain in supply chains and logistics.

3. Review results

Hourneaux and Gabriel (2018) introduce the concept of the triple bottom line (TBL), indicating that organizations need to emphasize the importance of economic, .social, and environmental performance. Sridhar and Jones, (2023) suggest that firms pursuing the three foundational dimensions of the TB L could achieve better economic performance. In the context of the S C, the organization's sustainability vision implies that these dimensions are equally crucial. In this review, we relied on the T BL framework to explores how B Ts could potentially impact various aspects of supply chain sustainability.

3.1. Economic Sustainability

The use of blockchain technology in supply chain provides a significant advantage: disintermediation. This approach, emphasized by Zamani & Giaglis (Tönnissen and Teuteberg, 2020), streamlines transactions by .directly connecting buyers and sellers, thereby avoiding the need for intermediaries, as indicated by Zhang et al., (2023). This disintermediation can reduce costs, simplify the system, and minimize product rejection by customers (Gamage et al., 2020). The blockchain serves as a central authority, validating transactions without the need for intermediaries (Ahamad et al., 2022). The example of the Bitcoin blockchain, eliminating the need for a third party through asymmetric encryption (Mut-Puigserver et al., 2020), illustrates this approach. Furthermore, the combined use of smart contracts and BT emerges as a promising solution to replace intermediaries, especially in the context of transshipment operations within global supply chains (Surucu-Balci et al., 2024).

BTs can significantly streamline entire business processes and make the entire S C more responsive and efficient (Dutta et al., 2020). Through a blockchain-enabled SC, firms can benefit from increased levels of verification efficiencies and automation (Jabbar et al., 2021). For example, blockchain facilitates the digital and authentication of food products throughout the entire SC from .suppliers .to .store shelves and finally to end consumers (Bhat et al., 2021). BT, ensures end-to-end product .tracking and enables multiparty authentication of the possession of products and real-time information sharing (Syed et al., 2020). With such enhanced visibility, SC partners can eliminate several non-value adding activities as they will be able to monitor the progress of goods and their movements along the SC. (Bala, 2014). The traceback capability of blockchain allows companies to quickly identify the inventory level of their products .and raw materials and .to make more integrated .and well-informed decisions across all stages of the SC. As a result, BT, offers a time-saving advantage and can simplify many business tasks, eliminating inefficiencies resulting from archaic processes, trade-related paperwork, complex bureaucratic procedures, and stringent institutional requirements. As noted by Choi et al. (2020), familiarity with B T can lead to shorter task completion times, increased simplicity, and .enhanced job performance.

Blockchain leads to .the .establishment of robust integration links between supply chain partners, enabling swift verification of outsourcing chain partners' documents such as certificates, licenses, proofs of records, transactions, processes, and events (Agrawal et al., 2023). In trade finance, blockchain technology can

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ensure real-time approval and payments of transactions (Chang et al., 2019). Omar et al. (2021) developed an efficient supply chain management system using smart contracts features in the Ethereum blockchain to manage items shipped via smart containers and to govern and orchestrate interactions between the sender and receiver. Therefore, blockchain can significantly enhance operational efficiency, optimize resource allocation, and free up resources that can be used to mitigate the variability of supply chain demand and supply (Dutta et al., 2020).

The effective application of blockchain technology to supply chains can reduce several costs associated with product quality verification, distortion of business processes, and transfer of ownership among supply chain partners. The disintermediated approach of blockchains can dramatically reduce transaction costs that were economically unfeasible (Shmidt and Wagner, 2019). Moreover, the pressure to reduce the costs of products and services constitutes an impetus for firms to use the technology for removing the overhead costs required for the exchange of assets. For example, Rehman et al., (2023) note that blockchain technology can decrease manufacturing firms' networking costs and usher in the construction of new market platforms in the manufacturing industry. Results before and after blockchain adoption have also shown that firms could improve their profits through the transparency and cost-saving nature of blockchain (Rehman et al., 2023). Because of these key characteristics, companies can be profitable and produce at smaller marginal and competitive costs when they incorporate blockchain technology into their business processes. Costless verification enabled by blockchain can benefit all the actors in the supply chain by eliminating or reducing costs related to the certification of products and their ingredients (Li et al., 2023). As a result, supply chain partners would have the opportunity to generate significant savings on costs associated with enforcement, such as labor expenses, legal fees, taxes, and court costs. Moreover, companies may realize cost savings from the reduction of waste and all .adverse outcomes. Information on .the blockchain

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can then be used to take proactive actions, mitigate process frictions, and shorten the time-to-market.

A promising application of blockchain technology lies in its potential to efficiently allocate resources among supply chain partners. As such, sharing models powered by lockchain technology enables businesses to gain visibility into the availability of all underutilized logistics assets (trucks, vehicles, machinery and equipment, warehouse capacity, etc.). Similarly, blockchain possesses the digital capabilities to establish a new realm of collaborative and decentralized logistics (Ertz and Boily, 2019). Which hosts a vast network of supply chain actors, matches firms on-demand, and enhances the availability and utilization of logistics resources. Blockchain helps create a fair economic business model and preserves the benefits of the sharing economy, as companies based on resource sharing will be .subject to strict monitoring and scrutiny (Muñoz and Cohen, 2017).

3.2. Social Sustainability

(BT) introduces a paradigm shift by fostering increased trust and authority within decentralized networks, moving away from traditional supply chain management practices. With blockchain, trust becomes a key element that significantly reduces risks and uncertainties among exchange partners. Transparency and completeness of information and transactions on the blockchain form the foundation for establishing mutual trust relationships among (SC) stakeholders. (Yavaprabhas et al., 2023).

Blockchain creates an atmosphere of trust, promoting continuous ethical behavior, fairness, and honesty. This trust becomes a crucial prerequisite for effective sharing of information and resources within supply chains. In various contexts, such as ensuring the reliability of records, blockchain technology plays a vital role as a critical infrastructure necessary to achieve development goals (Kumar et al., 2022). In business relationships, blockchain addresses the challenge of lacking trust among numerous untrusted stakeholders, serving as a cornerstone for

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cooperative and collaborative connections in the supply chain (Wang et al., 2024).

The technology's contribution to trust is further emphasized by its role in ensuring data integrity, security, and protection against fraud, infringements, and cybercrime (Chantzos and Alam, 2016). Therefore, blockchain establishes a new ecosystem where shared values, strict regulations, control mechanisms , reputation, and healthy relationships collectively enhance a company's social capital, notably in terms of trust.

Food safety, an increasingly crucial public health concern, finds potential solutions in blockchain. By promoting transparency, efficiency, and accountability, blockchain-enabled traceability can significantly reduce healthcare costs and enhance the public perception of the food industry (Cao et al., 2023). Blockchain technology enables a swift response to food recalls, minimizing the spread of foodborne illnesses (Wang et al., 2024). Ensuring end-to-end traceability of food products, it meets consumer requirements and supports the expansion of global food chains (Mohan, 2018). Partnerships, such as the one between Walmart, Nestlé, and others, demonstrate how blockchain can ensure food safety and reduce consumer anxiety during crises (Wang et al., 2024). The technology thus addresses the growing demand for food safety while adhering to quality standards.

Blockchain Technology holds promising prospects beyond economic considerations, enabling organizations to address their social responsibilities and support humanitarian operations in the supply chain. During crises and disasters, blockchain can streamline humanitarian aid, eliminate bureaucratic delays, and enhance transparency in donation tracking (Coppi and Fast, 2019). It provides a robust information infrastructure to manage humanitarian contingencies, reduce delivery times, and optimize the accuracy of necessary goods or services (Nagendra et al., 2022). The use of blockchain-based smart contracts facilitates automated remittance transfers (Nagendra et al., 2022). Studies like that of Rodriguez, (2021) indicate successful pilots of blockchain in refugee camps, demonstrating its potential to build trust, promote solidarity, improve supply chain transparency, and combat human rights abuses,, child labor, and corruption. (BT) also, contributes to greater financial inclusion by integrating the unbanked population, smallholding farmers, and, businesses (Roopa et al., 2022).

3.3. Environmental Sustainability

The adoption of blockchain technology has the potential to strengthen the ecological dimension of sustainability by reducing the environmental logistics footprint (Parmentola et al., 2022). Blockchain and smart contracts provide the opportunity to integrate environmental protection initiatives by monitoring production parameters such as energy consumption, raw material processing, and emissions (Shmidt and Wagner, 2019). This technology facilitates participation in low-carbon energy initiatives, the implementation of environmental protection programs, and consumer access to clean energy (Shmidt and Wagner, 2019). Additionally, blockchain contributes to sustainable manufacturing by helping companies identify and eliminate the use of non-renewable resources, promoting energy circularity (Kouhizadeh et al., 2019).
The blockchain stimulates the transition towards efficient and sustainable energy use and the production of sustainable products. The transparency offered by the blockchain can ensure the authenticity of environmentally friendly products (Nygaard and Silkoset, 2023). Participation in a blockchain network emphasizes businesses' commitment to various environmental issues (Parmentola et al., 2022). By collaborating with supply chain partners, the blockchain enables efficient resource allocation based on precise planning and real-time data from production processes (Al Sadawi et al., 2021). The collaborative capabilities of the blockchain avoid unnecessary transportation processes, allowing effective coordination among supply chain partners (Al Sadawi et al., 2021). Furthermore, the blockchain enables the tracing of the carbon footprint of products, facilitating cooperation and the exchange of carbon assets in green markets (Al Sadawi et al., 2021). By mapping the product's journey in the supply chain, the

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blockchain identifies the applicable carbon tax, contributing to the reduction of carbon emissions and air pollution (Al Sadawi et al., 2021).

4. Conclusion

In summary, this comprehensive study on the integration of blockchain technology in supply chain sustainability highlights its promising potential across economic, social, and environmental dimensions. The systematic literature review demonstrates that blockchain can transform supply chain operations by introducing innovative economic models, improving operational efficiency, and creating value. Socially, it enhances trust among supply chain actors, improves food safety, facilitates humanitarian logistics, and promotes social equity. Environmentally, blockchain offers opportunities to reduce ecological footprint, promote sustainable manufacturing, and ensure traceability of environmentally friendly products.

The increasing engagement of academic research in this field underscores the importance and dynamism of exploring blockchain applications to support supply chain sustainability. The findings of this study can serve as a foundation to guide businesses, researchers, and policymakers in the integration and judicious exploitation of blockchain technology to promote sustainable practices in their logistical operations and interactions within the supply chain.

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