Blockchain for a Circular Digital Built Environment

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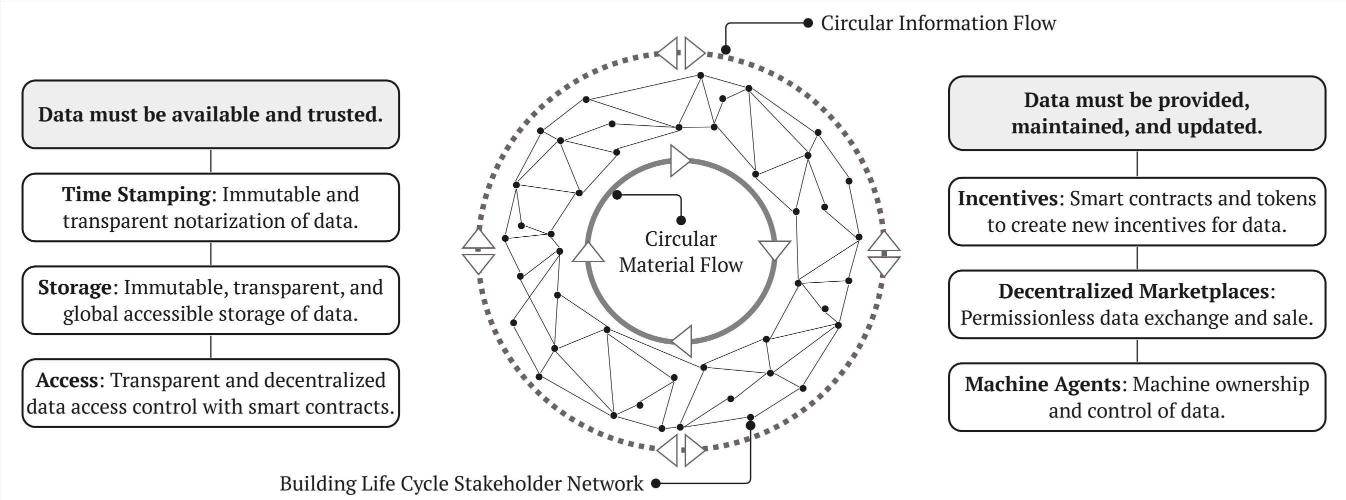

Fig. 1. Two proposed data prerequisites for enabling circular information flows between stakeholders throughout the lifecycle of physical built assets, and for each, three possible applications of blockchain to support a circular digital built environment.

Abstract

Blockchain was repeatedly mentioned as a promising solution for a circular economy in the built environment, while others remain critical of its applicability and disruptive potential. Proposed applications remain scattered, mostly at a conceptual or prototypical level, and focused on track and trace aspects. This paper proposes six promising applications of blockchain related to data-level requirements for enabling circular information flows: time stamping, storage, access, incentives, decentralized markets, and machine agents. The applications presented, linked to the technological characteristics of blockchain, should help the reader to better understand the promise and associated challenges of blockchain towards a circular digital built environment.

1. Introduction

Various articles have positioned blockchain as a promising solution for a circular economy (CE) [Kouhizadeh et al. 2022; Rejeb et al. 2023; Figueiredo et al. 2022; Kofos et al. 2022], also for the built environment [Çetin et al. 2021; Li and Kassem 2021] to "provide a transparent ledger of transactions to give all participants real-time information about a material's location, ownership and audit history" [Acharya et al. 2020]. At the same time, this remains mostly at a conceptual or on a prototypical level, which also leaves open questions about "[...] how far blockchain can accelerate the change towards CE [...]" in practice, and consequently, its "[...] disruptive potential for a sustainability transition."[Böckel et al. 2021]

In this brief reflection, we aim to outline and analyze the role of blockchain towards a circular built environment. Our goal is to encourage further research and industry initiatives to gather more evidence on whether this technology is indeed practical. For now, it appears that ideas and use cases are still scattered in the literature. The emphasis seems to be on track and trace aspects, while the potential of economic governance through blockchain, the key innovation of this technology [Davidson et al. 2018; Hunhevicz et al. 2022a], is currently underrepresented in discussions. Furthermore, we note that there may be confusion between the applications of blockchain for circularity and sustainability in general.

Therefore, we present our conceptual thinking on blockchain applications for circularity in two categories, "data must be available and trusted", and "data must be provided, maintained, and updated", related to data-level requirements for enabling circular information flows in the built environment. We provide examples of existing research and applications and offer ideas for future exploration. Finally, we discuss and reflect on various aspects related to the presented content.

2. Towards a Circular Built Environment

Kirchherr et al. [2017] defined CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes [...], with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers." Given the significant role of the built environment regarding emissions [Hoornweg et al. 2011] and resource consumption [Herczeg et al. 2014] due to global urbanization [Sun et al. 2020], the idea of a CE in the construction industry has received substantial research attention [Munaro et al. 2020; Hossain et al. 2020; Benachio et al. 2020].

The most discussed context in construction is the physical side towards circularity of resources and products [Munaro et al. 2020; Charef et al. 2022], which is understandable given the physical nature of the industry. Adapting resource flows must be coupled with circular design elements [Acharya et al. 2020], as well as new business models that encourage stakeholders to adopt circular practices [Carra and Nitesh 2017; Bocken et al. 2016]. However, a tremendous barrier to the transition to circular construction is the lack of existing or accessible information [Acharya et al. 2020; Heinrich and Lang 2019], necessary to enhance coordination of the typically complex [Bertelsen 2003; Gidado 1996] and fragmented [Sheffer 2011; Hall et al. 2018] construction

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supply chain, and to make informed decisions concerning both design and business models.

Strategies to overcome the information scarcity include material passports or digital product passports. These passports contain life cycle data related to built assets [Heinrich and Lang 2019; Honic et al. 2019a]. Although promising, it is important that these passports stay available to stakeholders throughout the entire life cycle of buildings. While for new buildings usually CE-relevant data exists [Atta et al. 2021; Honic et al. 2019b], creating passports for existing buildings or constantly updating and maintaining them during the operation phase of a built asset remains a challenge [Honic et al. 2021]. In addition, Çetin et al. [2023] identified several critical gaps in data availability to enable circularity.

In summary, not only does the physical side of the supply chain need to be circular, but the data needs to enable a *circular information flow*. This is one of the most pressing issues that needs to be addressed if we are to move towards circular business models. Achieving better-informed design and supply flows throughout the lifecycle of built assets requires the following:

1) *Data must be available and trusted*, to ensure relevant stakeholders can access and rely on it for decision making throughout the entire life cycle of the built asset.
2) *Data must be provided, maintained, and updated.* The usefulness of available and trusted data is diminished if it is not shared; the data format, access and storage are not consistently maintained; and changes are not updated.

3. The Role of Blockchain

Enter blockchain, a technology that establishes confidence in the transactional exchange between parties over the internet through transparent governance mechanisms in a distributed network of computers handling these transactions [De Filippi et al. 2020]. The technology emerged with Bitcoin for the transfer of monetary value, shifting trust from traditional institutions to the blockchain. Nowadays, there are many blockchain protocols that differ in their governance structure, impacting the technological performance, the set of trusted actors in the system, and additional functionality, such as the support for smart contracts. Some of the features typically associated with blockchain technology today are the immutability and peer-to-peer (P2P) nature of transactions, the transparency of the system that allows transactions to be verified for integrity, the ability to automate transactions through smart contracts, and tokenization representing transferable units of value [Hunhevicz et al. 2022a].

Often, research has examined the application of blockchain to facilitate a circular economy due to its ability to enhance transparency in transactional relationships [Kouhizadeh et al. 2020; Rejeb et al. 2023; Figueiredo et al. 2022; Kofos et al. 2022]. One example is the investigation by Erol et al. [2022], which refers to supply chain traceability as the most important blockchain function to overcome the lack of visibility and traceability. Also, blockchain's most mentioned use case related to circularity in the construction industry suggest utilizing blockchain in conjunction with the internet of things (IoT) to track and trace materials and products, with the aim to increase visibility throughout the supply chain process [Brandín and Abrishami 2021; Çetin et al. 2021; Chen et al. 2022; Yu et al. 2022].

While we recognize the importance of blockchain to track and trace supply chain information towards a CE, it is often not clear how the proposed applications process data with or on the blockchain. Moreover, we believe there exist applications that are less mentioned and more disruptive in nature. Currently, the focus often lies on applying blockchain to existing systems, while the potential lies in novel forms of economic coordination previously impossible for institutional coordination [Davidson et al. 2018; Hunhevicz et al. 2022a].

Below, we summarize and propose applications of specific technological aspects of blockchain for a circular built environment and, where helpful, list selected examples and relevant research. Of course, they can also be combined into larger applications. The six applications are structured according to the circular data requirements mentioned above: data must be available and trustworthy (see section 3.1), and data must be provided, maintained, and updated (see section 3.2).

3.1. *Data must be available and trusted*

Time stamping

At its core, blockchain is a time stamping machine for transactions. Each transaction is hashed and included in the merkle root of a block, and each block has a timestamp. This allows anyone to determine when a transaction was included in the blockchain, simply by searching for the transaction hash. By attaching data to a transaction, it is therefore possible to create a proof of existence, commonly known as notarization, of data that is not stored on the blockchain, i.e. "off-chain". Time stamping is particularly useful for circular data flows in the construction industry, where many files (such as drawings, contracts, or images) can benefit from trusted notarization without having to store data on the blockchain, i.e. “on-chain”. It requires very little effort, can run in the background of existing processes, and with some time-stamping services such as OpenTimestamps[1] or Timestamply[2], does not even incur transaction costs, since it does not require any additional on-chain storage or computation via smart contracts. Even though very useful and also related to the often managed track and trace aspect of blockchain to increase trustworthiness of data between stakeholders and over the built asset life cycle, we are not aware of much research using blockchain predominantly as a time stamping service. Das et al. [2022] proposed storing data off-chain and use time stamps for versioning. Similarly, Tao et al. [2021] records the identifiers of distributed off-chain data storage on-chain.

Storage

In most cases, when referring to track and trace with blockchain, applications store data on-chain. This is typically accomplished through the use of smart contracts that define custom state variables, which are variables assigned data that is stored on-chain. State variables can be grouped and related within the smart contract to ensure the data is well-organized and can be efficiently retrieved. To add new data to the blockchain, a transaction with the data input must interact with the defined smart contract to assign the value to the state variable. This process usually involves a monetary cost for executing that transaction. Storing data on-chain has specific characteristics, such as the transparency aspect, where the data is visible to everyone (in public blockchains), the immutability of data, and the availability of the data as long as the blockchain exists. These aspects could be useful to make not sensitive circular data publicly available and trusted. Research on circular data suggests the use of on-chain data storage for BIM to provide reliable delivery and management of trusted data [Hijazi et al. 2021; Shojaei et al. 2021; Elghaish et al. 2023], occasionally in combination with IoT to capture physical supply chain data [Li et al. 2021].

Access

Time stamping and storage represent ways to track and trace data to make it trustworthy to the value chain through on-chain verification, either storing the data itself off-chain or on-chain. To further support data availability, blockchain can derive access control mechanisms in smart contracts through addresses, which are the unique identifiers used in blockchain systems to send and receive transactions and store digital assets. When data is stored on-chain, access control means defining which address can write or modify data, but the data remains public (in public blockchains). If data is stored off-chain and timestamped, or if it is linked to off-chain data through identifiers because the data should remain private, smart contracts can also be used to define which address can access the data. In combination with a full Web3 technology stack, i.e. using blockchain together with decentralized data storage protocols [Hunhevicz et al. 2023], this could guarantee lifecycle access to data, even if the data is not stored on the blockchain itself. The assumption is that smart contract-defined access logic will persist throughout a typical

[1] https://opentimestamps.org/, accessed 11.09.2023.

[2] https://timestamp.decred.org/, accessed 11.09.2023.

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built asset lifecycle due to the persistence of the blockchain network. With that data access loss may be prevented compared to current data storage and access solutions, because of lost passwords, disappearance of stakeholders, or because storage service providers go out of business. Hunhevicz et al. [2023] prototypes such access mechanisms through role-based and token-based smart contract access logic. In addition, Tao et al. [2021] uses smart contracts to control access to the proposed distributed common data environment.

3.2. Data must be provided, maintained, and updated

Incentives

One of the most fascinating elements of blockchain technology is the creation of incentive structures using smart contracts and tokens. Tokens serve as units of value that can be exchanged throughout the blockchain network. Smart contracts incorporate these tokens and the associated system logic. There is a vast design space for tokens, such as the number of tokens that can be in circulation, who can transfer them and under what circumstances, and whether they are destructible. The emergent design discipline that creates these new digital economies is commonly referred to as cryptoeconomics or tokenomics [Voshmgir and Zargham 2019]. Cryptoeconomic incentive systems could be designed to encourage sustainable behaviour [Dapp 2019]. This potential has inspired research investigating cryptoeconomic incentive systems in the context of the built environment, such as performance-based smart contracts that incentivize energy efficiency in buildings through performance-based payments [Hunhevicz et al. 2022c].

Kouhizadeh et al. [2022] identified incentivization and tokenization as promising approaches for assessing CE performance, albeit without providing much detail. From a data perspective, blockchain-based incentives have the potential to facilitate bottom-up procedures for ensuring that data is accessible, maintained, and updated throughout the built asset life cycle. For now, enforcing data availability usually requires a top-down approach, whereby project owners contractually specify which information consultants and contractors must provide. The data set is then delivered after construction, but is often not maintained and updated during the building's operations. Additionally, creating post-hoc data sets for existing buildings is often difficult. Token-based incentives could motivate stakeholders to provide, maintain, and update high-quality data sets [Hunhevicz et al. 2020]. Moreover, turning data into a tokenized asset itself could potentially create new economic systems that incentivize data availability [Venugopalan and Aydt 2023].

Decentralized Marketplaces

The possibility to transact with blockchain P2P can create opportunities to match assets in a decentralized manner, independent from third-party platform operators who may restrict or monetize these services. Financial markets [Schär 2021] and energy markets [Andoni et al. 2019] are currently the primary focus of research for blockchain-based marketplaces. This may be attributed to the fact that these marketplaces already existed in digital form before the advent of blockchain technology. Nonetheless, such decentralised marketplaces could also be applied to lifecycle data in the built environment [Bucher and Hall 2022], potentially helping to make data easier to share and access across the built asset life cycle and across geographic or jurisdictional boundaries. In addition, the associated market mechanism could create business and revenue models to incentivize the provision, maintenance, and updating of data. Such circular data markets would probably serve as the basis, or at least a component, of recently proposed blockchain-based marketplaces in the context of the circular built environment, such as built assets [Venugopalan and Aydt 2023], building components [Dounas et al. 2021], waste [Wu et al. 2023], recyclable construction materials [Akbarieh et al. 2022], or carbon [Woo et al. 2021].

Machine Agents

Finally, actors transacting on the blockchain are identified solely by their address. This means that anyone capable of controlling an address can participate in the economic coordination of a blockchain system, including machine agents. Smart contracts further enable the definition of interaction rules for such agents, resulting in the creation of self-executing and self-owning autonomous agents on the blockchain [Wang et al. 2022]. This concept has also been prototyped in the context of the built environment with no1s1, a self-owning meditation pod [Hunhevicz et al. 2021]. Along with the other blockchain applications introduced above for a digital circular built environment, this implies that autonomous agents could not only participate in the creation and maintenance of data through blockchain-based marketplaces, but also own and control it through smart contract logic and incentives. Data owned by the built asset infrastructure could ensure that the data remains accessible with the infrastructure throughout its lifecycle to support its reduction and potential for reuse, recycling, and recovery of materials and components.

4. DISCUSSION

The applications of blockchain presented above and visualized in Fig. 1 could potentially support a circular digital built environment, and should be understood as a potentially incomplete list that may be further expanded or invalidated as our understanding of this young technology matures. Nonetheless, the proposed data lens suggests that in the context of CE in the built environment, the main potential of blockchain lies in enabling circular information flows to better coordinate physical resource flows. In addition to the application of blockchain to track existing supply chain processes, cryptoeconomics for institutional governance mechanisms could regulate behavior and create new business models for actors to participate in a more proactive manner. We encourage researchers and practitioners to explore applications along these lines. The presented CE data lens could also aid in differentiating among the various proposed applications of blockchain for the broader context of sustainability [Upadhyay et al. 2021] or a regenerative built environment [Wang et al. 2023].

Our reflection started with a quote from Böckel et al. [2021], who stated that the potential of blockchain beyond research in practice remains vague and needs further proof. We agree, but also point out the early state of the technology and the fact that the disruptive potential of blockchain lies more in the cryptoeconomic systems than in the track and trace of existing systems. However, the latter is the foundation of the former. Moreover, it is a systemic innovation, where the value of cryptoeconomic systems is only realized at scale when many actors are involved [Murphy; Hunhevicz et al. 2022b]. Single case studies that examine blockchain for one project or a limited number of actors are unlikely to be representative of this potential, as the actors are mostly known, and other technical systems could be used instead of blockchain [Hunhevicz and Hall 2020]. Of course, we acknowledge the difficulties of conducting such research and practical implementation and encourage thinking about creative approaches, such as using blockchain-based incentives for coopetition towards CE [Narayan and Tidström 2020].

The potential of this technology is promising, but the reality is that we will probably have to wait to see its expected disruptive effects applied to a circular built environment. In addition to the difficulties mentioned above, the implementation of use cases also depends on the technological maturity of blockchain systems [Huang et al. 2022; Sadeghi et al. 2022], as well as the simultaneous development of other Industry 4.0 technologies that can manage and feed data into such a system, such as digital twins, IoT systems, or visual identification systems [Elghaish et al. 2022; Dounas et al. 2023]. In addition, we believe that the structure of the industry can influence the need for blockchain technology. In a more industrialized construction environment, circular information flows can also be improved through traditional product platforms [Kedir et al. 2023], while in a more networked and decentralized construction project environment, it is likely that the capabilities of blockchain can play more to its strengths [Hunhevicz et al. 2022a]. Other potential unknowns affecting adoption relate to the energy consumption of blockchains [Schinckus 2020], the transaction cost perspective of the supply chain in question [Schmidt and Wagner 2019], regulatory and legal aspects [Garcia-Teruel 2020], and socio-technical aspects [Li et al. 2023]. However, individual use cases in more specific contexts could be applied earlier to demonstrate the potential of this technology.

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