Chapter 12
Blockchain Technology for a Circular Built Environment

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Abstract The built environment fundamentally suffers from organisational fragmentation in various aspects, such as data flow, finance, and supply chains. Blockchain technology can be considered a transformative solution to the inherent fragmentation of this industry. This chapter first defines the basics of blockchain technology to show how a peer-to-peer network could enable a decentralised, traceable, and immutable information system across the life cycles of built assets. Then, an overview of blockchain literature within the context of a circular economy, with real-life examples and the current state of blockchain adoption in the circular built environment, is presented, and the role that this technology plays in addressing certain circular strategies is discussed. Afterward, implementation challenges and incentives are identified to set realistic expectations regarding the capabilities of blockchain technologies. Emerging concepts within blockchain technologies are then presented to give insights into prospects beyond current literature and use cases in the circular built environment. Finally, the future of blockchain technology in a circular built environment is discussed to present the applicability of blockchain and its possible integration with other emerging digitalisation tools, such as building information modelling (BIM) and material passports, in wider domains of circular, smart cities and communities.

Keywords Distributed ledger · Blockchain technology · Decentralised technologies · Circular economy · Built environment

12.1 What Is Blockchain Technology?

Blockchain technology is an advanced database that is dispersed across many computers (each called a node) and eliminates the need for a central authority or intermediaries. Since all nodes are equally privileged on the network, it creates a

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peer-to-peer network that creates trust among all peers because each transaction is securely signed by cryptography algorithms that ensure consistency, immutability, and traceability (Ledger 2022). To add information to this database, a validation process, called consensus, is performed to cryptographically link each block of information to the previous one. As new blocks are added, older blocks become more difficult to modify. New blocks are replicated across copies of the ledger within the network, and any conflicts are resolved automatically using established rules of the network (Yaga et al. 2019).

In the following sections, two terms are frequently used: blockchain technology and blockchain network. The first term refers to a general concept of blockchain and its associated features, while the second is related to a decentralised network that is built using blockchain technology (see Fig. 12.1).

The structure behind blockchain technology provides it with some fundamental features that can revolutionise open issues across a variety of fields, including the built environment (Li et al. 2019). The first notable feature is immutability, which means that data cannot be changed once added to the blockchain network. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction information. As a result, data stored in a block cannot be altered since all subsequent blocks would need to be changed as well (Atlam et al. 2018). Another feature is the consensus mechanism, which brings reliability to the blockchain network. A consensus algorithm (for example, Proof of Work in Bitcoin's case) ensures that all transaction data are identical between blocks. In simple words, the Proof of Work can be explained as the mechanism that requires nodes in the

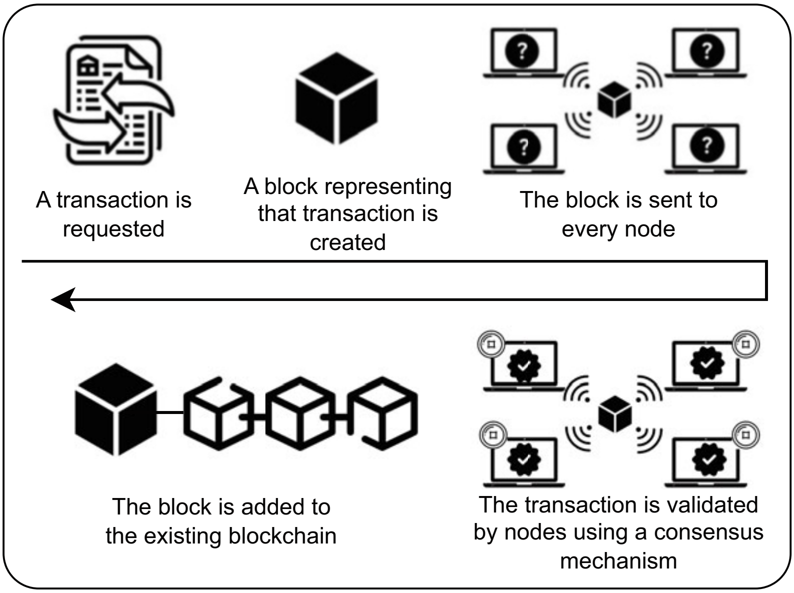

Fig. 12.1 Process of adding a block to the blockchain. (Adapted from Euromoney 2023)

blockchain network to solve a complex mathematical problem in exchange for cryptocurrency incentives (Euromoney 2023). Data traceability and integrity can also be considered other features of blockchain technology. By accessing any node in the blockchain's distributed network, users can easily trace previous transactions that have been validated and recorded on the blockchain (Perera et al. 2020). Moreover, all blocks link to the genesis block (the first block on the chain), ensuring the integrity of the blockchain (Nofer et al. 2017).

Nevertheless, while the general characteristics are the same, these features differ among different types of blockchain technologies, and it is important to note that each blockchain network has its own characteristics. Blockchain technology can generally be divided into two types, public and private, each with its own characteristics (Tasca and Tessone 2019). Bitcoin and Ethereum are two of the most well-known public blockchains. The public blockchain, also called permissionless blockchain, is accessible to everyone. Given this wide accessibility, more peers can participate and validate the network transactions, resulting in a more immutable, transparent, and traceable network with almost no downtime (Tapscott and Tapscott 2016). However, permissionless blockchain technologies have disadvantages: the fact that they are fully transparent and accessible makes them inappropriate in situations where nodes need to keep the transaction information protected from other users. As a constantly evolving technology, blockchains are gaining new capabilities. Ethereum introduced smart contracts, which allowed peers to execute codes and enforce terms of contracts on blockchain networks without reliance on a trusted third party (Han et al. 2020).

Unlike a public blockchain, a private blockchain has only a few participants (who are authorised by the owner of the network), and changes are made when the majority of nodes (or all of them unanimously, depending on the network structure) reach a consensus (Perera et al. 2020). Hyperledger Fabric platform, which is developed by Linux Foundation, is one real-life example of a private or permissioned blockchain platform. A private blockchain gives users control over the level of data transparency, which makes it an effective option in situations where users are reluctant to share data with other participants (Boucher 2017). Moreover, the limited number of participants not only makes this type of blockchain faster but also provides a more manageable ecosystem (Haritonova 2021). However, considering the limited number of nodes in this type of blockchain, they cannot provide a fully decentralised system compared to public blockchains. Additionally, few nodes can bring an additional risk of database downtime, which can result in disruption in the network operation.

12.2 Blockchain Technology in the Built Environment

The architecture, engineering, and construction (AEC) industry is frequently referred to as a fragmented industry that suffers from a lack of transparency (Bakis et al. 2007; Jiao et al. 2013). Projects within the built environment usually involve organisations from a number of disciplines, which can create conflicts due to a lack of control over data. Moreover, these projects have a long lifespan, which poses additional risks to the cybersecurity of data and data accessibility. In such projects, blockchain technology and its inherent features are frequently employed as possible solutions (Lee et al. 2021; Wu et al. 2022). One recent study reported a 192% annual increase in the average number of blockchain-based academic publications from their first appearance in 2017 to 2020 (Scott et al. 2021). However, most of these publications only propose a conceptual framework or review of blockchain technologies; practical implementation of blockchain technology within the built environment has remained less explored. The following sections offer an overview of blockchain technology applications in the AEC industry as they relate to the circular economy.

12.2.1 Supply Chain Management

Increasing transparency and reliability of the information in the supply chain is critical in achieving a circular economy in the built environment. Blockchain technology can potentially address this gap and thus facilitate a circular economy. For example, Wang et al. (2019) conducted an interview with 14 supply chain practitioners who validated the advantages of blockchain technology in the supply chain field.

It is virtually impossible to have smooth construction supply chain management in complex and hard-to-reach construction sites without real-time and reliable information among all parties. To address this issue, many researchers have focused on blockchain technology. For example, Wang et al. (2020) proposed a blockchain-based information management framework based on a model for real-time information sharing in a supply chain for precast components. Their results showed that the proposed model positively impacted the tracking of precast components and helped find the root causes of disputes about the precast supply chain.

Tracking materials or assets also plays an important role in the transition to a circular economy. In this situation, blockchain technology can be used to improve the traceability of materials in projects. For example, blockchain technology and radio-frequency identification (RFID) have been applied to track ready-mixed concrete in construction sites (Lanko et al. 2018).

12.2.2 BIM and Digital Twins

Since building information modelling (BIM) is the primary source of construction data and blockchain facilitates the handling of data, many researchers are focusing on the integration of these two technologies. Ye et al. (2018) identified the Internet of Things (IoT) and blockchain as two potential technologies for integration with BIM in terms of bringing a single source of truth within the context of digitalisation in the AEC industry. Shojaei et al. (2019) also proposed a blockchain solution based on the Hyperledger Fabric platform that can maintain a record of project progress and thus automatically govern construction contracts and avoid many potential disputes. For digital twin technology, Lee et al. (2021) proposed an integrated digital twin and blockchain model for communicating traceable data among project stakeholders. The integration of blockchain and BIM technologies will further ensure data availability and reliability for all stakeholders.

12.2.3 Cost Saving

Construction projects often struggle with a considerable number of disputes and transaction costs, mostly due to a lack of trust and transparency in the contract administration (Cheng et al. 2021). Blockchain technology is suggested to solve this issue by eliminating intermediaries in construction agreements. In this regard, Dakhli et al. (2019) examined the amount of cost savings after applying blockchain technology in a real estate company and found that deploying blockchain technology in residential construction could save 8.3% of total cost. Hamledari and Fischer (2021) also discussed the inappropriateness of current centralised workflows for automatic payments based on project progress. To tackle this problem, they proposed a decentralised smart contract framework enabling construction progress payments to be made automatically based on an unmanned vehicle-based progress monitoring process. These applications indicate how blockchain technology can enable industry actors to gain more value with fewer costs.

12.2.4 Information Management

Blockchain technology features are suitable to address the challenge of transparency, trust, and intellectual property protection in construction documents. A primary challenge of construction quality management is that, traditionally, quality information is recorded on paper by specialists, which can lead to data loss. To address this issue, Wu et al. (2021) proposed a conceptual framework based on Hyperledger Fabric and the consortium blockchain network that records all data on an immutable network making it more reliable than paper reports. The immutable feature of the blockchain network facilitated data integrity in the proposed document management system. In some cases, the large amount of data makes decision-making susceptible to error. To overcome this problem, Ciotta et al. (2021) proposed smart contracts with different levels of complexity, focusing on reducing human error and increasing the reliability and transparency of the decision-making processes in construction.

12.3 Circular Economy Through Blockchain Technology

Blockchain technology has been identified as a promising tool to support circular economy strategies in a variety of ways (Kouhizadeh et al. 2019). This section investigates how blockchain technology and its features can improve different circular economy strategies (particularly, *regenerate*, *slow*, *narrow*, and *close* strategies) in the built environment.

The *regenerate* principle contains efforts to transition from fossil fuels to renewable energy and materials, avoid the use of hazardous contents, and improve biodiversity (Çetin et al. 2021). To this end, traceability and immutability features in blockchain technology enable industry actors to manage and track energy and material flows from production lines to specific points of consumption. This brings about a level of transparency to the system that can promote renewable energy and material use. This strategy can also benefit from the decentralised structure of blockchain through leveraging material or energy trading on a peer-to-peer network without relying on third parties.

The *slow* strategy includes efforts to maximise value through sharing goods while minimising duplications and waste (Çetin et al. 2021). Utilising used goods or sharing assets can be classified in this category. An immutable and secure network of blockchain lays a solid foundation for sharing material and goods while tracking ownership and usage information. For example, blockchain technology has been utilised to provide a secure platform for car-sharing (Shrestha et al. 2020; Auer et al. 2022).

In addition, the slow strategy is defined as a circular path for remanufacturing goods or components instead of a linear path of make-use-dispose (Çetin et al. 2021). To this end, we need effective ways to track and trace materials, components, and products from the production point to the end of life. In this situation, blockchain technology can provide a reliable way to trace information for logistic activities, history of energy use, etc. In one example, a Hyperledger Fabric network (a type of private blockchain) is applied to provide a traceable network of material data. This framework allows preplanning for reusing materials in the built environment (Shojaei et al. 2021).

The *narrow* strategy aims to boost system performance by minimising non-value-added activities in processes of manufacturing, operating, and consuming (Çetin et al. 2021). The application of big data analytics in this strategy has drawn considerable attention as one of the most promising technologies (Marinakis 2020). Additionally, automation and enforceability of smart contracts in blockchain networks can facilitate the transition to more optimised business systems. Many existing manual workflows, which are highly reliant on centralised workflows, can be upgraded to automated workflows based on decentralised systems (Hamledari and Fischer 2021).

In addition, the narrow strategy includes dematerialising efforts by delivering utilities virtually (such as e-documents, online conferencing, etc.). Intrinsic features of blockchain technology can support this strategy in various ways. Trading goods, energy, and components with cryptocurrency can help reduce issues such as lack of trust, transparency, and the need for intermediary facilitators related to current trade

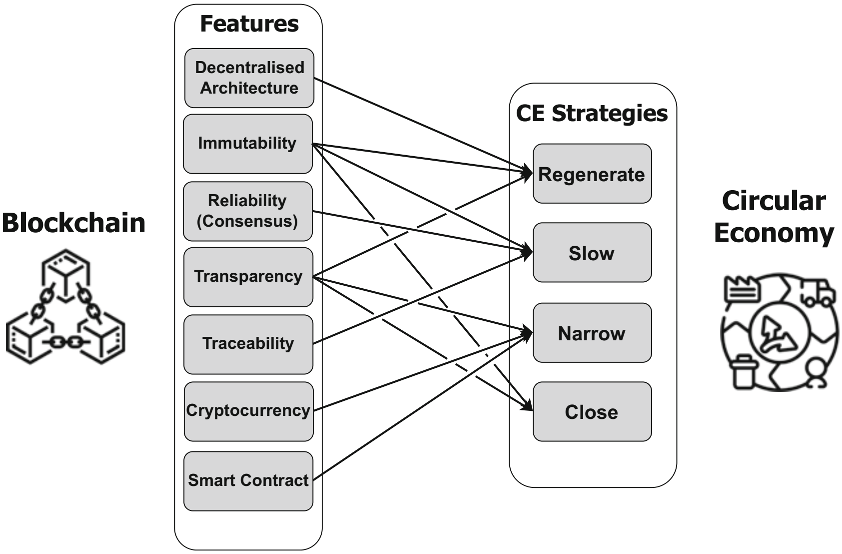

Fig. 12.2 Links between blockchain features and main circular economy strategies

practices. Blockchain technology's transparency feature can also help reduce the massive paperwork currently used in business practices without sacrificing trust and traceability. Furthermore, smart contracts can help automate manual and labour-intensive workflows.

Using the *close* strategy, buildings' end-of-life resources can be reintroduced to the economic cycle (Çetin et al. 2021). Traceability, transparency, and immutability are all features associated with blockchain technology that can improve this strategy. Blockchain-based systems can provide a more reliable platform for material flow during the whole life cycle of buildings through their applications in supply chain. In summary, Fig. 12.2 presents how blockchain features and advantages are aligned with the four discussed circular economy strategies.

12.4 Examples of Blockchain Applications for a Circular Built Environment

Although much attention has been given to conceptual frameworks based on intrinsic features of blockchain technology, practical services using blockchain features have remained mostly unexplored. In this section, we examine some real-life examples of blockchain technology adoption for a transition to a circular economy in the built environment.

Nowadays, a considerable number of distributed energy resources enable us to access renewable energy microgrids on a range of buildings. However, balancing loads from different inputs and outputs is a major barrier to this opportunity. In this situation, blockchain technology has been applied as a solution in some real-life services explained below. Immutability along with transparency in a blockchain network is, for example, being utilised along with artificial intelligence (AI) tools in the Port of Rotterdam to create an energy market for trading renewable microgrid energy on the buildings. This platform reduced user costs by 11% in 2021 and has attracted much attention for a promising future solution (Distro 2021). In a similar effort in Australia, Powerledger (a software and technology company) provides a decentralised market for renewable energy generation, storage, and purchasing in an optimal manner. A blockchain-based software has been developed based on this solution to trade rooftop solar power between international schools, apartment complexes, shopping centres, and dental hospitals in Bangkok. Therefore, these services support regenerating the resource loops. The traceability of the blockchain network is utilised in a pilot project by the Iberdrola company (a company working in the field of renewable energy) to certify sources of green energy to build trust among users and encourage them to adopt renewable energy sources. This is aligned with the *regenerate* strategy in the previous section.

Blockchain technology is not always utilised as a tool to add traceability and transparency values to old systems; it can be used to change the whole business model. The Brooklyn Microgrid in the United States is a good example of this change. Instead of using a central grid network, this platform redesigned the energy grid model by providing a community-based and decentralised network applying blockchain technology. According to this concept, the actual energy in the system is generated, stored, and traded locally by community users instead of using a third-party utility company. Users on this platform can contribute to electricity generation by solar panels in their own buildings or the energy stored in electric cars. Users who need more energy can buy energy directly from other users. Extra energy in the network is shared and stored among all users and allows them to be a step closer to implementing a circular economy in their community. This example utilises almost all strategies for reaching circularity at a community level.

A carbon credit market in China is based on a blockchain network, where individuals can track carbon emissions on a smartphone app in a reliable manner and trade with those who need carbon credits (ECO2 2015; Jackson 2022). (The same concept could be applied in the built environment to enable buildings with high energy efficiency or low carbon footprints to monetise their savings.) For another example, EZ Blockchain in the United States utilises waste natural gas that cannot be effectively sold as fuel to mine Bitcoin. Similar solutions could be applied to waste materials in the built environment to recreate value from waste. This alignment with the *narrow* strategy demonstrates additional real-life efforts to transition to a circular economy.

The potential to use blockchain for a more circular economy is not limited to examples within the energy context. A significant number of real-life examples utilises blockchain technology to create a more efficient supply chain. For example, Circularise partnered with the City of Amsterdam to improve sustainability within the construction procurement process by proposing a traceable and transparent platform for tracking material information. This platform answers the need for effective ways of tracing materials from the production point to the end of life.

The provided traceability enables companies to circulate material effectively and also mitigate risks across the supply chain. However, transparency, while offering benefits, can also create concerns about data privacy and confidentiality. Different types of blockchain technology can be utilised to address this issue. For example, Circularise developed a solution called ‘Smart Questioning’, based on a public blockchain, which not only provides transparency but also preserves companies’ confidential data in a secure and reliable manner. Another example is BanQu, which created a supply chain platform to authenticate transactions during the whole extent of the supply chain. This service allows active players to manage records. These innovations are aligned with the *close* strategy.

Furthermore, material management during the construction phase of the built environment is critical. Despite academic efforts to apply blockchain technology as a solution to the construction supply chain (Tezel et al. 2020; Shemov et al. 2020), there are few real-life examples of these efforts. As one of the few examples, DigiBuild developed a blockchain-based solution to provide trusted material management among all parties involved in construction projects. Another example is the company Empower, which motivates transparent and traceable waste collection through the use of blockchain technology. ReCheck is another example of a company putting efforts into creating a material circularity passport for the built environment. Through a blockchain-enabled network, this platform records the material information in an immutable and transparent environment. Such information provides us with an easier process of recycling at the end of the building life cycle.

12.5 Challenges of Applying Blockchain Technology

Despite the advantages of applying it towards a circular economy, blockchain, like many other emerging technologies, faces considerable challenges for practical implementation. In this section, some of the most significant barriers are discussed to set realistic expectations for this technology. Furthermore, despite efforts noted in the previous section, real-life examples of blockchain technology for circular economy practices in the built environment are very limited. The reason for this scarcity can be explained by various challenges in implementing blockchain technology in practice.

First of all, although blockchain technology started in 2009 (the year of the first mined Bitcoin), it still can be considered an emerging technology, as it has experienced significant changes from its first appearance. Its constantly changing nature has led to many challenges for its implementation. The lack of sufficient experts is one of these challenges (Connolly 2021), which poses an additional risk when deciding on technologies for the relatively new concept of a circular built environment. Furthermore, the multi-stakeholder structure of a circular built environment makes it hard to get all parties on the same page, especially when they must decide whether to use a technology with only scant resources and few experts who understand it well. Moreover, AEC tends to be a risk-averse industry that is very slow to adopt new technologies (Oesterreich and Teuteberg 2016; Li et al. 2019). Creating a solution that brings all these stakeholders together in a unified platform is a challenging task.

Blockchain interoperability is another challenge in decentralised networks. This means that each blockchain network has a unique structure, making it incompatible with some or all other networks. For example, if the Ethereum blockchain, one of the most well-known public networks, is chosen for implementing a circular economy solution, any platform developed with it will be incompatible with many other blockchain networks.

The next challenge is the speed and performance (including costs) of blockchain networks. Blockchain technology is relatively slow when applied to massive amounts of everyday data, be it energy or any other type of data. Each transaction in Ethereum can take to several seconds, making applications function very slowly, especially in comparison to centralised common databases (Wang et al. 2020). However, it should be noted that many new blockchain networks have been developed to address this issue. For example, while Ethereum can perform 15 transactions per second, the Polygon blockchain can perform more than 65,000 transactions per second. Applying blockchain technology is also associated with implementation costs because each transaction has a transaction fee. It can make decision-makers reluctant to apply this technology early in their transition to a circular economy. However, some new blockchain networks, such as Polygon, offer more affordable transaction fees.

Another challenge is related to regulatory issues within and beyond organisations. For example, regulations in governmental agencies may not allow the implementation of a new technology like blockchain that can potentially change existing workflows. This is particularly evident in the public sector, where all workflows are governed by legislation. There is no solid and certain standard for the proper implementation of blockchain technology (Alaloul et al. 2020), which in part hinders the development of appropriate legislation for implementing blockchain technology in practice. In addition, a fully integrated adoption of blockchain technology in the various fragmented organisations of the AEC industry requires regulatory changes, which brings additional time and costs for organisations.

Kiu et al. (2019) have mentioned the challenge of developing a smart contract and its associated coding, especially when it comes to encoding the developing concepts in the circular economy field. Although the immutability and enforceability of smart contracts were mentioned as advantages above, they also can become a challenge as codes cannot be updated after final execution. This can be challenging in the field of circular economy, which is an emerging field that needs constant improvements.

The interaction between a blockchain network (on-chain) and technologies outside of the blockchain (off-chain) is also mentioned as one of the most serious challenges for developing an automated solution based on blockchain technologies. Oracles are middleware agents that bridge real-world, off-chain data to on-chain networks (Al-Breiki et al. 2020). However, the main problem with widely used oracles is that they are centralised services and are thus vulnerable to all the traditional problems associated with centralised systems, such as single points of failure and lack of transparency, cost, and dependency. This challenge can impact the functionality of digital twins and IoT when they are integrated with the blockchain technology. As a result, it can impact the performance of applications developed for building industry based on these tools.

It should also be noted that although there is a considerable number of open challenges for adopting blockchain technology, potential solutions are being provided on a daily basis, making the future of adoption more promising. For example, decentralised oracle networks were recently developed as a solution for avoiding the problems associated with centralised oracles that were mentioned above.

12.6 Future of Blockchain Technology in a Circular Built Environment

Blockchain technology has experienced numerous innovations since its introduction in 2008 (under the pseudonym Satoshi Nakamoto). In this section, we explore some of these concepts that can potentially influence the future adoption of blockchain in a circular built environment. Decentralised application (dApp) is one of these new concepts, which refers to a kind of application built over smart contracts. These kinds of applications are almost similar to web applications in how they look and are accessed (front-end), with the difference that they mostly use smart contracts as their functioning mechanism (back-ends) (Ethereum 2022). These applications are associated with intrinsic transparency and accessibility of the Ethereum network. Most real-life examples introduced in Sect. 12.4 were developed as dApps powered by smart contracts for the purpose of each platform. However, dApps hold much more potential for future developments. BIM and digital twin assets can be integrated with smart contracts for building dApps that improve the circular built environment based on strategies discussed in Sect. 12.3. For example, integrating BIM with blockchain technology allows us to create material passports in a secure and immutable manner integrating into the design workflow or maintenance operations to inform the users in decision-making processes. Furthermore, material information is stored on a blockchain network and then can be used by different parties to select the best strategy for a transition to a circular environment.

Smart contracts also can be applied to generate crypto tokens. Tokens are digital representations of assets or interests that have been tokenised on the blockchain of a cryptocurrency (Frankenfield et al. 2023). Basically, tokens can be divided into two categories: fungible tokens (FTs) and non-fungible tokens (NFTs). FTs are divisible and interchangeable tokens, each equivalent to another, such as cryptocurrencies. NFTs, however, are indivisible, verifiable tokens representing a piece of information on a given blockchain network, whether digital art or any other kind of information (Bal and Ner 2019). Although few examples use FTs to trade energy (see details in Sect. 12.4), to the best of our knowledge, NFT features have not yet been used in the transition to a circular built environment. For example, NFTs can be used to monitor, verify, and report building energy performance or dynamically present an asset status during its life cycle or circular economy strategies (regenerate, slow, narrow, close) implemented on it. To be more specific, the efforts to maximise sharing goods through its life cycle can be tracked using dynamic NFTs as a way for monitoring slow strategy in implementing circular economy in the built environment. This capability builds lost trust among stakeholders and enables them to clearly track, monitor, and manage the building energy performance or the status of an asset in a secure and immutable manner. This can increase the investments and buy-in on green buildings and circular strategies.

There are also other emerging concepts under the general term of blockchain that need more investigation. Decentralised autonomous organisation (DAO) is one of these concepts. Instead of relying on a central governmental component, DAOs are controlled by various users in a decentralised network (Reiff 2022). DAO is a community-based organisation that distributes decision-making without any intervention from a centralised power. This decentralised structure brings about a true bottom-up management approach, which can offer opportunities for transition to a circular built environment. Integrating DAO and digital twins in the built environment can bring a higher level of functionality. For example, a decentralised autonomous organisation (DAO) prototype to build a self-governing house (Hunhevicz et al. 2021). This integration can eliminate the reliance on a single authority for decision-making. This integration can be applied to create an autonomous built environment that runs its decisions automatically, optimising the use of resources and energy. This opportunity can save considerable time and cost in building operations and lead the built environment function with circular principles.

Another newly discussed concept, which is rarely explored, is decentralised finance (DeFi). This financial system is powered by smart contracts and a decentralised blockchain network without relying on intermediaries such as banks (Sharma 2022). DeFi can enable public users to fund circular building projects securely and quickly without being charged bank service fees. This opportunity can promote circular economy projects and lead to achieving sustainable goals quicker.

In conclusion, the potential for blockchain technology to revolutionise the circular built environment is immense, offering a myriad of opportunities for stakeholders to enhance transparency, efficiency, and collaboration. This technology can be particularly transformative in areas such as energy and resource management, waste reduction, and promoting sustainable practices throughout the entire life cycle of buildings. While there have been some promising real-life examples of blockchain technology being applied to the built environment, its full potential has yet to be realised due to the numerous challenges and barriers that must be addressed, including the emerging nature of the technology, interoperability, performance, regulatory issues, and integration with other technologies.

As we look to the future, emerging concepts such as dApp, NFTs, DAO, and DeFi present new avenues to explore for the integration of blockchain technology in the circular built environment. By fostering innovation and collaboration among stakeholders, addressing the challenges facing the technology, and promoting regulatory changes, the full potential of blockchain technology can be harnessed to create a more sustainable and circular built environment, ultimately contributing to the broader goal of a more sustainable and resilient society.

12.7 Key Takeaways

- Blockchain can create a transparent, traceable platform for tracking materials and managing waste in the built environment, supporting a circular economy.
- Blockchain-based solutions can protect data privacy while offering transparency and traceability.
- Blockchain technology faces challenges like lack of experts, interoperability, and regulatory issues that slow down its adoption in the circular built environment.
- Decentralised applications, tokens, and decentralised autonomous organisations can unlock new opportunities for blockchain in the circular built environment.
- Blockchain integration with digital twins, BIM, and decentralised finance can promote efficient resource use, optimise decision-making, and support a sustainable circular economy in the built environment.

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