Digital building logbooks on the blockchain: first conceptualisation and future research directions

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Chapter 6

Digital building logbooks on the blockchain: first conceptualisation and future research directions

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The built environment and its industries lie at the core of the twin transitions of the European Union. Twin transitions aim at uniting ongoing green and digital transformations to address the climate crisis, reduce dependency on finite natural resources and ensure European companies remain competitive in the future. Furthermore, climate goals and the need for digitisation are interdependent – as noted in the Energy Efficiency Directive (EED) EU/2023/1791 [1]. Ongoing programmes such as the *European Green Deal* [2] and *A Europe Fit for the Digital Age* [3] reflect these aims as well. Such programmes ascertain that achieving a truly sustainable and circular built environment in Europe, requires gathering, maintaining and operationalising detailed data about buildings over long time horizons (European Commission 2022, 2023) [2,3]. Thus, there is a need for many types of building information including their history, physical characteristics, material composition, energy usage and operational performance.

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Digital building logbooks (DBLs) is a recent concept proposed by the European Commission [4,5] that can act as the repository for most aforementioned information. A DBL is defined as a centralised, dynamic repository that captures and organises all relevant data throughout a building's lifecycle [6]. Widespread usage of DBLs can enhance transparency, facilitate informed decision-making and support data sharing across various stakeholders including building owners, occupants, financial institutions and public authorities [7]. Furthermore, users can use the DBL to document significant changes such as ownership transfers, usage modifications and updates from renovations or maintenance [8]. The DBL can include detailed records like administrative documents, building plans, descriptions of the property and its surroundings, technical systems, material traceability and performance data like energy consumption and indoor environmental quality. By linking to building certifications and utilising data from intelligent systems, the DBL not only helps manage a building efficiently but also supports sustainability and compliance with regulations [6,7].

However, the implementation of DBLs faces three significant barriers [4–7,9]:

1. **Incentives.** There is often a lack of motivation to update the logbook contents, a critical component that requires user engagement and awareness of the DBL's benefits. Users, such as facility managers or homeowners, often do not see the immediate benefits of updating the logbook, which can diminish their motivation to engage with the system regularly.
2. **Administration costs.** The administrative burden and high costs associated with maintaining DBLs can deter stakeholders, especially when these costs are passed on to homeowners or end-users. This issue is exacerbated by the absence of a clear business model for the operation and sustainability of DBLs.
3. **Data interoperability, privacy and security.** The challenges of interoperability, data privacy and security must be addressed to ensure seamless integration with other systems and compliance with data protection regulations (including General Data Protection Regulation (GDPR), see EU Document 32016R067). There is a need for systematic and standardised approaches to data collection, storage, processing and updating, while also acknowledging that there are many differences that exist across regions and contexts, adding another layer of complexity.

These barriers necessitate a strategic approach, including clear legislative frameworks and incentives, to encourage widespread adoption and effective utilisation of DBLs. However, a review of the current state-of-the-art finds that most ongoing efforts in research and industry cannot meet the long-term needs of DBLs. Instead, we find three main technological solutions proposed, each with their own limitations. The *open Building Information Modelling* (openBIM) approach relies on file-based exchange executed between silos of information on local machines or common servers [10]. However, there is currently no sufficient evidence that this necessarily provides a long-term immutable record or loss-free interactions within a complex network of participants, even though automatically generating Information Delivery Systems files could improve model verification [11]. Furthermore, building information modelling (BIM) systems do not address all stakeholders downstream without extensive retooling of the data. The *standard platform* approach offers a unified approach to logbook data within centralised platforms, but at times these can create lock-in effects to specific vendors or governmental systems [12]. The *linked data and semantic web approach* shows promise for interconnected data but could be augmented with approaches to further incentive users towards trusted data governance [13].

In the proceeding sections, we position a blockchain-based approach as the appropriate technical solution for the DBL. We first describe our motivations for this; we believe that the fundamental characteristics of blockchain – trust, immutability and decentralised peer-to-peer (P2P) transactions – are both a good fit for data in the built environment and the needs of the DBL. Second, we propose a conceptual architecture for a blockchain-based DBL technical system, across the data, logic and services, and user layers. Overall, this consists of a novel decentralised data architecture, a novel smart contract blockchain architecture, data bridges to legacy data (either found in databases or standalone) and a series of user-friendly interfaces for a multitude of stakeholders. Finally, we describe the implications and future research directions for such an approach to DBLs, including the development of novel business models, decentralised marketplaces and a new legal framework for DBLs.

6.1 Background

6.1.1 Implementation challenges for digital building logbooks

The design, construction, operation and decommissioning of a building require many stakeholders with various incentives to interact over long time horizons – especially in the current European context, where the drive for renovating the existing building stock to account for current energy and quality-of-life demands is extending such horizons even more [14]. The design and construction of a building can take years and the average lifespan of a building is over five decades – although this can vary depending on the building typology [15]. In this setting, it is difficult to assemble a complete information record such as a DBL. The European Union Framework [4,5] identifies nine gaps across finances, user needs, data and legal requirements that restrict the implementation of the DBL (see Table 6.1).

6.1.2 Possible technical approaches to digital building logbooks

In a review of current approaches to solve these challenges for DBL, we generally observe three current approaches. However, each approach has key limitations.

The first technical approach is the openBIM approach [16]. This approach advocates for the use of open BIM standards such as Industry Foundation Classes (IFC). Development attempts might look to standardise the parameters of DBLs within the IFC data schema [17]. However, the openBIM approach suffers from

Table 6.1 Identified gaps to implementing the DBL [4,5]

Gap	Description
1. Lack of sound funding model	There is a lack of a sound funding model, including sustainable financial strategies to support the initial development and ongoing maintenance of DBL systems.
2. Benefits not clear to all stakeholders	The benefits of DBLs are not clearly defined or communicated to stakeholders, resulting in lower engagement and adoption rates.
3. Inconsistent scope and purpose	The scope and purpose of DBLs are not always clear or aligned with the users' needs, which can lead to misalignment in expectations and usage.
4. Lack of user-friendliness	DBL systems often suffer from poor user interface designs, making them difficult to use and deterring stakeholders from regularly updating and using the logbook.
5. Barriers to updating the DBL	The process for updating DBLs is cumbersome, potentially requiring automation to ensure data remains current without excessive manual input.
6. Low interoperability of the repository	Lack of interoperability with other data systems and tools complicates data integration and reduces the effectiveness of DBLs.
7. Poor data governance	Issues surrounding data privacy, ownership and access control are not adequately addressed, raising concerns over data security and usage rights.
8. Lack of a defined legal framework	There is an absence of a comprehensive legal framework that supports the proper use and operation of DBLs, potentially leading to regulatory challenges.
9. Uncertain role for government (e.g. for the EU and Member States)	The roles and responsibilities of local, regional, national and international governments and policy makers in promoting and governing DBLs need clearer definition to enhance coordination and support.

lack of cross-silo, flexible and long-term data storage. Additionally, it does not address legacy data, that probably exists in two-dimensional, paper format. Because it is a file-based approach and not a data-based approach, openBIM approaches struggle to deal with data outside of the project-specific environment; there is a need to constantly revise data until the completion of a construction process, then deliver, archive and occasionally aggregate the data with additional sources thereafter. Even if all DBL can be successfully compiled in an IFC file, there is a risk that this file can be lost or damaged over the long-lasting lifecycle of the building. Furthermore, IFC files use a single schema about the building as an object and do not encapsulate the rich datasets that a building operation produces. openBIM is therefore not a permanent record. There is a need for a data infrastructure that is flexible at the outset but provides a secure record of DBL in the long term.

The second is the standard platform approach. Software-as-a-service vendors that store DBL data tend to have a centralised structure. The platforms provide an infrastructure for data exchange (e.g. material passports) by acting as a digital intermediary, creating a link between data providers and data buyers. In addition, the marketplace operator acts as an overview agent, brings together supply and demand and coordinates pricing. They keep the DBL data – in the form of databases or uploaded PDF documents – on their own servers. The platforms are also hopeful to develop service layers that can calculate key performance indexes such as circularity or carbon performance [12].

While these platforms are an important development step for the DBL, the *standard platform approach can be limited by the platform lock-in effect and permissioned nature found in centralised solutions* [18]. Closed metadata schemas can create a lock-in effect by making users dependent on a specific software or vendor, limiting flexibility and innovation due to the costs and risks involved in migrating data across incompatible systems [12,19]. Even when platforms are developed by local or regional governmental consortia, the platform lock-in effect makes it very difficult for users to leave the platform and very difficult for different platforms to be compatible with one another, across a market that is theoretically integrated like the one of the European Union. From that point of view, a single platform, while serving one or two countries, is unable to adapt and serve all the needs of the EU and may not be desirable as it does not allow for a multi-segment and company size market to develop.

The third approach is the *linked data* approach. The linked data approach shows a lot of promise using principles of the semantic web for sharing machine-readable interlinked data on the Web [20]. Nonetheless, there is still a need to provide governance models for authorisation of data provision (i.e. who fills in which parts of a DBL) and for validating data across multiple platforms [21]. Stakeholders need to be able to trust that data is correct and that someone has not manipulated the inputs, through the ability to view a verified record of transactions. Further, stakeholder benefits need to be considered through the design of an incentive system for the data, to overcome coordination challenges such as a lack of trust, poor information exchange and supply chain fragmentation. In general, the linked data approach is flawed in one respect. Even though they promise interoperability and vendor-neutral data access, most implementations tend to be technologically centralised [22]. This eliminates incentives for stakeholders to participate, as they are still highly dependent on a standard platform. In addition to the need for an open access, vendor-neutral and decentralised data foundation, a trusted incentive system must also be elaborated to motivate stakeholders participating in the DBL to complement the linked data approach.

We therefore need a data and logic architecture for the DBL that can accommodate a decentralised architecture and governance, embeds incentives for all stakeholders into the operation and data integrity of the DBL, allows for interoperability while thriving for decentralisation and integrating legacy data. This data and logic architecture must also allow for the creation of cross-purpose and cross-countries markets and uses of the data and integrate into one golden thread the data that a user might need, while retaining the resiliency of the data for decades. We outline in the following part of the chapter how this can be achieved using distributed data networks, blockchains and smart contracts.

6.1.3 Distributed ledger technologies, blockchains and smart contracts

Distributed ledger technologies (DLTs) refer to distributed databases where each participant holds a copy of the data (across sites and geographies), supported by a consensus mechanism to synchronise between these copies [23]. In DLTs, security is achieved by using public-private key cryptography and signatures to establish identities [23]. Blockchains are a common subset of distributed ledgers [24] and a decentralised version was first created in 2008–2009 to facilitate the idea behind digital cash, specifically, Bitcoin [25]. Earlier computing implementations or proposals brought forward the idea of Merkle trees in collapsing arrays of transactions into hashes or using cryptography to solve the problem of communication in a Mutually Suspicious group cryptographically. Cryptographer David Chaum first proposed a blockchain-like protocol in his 1982 dissertation *Computer Systems Established, Maintained, and Trusted by Mutually Suspicious Groups* [26]. Each block in a blockchain is connected immutably with the previous one by containing its cryptographic hash; this mechanism along with the incentivisation, secures the immutability of the blockchain, as users cannot go back and change the data, while incentives hold computing nodes true to the purpose and mission of the network which is the reliability and security of the transitions in a peer to peer fashion [24].

Blockchains can be either public (accessible by everyone) or private (closed, not publicly accessible), and permissioned (i.e. have restricted participation in the network) or permissionless (no restrictions and control to participate in the network) [27]. For the purposes of this chapter, we will focus on public, permissionless blockchains with the following features:

- An incentive for computing nodes to stay honest via the awarding of new crypto-tokens to the nodes,
- The collapse of all transactions at a given moment in a cryptographic hashing mechanism called a Merkle tree [28], where transactions are reduced to a single hash by progressively hashing them in pairs,
- A timestamp feature,
- A consensus mechanism using a proof of stake algorithm and
- A nonce, which is a number for each block used only once to prove authenticity, that is, the previous hash in a block of information which the computing nodes store on their ledger.

Beyond their cryptography, blockchains have been expanded to include the potential for running virtual software machines in a distributed fashion. Software executed on the blockchain is called a 'smart contract' as its immutable nature equates the concept of code execution with law

In this chapter, we refer to smart contracts as code[1] that get executed reliably on a blockchain, as a result of a data transaction. Smart legal contracts can also be used to define and perform legally binding and enforceable obligations [29]. Note that a smart contract does not necessarily have to constitute a valid binding agreement by law, but it must comply with a relevant legal framework.

Smart contracts can be explained as the computing code equivalent of automated vending machines. Deployed smart contracts act then as automatons, with the blockchain automatically executing their code when specific events trigger the computation. This creates an infrastructure automation layer where public permission blockchains can be used as global computing platforms. Blockchains are an excellent fit for processes that require the coordination of a sequence of events (e.g. supply chains or events of changes in a building), the coordination of trust of multiple stakeholders, privacy and security of data, and the operation of projects where not all actors need to trust each other.

6.1.4 Other key enabling technologies

6.1.4.1 Decentralised storage

Although blockchains can also be used as a data storage system, the cost of doing so on a public blockchain is often prohibitive [30,31]. As a complement to blockchain, decentralised data networks have emerged to enable storage and provision of data through decentralised systems [12]. For example, the InterPlanetary File System (IPFS) aims to solve the web data's typical availability problems, such as the limited lifetime of content, firewall blocks and out-of-business services [32]. It uses cryptographic checksums (i.e. digits representing the sum of the correct digits in stored or transmitted digital data, against which later comparisons can be made to detect data errors) of file contents to address and link data, which originates in GIT, BitTorrent and distributed hash tables. IPFS provides content not via the address where the content is located, but via what the content is. As such IPFS browsers locate content based on its hash, avoid as such duplication across containers.

While the development of IPFS is primarily aimed at file systems, so-called blockchain databases can transform conventional storage systems. The advantages of such blockchain-like technology are decentralised control, tamper resistance, value generation and transmission. IPFS and similar decentralised data storage approaches offer the opportunity to replace current cloud-based, highly centralised solutions [32]. Blockchain applications consider not only the record of the ledger but also the fundamental strategy of data organisation and its impact on data availability.

[1]Our definition of smart contracts is specific to the context of a blockchain-based DBL. Even so, instructions executed by smart contract code may have legal implications. Broadly, the readers should know that the debate about the status of smart contracts as code or legal contract is still in the process of being settled.

6.1.4.2 Cryptoeconomics and decentralised marketplaces

Any system built using blockchain smart contracts requires a systems-level thinking logic to govern digital transactions and interactions; in an institutional setting, this would for example reflect the transactional incentives of different actors adhering to the respective context's rules, norms, symbols and beliefs [33]. The term *cryptoeconomics* describes the design of P2P cryptographic systems that guarantee certain kinds of information security properties using incentives and/or penalties to regulate the distribution of efforts, goods and services in new digital economies [34]. Such blockchain-based mechanisms potentially integrate the increasingly available digital information with economic coordination (i.e. processes, contracts and finance) towards a more efficient construction industry.

Part of the epistemic and practical novelty of blockchains as crypto-economic systems is that trust, transactional infrastructure and incentives are encoded in the computing protocol of the network rather than decided by existing structures [33,35]. As such the implementation of cryptoeconomics has the potential to radically change the way various industries operate, for example in the development of markets for data in the built environment [33–35].

Although the sale of data has been practised for a long time, a data marketplace is a relatively new business model – for example as is reflected in the integration of transactional encryption and private AI in e-commerce [36]. A data marketplace refers to an intermediary service for data exchange. The key difference with the centralised marketplaces is the level of privacy and security provided by having two decentralised components in the web3 technology stack [37]. In other words, the data owners have secure and smooth access to their data, while maintaining privacy and confidentiality. This is because ownership never shifts to a central entity, meaning the data creator is paid for the data, not an intermediary. As a result, network participants are motivated to make their data available collaboratively while benefiting monetarily. Moreover, the decentralised architecture based on the web3 technology stack offers the advantage that the implementation of an incentive system is simpler due to the characteristics of the decentralised trust layer.

6.1.4.3 Cryptographically secure digital building twins

Blockchain technology can also be used to create a cryptographically secure digital building twin. This offers a transformative approach to managing building data [38]. The digital twin acts as a dynamic and tamper-proof replica of the building, encapsulating detailed records from the inception of the building through its entire lifecycle [39]. Because the data is secured on a blockchain, it remains immutable, meaning once information is entered, it cannot be altered or deleted without a trace. This level of security enhances both transparency and trust among all stakeholders, from builders and owners to regulators and occupants. The digital twin thus serves not only as a fully trusted source of information but also as a tool for enhancing decision-making and improving building management practices, fostering a more integrated and accountable approach to construction and facility management.

6.2 Conceptualisation

6.2.1 Motivation and objective

In this section, we describe our motivations and conceptualisation of the technical architecture and associated services for a blockchain-based DBL. In response to the above limitations, we find that a blockchain-based solution is the most appropriate technology to answer all the gaps identified for implementation of DBLs. We believe blockchain technologies can and should act as the backbone of the DBL. Blockchain records are immutable and will not be lost; this provides data and infrastructure resilience over the long-time horizon of a building lifecycle. Blockchain enables system-level trust by shifting the trust of managing records and data to the computer protocol of the blockchain. It can ensure native encryption and data security while featuring embedded incentives that encourage stakeholders to update the logbook. Blockchain offers decentralised, P2P transaction approach for the DBL that can decouple the business model logic from the data storage. This enables an opportunity to create novel governance, operating and business models for the DBL data and the buildings themselves.

Blockchain technologies are particularly suited for this type of data architecture as they decouple access and logic of the data from their storage, that is, data can be stored in legacy databases, decentralised storage architecture or in simple files and still be easy to reference them in the DBL blockchain. Further blockchain technologies allow the participation of multiple stakeholders in maintaining and accessing the data without compromising user experience, usability, the integrity of the data or the custody and ownership of data.

Other industries have seen this potential. For example, the shipping company Maersk, in collaboration with IBM, developed TradeLens, a blockchain-based platform aimed at enhancing transparency, efficiency and security in the global shipping industry. Launched in 2018, TradeLens utilised blockchain technology to digitise and streamline supply chain processes, reducing reliance on paper-based documentation and improving real-time visibility of cargo movements. The platform facilitated secure information sharing among various stakeholders, including shippers, freight forwarders, port operators and customs authorities, thereby minimising delays and errors in shipping operations [40]. However, TradeLens faced challenges in achieving widespread industry adoption. In November 2022, Maersk and IBM announced the discontinuation of the platform, citing its inability to meet the necessary level of commercial viability and industry collaboration. There are also other attempts at digital product passport traceability. For example, the company Circularise3 already works with manufacturing companies to digitise and trace materials across complex supply chains on a public blockchain without risking confidentiality.

To summarise, the characteristics of blockchain – trust, immutability and decentralised P2P transactions – are well aligned with the needs of the DBL and the loosely coupled, project-based built environment. Efforts to use blockchain has been done for product passports and supply chain tracing in other industries.

Through blockchain, there is opportunity to make the DBL more efficient, transparent and accountable between all involved participants.

6.2.2 Conceptual architecture

We envision a DBL standard that is constructed as a hybrid model, allowing the stakeholders and homeowners to use it either as a simple gateway to existing legacy data and databases but also, should the infrastructure and type of building allow it, as a container for decentralised data storage for the building. This is a deliberate architecture that allows the DBL to be future proof and resilient data architecture, that can adapt and evolve according to needs of the stakeholders and the industry.

There are three main layers to the system: data layer, logic layer (including services) and user layer (Figure 6.1). Within these three layers, we identify six key technical innovations of the blockchain-based DBL (see Table 6.2).

6.2.2.1 Data layer

The foundation of the data layer is a decentralised data network. Based on Table 6.2, we suggest that there is a need for a custom decentralised infrastructure that will be created for the purposes of hosting the various types of DBL data (see Table 6.3). There are many possible ways to organise this; the reader is referred to [41] for guidance on selecting a decentralised data network. One example approach would be to set up multiple IPFS nodes. Although it is possible to use public, permissionless blockchains for the infrastructure of the demonstrator, there are several issues related to speed of development, the possibility to test various consensus and the participation mechanisms that motivate this approach [42].

Within this infrastructure, users can integrate legacy data containers and existing databases alongside IPFS storage, resulting in a hybrid data storage system with both decentralised and centralised data. The IPFS nodes can run in cluster mode and as such will appear as one storage container where data is addressed by content identifiers (CID), ensuring that there is no unneeded duplication of data, that is, anyone uploading a second set of an existing data point/set will be informed that it already exists along with its CID.

In our conceptualisation, we suggest that user interfaces that will allow the stakeholders, data owners, users, data marketplace users and anyone downstream to access the DBLs when they have the appropriate access rights. The smart contracts architecture will be governed with a three-tiered structure of smart contracts: one that is the minimum viable product for a DBL, a second tier that deals with tokenisation and governance smart contacts and a third tier that establishes the smart contracts which deal with zero-knowledge proofs (protocols used between parties affiliated with a smart contract, where one party uses them to convince another that a given statement is true, without conveying any information beyond the fact of that statement’s truth) a privacy enhancing tool of blockchains and a smart contract that manages data for a digital twin of the building. A web-layer will play the role of the user interface, that is served by visiting the address of the demonstrator. This layer

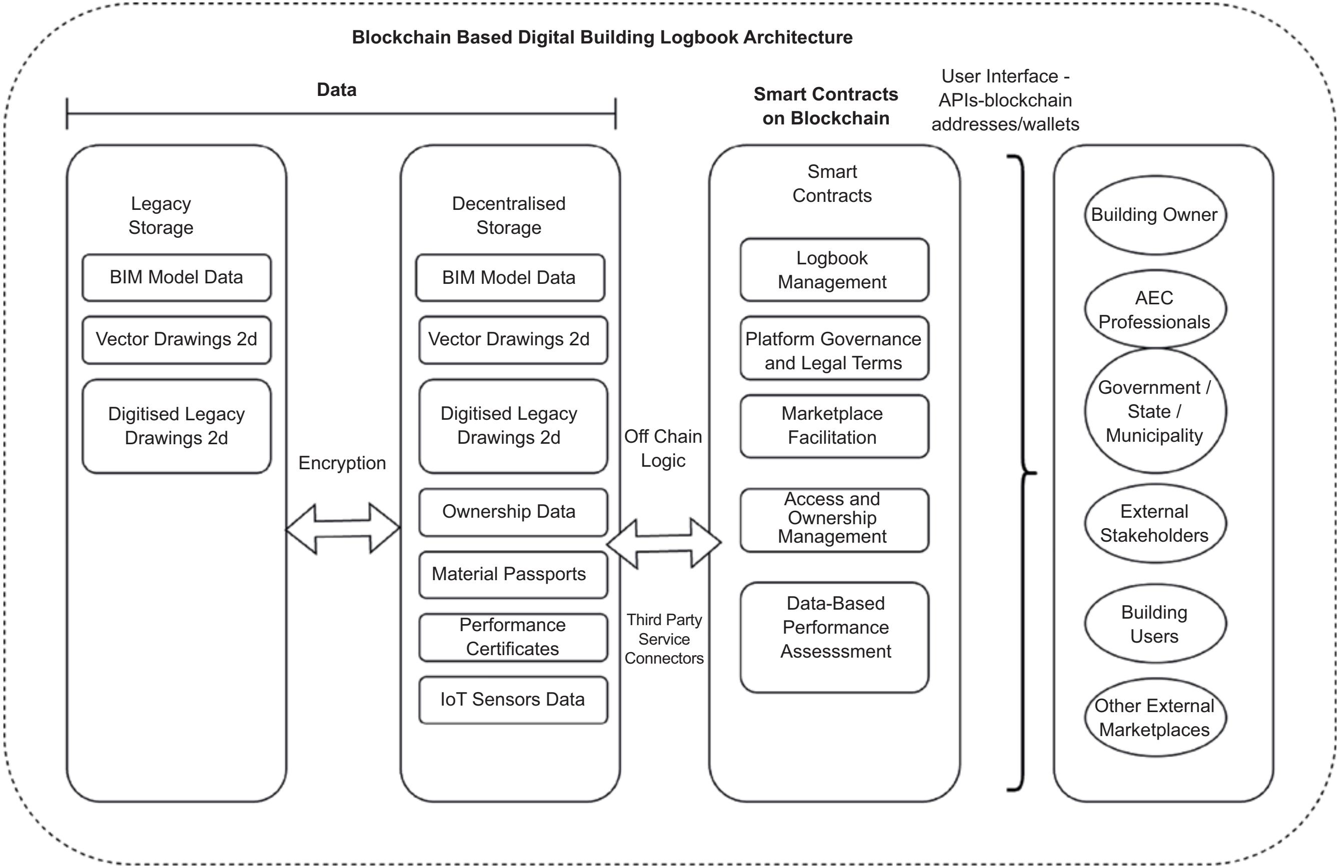

Figure 6.1 Conceptual diagram illustrating the three pillars of the conceptualisation

Table 6.2 The six key technical innovations identified for a blockchain-based DBL

Layer	Features	Description
Data layer	Decentralised data storage	Data is stored either on decentralised data networks or linked cryptographically to legacy databases. This hybrid approach ensures robustness and flexibility, allowing new buildings with IoT integration and older buildings under refurbishment to maintain a consistent and secure data architecture. This setup provides resilience against data loss and unauthorised access.
	Cryptographically secure digital building twin	Utilising blockchain creates a digital twin of the building that is secure and tamper-proof. This digital twin provides a detailed, immutable record of the building's data across its lifecycle, enhancing transparency and trust.
Logic and services layer	Smart contracts	The use of smart contracts automates the recording of changes to the DBL, including legal and ownership data. Operating on a proof of stake blockchain, these contracts provide a secure and efficient way to handle transactions and updates, minimising errors and enhancing processing speeds.
	Legacy data integration	Blockchain's architecture supports the integration of existing, older building data, ensuring that valuable historical information is preserved and utilised alongside new data. This integration is crucial for buildings under refurbishment, allowing for a seamless transition and maintenance of comprehensive data records.
User layer	Crypto-economic incentive system	Blockchain introduces incentives for various stakeholders to participate and update the DBL reliably. These incentives ensure active and honest participation, enhancing the data's integrity and reliability.
	Decentralisation of participation	Blockchain allows for decentralised control over the DBL, enabling various stakeholders such as owners, builders and regulators to participate without a central authority. This decentralisation increases engagement and accessibility while reducing the risk of data manipulation or control by a single entity.

will allow the registration of users, manage access to the rights, interact with both the decentralised storage clutter and the smart contract architecture and enable a streamlined experience for users.

Table 6.3 Data types that should be captured, stored and/or calculated by a blockchain-based DBL

Scale	**Category**	**Data types**	**Primary source**
Building	Contracts	Contract to design, contract to construct, other services contracts, build permit, asset ownership, tenancy agreement, maintenance service contract, warranty and guarantee, insurances, contract to demolish	PDF
	Building description	Unique building identifier, dimensions, floor area, room definition, fire safety plan, accessibility plan, water system design, heating system design, electrical system design	BIM, GIS
	Design and construction record	Architectural design record, structural design record, structural design calculations, mechanical design record, electrical design record, plumbing design record, cost data, schedule, information required by regulation (such as health and safety plans)	BIM
	Operational data	Renewable energy production, heating consumption, electricity consumption, hot water consumption, energy performance certificate, rainwater collection, weather, surface temperature	Digital building twin
	Performance data	Circularity indicator (e.g. by Madaster), building circularity index, life cycle analysis, material flow analysis, sum of embodied carbon, sum of operational carbon, whole lifecycle carbon, climate resilience potential, EPC rating, structural reliability index, residual structural service life	External assessment tools (e.g. Madaster)
Product	General information	Product name, purchase order, manufacturer's details, manufacture date, global trade item number, product owner, function, dimensions, weight, density, thermal resistance and conductivity	Material passport
	Material health and sustainability	Health and safety certifications, fire resistance class, embodied carbon, operational carbon, percentage of renewable materials, percentage of recycled material amount, material circularity indicator	Material passport, external assessment tools
	Production information	Quality test, waste, product certifications and labels, humidity, temperature	Material passport
	Construction log	Current geolocation, present status, assembly instruction, tracing mechanism, acceleration, rotation, humidity, temperature, date of installation	Digital construction twin
	Product performance data	Life cycle analysis, embodied carbon, construction carbon, target service life, compatibility with design, Product circularity index	External assessment tools
	Use, maintenance and end of life	Cleaning and maintenance instructions, warranty and guarantee, maintenance contractor details, maintenance service dates, storage requirements, service life and expected use times, availability of spare parts, proof of recycling	PDF

6.2.2.2 Logic and services layer

The logic layer of a blockchain-based DBL enables a transparent and efficient management system on top of the data layer. There are five categories of smart contracts that could be developed: logbook management, platform governance and legal terms, marketplace contracts, access and ownership management, and data-based performance assessment. Table 6.4 provides a summarised table capturing the five main categories of smart contracts for a blockchain-based DBL.

Table 6.4 A description of the five main categories of smart contracts for the DBL

Logic and services	Specific functions of smart contract	Further description
Logbook management	Recording	Automates the entry of new building data into the logbook.
	Verification	Validates the accuracy and authenticity of the data recorded.
	Updating	Manages updates to the logbook, ensuring data integrity and accurate history via timestamping.
	Event logging	Captures and records construction milestones and maintenance activities automatically.
Platform governance and legal compliance	Role definition	Specifies roles and responsibilities for each blockchain participant.
	Operational rules	Establishes the guidelines for how the blockchain operates.
	Legal alignment	Ensures that smart contract operations comply with relevant laws and regulations.
	Decision-making	Facilitates governance decisions through smart contracts based on predefined rules.
Access and ownership management	Access control	Regulates who can access or edit the DBL data, ensuring privacy and confidentiality.
	Data protection	Protects sensitive information by restricting access to authorised users only.
	Ownership rights	Clarifies and enforces data ownership rights on the blockchain.
	Legacy system integration	Manages the inclusion and integration of data from existing systems into the blockchain system.
	Data trading	Enables direct P2P exchange of data, eliminating the need for intermediaries.
	Privacy and anonymity	Ensures that participants can interact anonymously and securely in the marketplace.
	Transparency	Provides transparency in transactions, making all details visible and verifiable by participants.
	Ownership transfer	Manages the legal and technical aspects of transferring data ownership and rights during transactions.
Data-based performance assessment	Performance metrics	Establishes performance criteria such as energy efficiency and sustainability benchmarks for buildings.
	Real-time monitoring	Allows for continuous monitoring and evaluation of building performance against set criteria.
	Decision support	Provides actionable insights based on performance data to support maintenance, retrofitting or redevelopment decisions.
	Environmental impact	Evaluates and reports on the impact of buildings on the environment, promoting sustainability.

The first set of smart contracts for *logbook management* serve as the backbone of the DBL, enabling the recording, verification and updating of building data throughout its lifecycle. They ensure the integrity of the logbook entries, allowing for accurate tracking of a building's history, renovations and transactions. Through timestamping, these contracts would automate the logging of events, such as construction milestones or maintenance activities, ensuring that the logbook is an immutable and reliable source of the building's history.

A second set of smart contracts serve as the guidelines for *platform governance and legal compliance*. Together, these smart contracts implement a comprehensive governance framework that dictates how the blockchain operates, defines the roles and responsibilities of all participants and establishes the decision-making process. Such smart contracts could include a Non-Fungible Tokens Generator and a Fungible Tokens Generator. This model should align with the legal and regulatory requirements of the industry and the jurisdictions in which the system operates. They act as a framework within which all other smart contracts operate, thus serving as a legal and operational guideline for the DBL ecosystem. They also act as a point in which those regulatory requirements which relate to the collation and sharing of information can be met, stored and interacted with.

The third set of smart contracts are for *access and ownership management.* These contracts govern the permissions and rights associated with the DBL data, determining who can view or modify the logbook entries. They ensure that sensitive data is accessible only to authorised stakeholders and that ownership rights are clearly defined and protected. This category is crucial for managing the data inputs from legacy systems, as well as integrating new data streams in a controlled manner.

The fourth set of smart contracts comprise the *Decentralised data marketplace*. The decentralised data marketplace is a P2P system where participants can trade with each other and exchange information. The marketplace should be open so that anyone can join and add value to the network and community. At the same time, the marketplace will provide privacy, anonymity, transparency and access control. In practice, this means a data owner can be directly paid for the provision of data used by third-party services, instead of paying fees to an intermediary or the data being sold by a centralised platform. The smart contracts will encode the logic to access, modify and transfer data and their respective ownership (Figure 6.2).

The fifth set of smart contracts act as a service layer for *data-based performance assessment*. Smart contracts in this category would, for example, automate the evaluation of building performance against predefined criteria, such as energy efficiency benchmarks, sustainability indexes or circular economy standards. These could be connected to a blockchain-assured digital building twin. These contracts would enable real-time performance tracking, providing insights for optimisation and supporting decision-making for maintenance, retrofitting or redevelopment projects. They are essential for assessing the long-term value and impact of buildings on the environment and society.

The above two main components (data and trust layer) need to be connected to each other and legacy systems with what we call data bridges. The connection

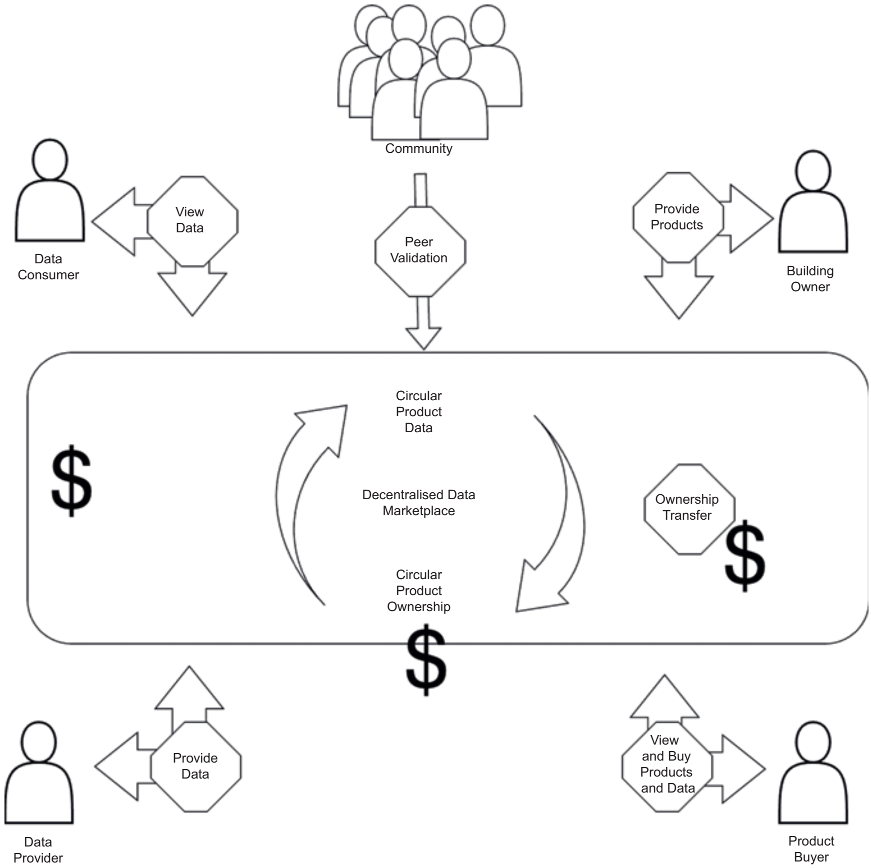

Figure 6.2 Example of a decentralised data marketplace set on top of the data layer (adapted from [43])

between the decentralised data storage and the blockchain will be enabled through third-party service connectors. In brief these servers will route data over APIs (e.g. the Web3.js or Web3.py libraries) between the two systems. In a similar way, the user interfaces needed for the stakeholders to interact with the data and logic will route data using third party servers and APIs between the web front end, the blockchain wallet, the blockchain smart contracts and the decentralised data storage. Finally, a series of processes and tools will be developed to ensure transfer of data between legacy data systems and the here proposed decentralised system. This ensures that stakeholders can input data from existing buildings in the most used data formats.

There is one important remaining point about the relationship between the logic layer and the data layer. The smart contracts can timestamp and record changes to the DBL legal on the decentralised data network. However, as a hybrid system is imagined, the smart contracts should also be designed to interact with legacy databases and data storages. As such, it is possible to use the same smart contracts to monitor a new building with embedded IoT sensors while maintaining the same legacy data of an existing older building that would be under refurbishment. In other words, blockchain allows a separation of the governance and economic layer from the data layer, so that multiple different types of data storage systems can be used underneath the same network of smart contracts.

6.2.2.3 User layer

In the blockchain-based DBL system, crypto economic incentives play a pivotal role in motivating stakeholders to share valuable data while ensuring their privacy and control. These incentives are designed to create a virtuous cycle where information exchange is not just encouraged but rewarded, balancing transparency with the stakeholders' need for anonymity. Such an incentive system can target data quality, seamless interoperability, availability, usability, classification, consistency, integrity, security and control models. For example, sharing high-quality data can be incentivised by a mix of monetary and non-monetary incentives. By aligning user actions with the overall health of the DBL, these incentives create a participatory ecosystem where each stakeholder is motivated to maintain the integrity and richness of the database.

For instance, a crowdsource incentive could refer to a user who contributes to the digital twin's accuracy by providing timely updates may receive tokens, which could in turn be used for services within the platform or gain access to advanced analytics that can inform better decision-making for future projects. This symbiotic relationship between users and the DBL enhances the system's value and ensures its sustainability, as each participant becomes a custodian of the shared digital infrastructure, empowered by the very act of contribution and incentivised through tangible rewards that reflect their effort and input.

To develop the crypto economic incentive system, the following future research steps are needed. First, there is a need to determine which actions within the DBL should be incentivised. These actions could include data entry, validation, updates, quality checks and the provision of resources for the platform. Where possible, these should reflect criteria which can be objectively determined to mitigate the risk of disputes as to whether these actions have been accurately carried out. The identification process should focus on activities that add value to the DBL's accuracy, completeness and reliability. Second, there is a need to create a system of rewards that will motivate users to perform the identified actions. This can include tokens, access rights or other benefits, as well as deciding on the form these incentives will take (e.g. cryptocurrency, service discounts, enhanced platform features), and ensuring they align with the users' values and needs. Third and finally, these rules can be encoded on the trust layer via smart contracts that can automate these processes transparently and without the need for a central authority.

A web-layer will play the role of the user interface, that is served by visiting the address of the demonstrator. This layer will allow the registration of users, manage access to the rights, interact with both the decentralised storage clutter and the smart contract architecture and enable a streamlined experience for users. The user interface should make it easy for users to understand how to earn and use their incentives. It should clearly display earned rewards, available actions that yield rewards, and provide a simple way to redeem or spend tokens.

6.2.3 Summary

As described above, we conceptualise three layers of architecture to the blockchain-based DBL.

At the core of the DBL's data layer lies a secure, accessible storage environment, allowing participants self-service access to information they can trust and understand. To enhance this trust, the DBL leverages cryptoeconomic incentives to encourage the sharing of high-quality data. These incentives are thoughtfully constructed to include monetary rewards, such as tokens for consistent contributors of verified data, and non-monetary benefits, like enhanced reputation within the platform or access to exclusive analytical tools. This multifaceted incentive system ensures that the data within the DBL is not only abundant but also accurate, reliable and valuable for all users.

The trust layer underpins the DBL's data marketplace, establishing the rules and logic that govern data exchange. Here, smart contracts play a critical role in automating the transfer of rights, such as allocating the future reuse of building materials, exemplified by the door trading scenario. This mechanism introduces a new dimension to the construction industry's marketplace, where not only goods and services but also potential future uses of a building's components can be commodified and exchanged. Such innovations pave the way for a sustainable and circular economy, rooted in the principles of transparency and conservation.

The integration of data bridges forms the final piece of the puzzle, linking the decentralised data storage and smart contracts with legacy systems. This connectivity ensures the platform's robustness, allowing a seamless flow of diverse data types, including real-time IoT feeds and historical records from conventional databases. Special attention is given to crafting a user-centric interface, where stakeholders interact through intuitive protocols, enabled by APIs that connect the blockchain layer with the user-facing web front. By prioritising ease of use and streamlined interaction, the DBL not only appeals to current users but is also positioned to adapt to future developments in data management and stakeholder engagement.

6.3 Potential impacts and future research directions

What would a blockchain-based DBL offer? Should the concept be implemented, we describe below seven potential impacts for the built environment that would come with such a new system. We further describe possible areas of future research for each of the areas. Table 6.5 summarises these areas.

Table 6.5 Impacts and future research directions for a blockchain-based digital building logbook

Potential impact	How it works	Future research
Enabling a new information infrastructure backbone	Acts as a consolidated platform for diverse building data, enhancing visibility and trustworthiness of information.	Investigating how decentralised networks support a circular economy and integrating fragmented industries like AEC. Exploring open-source smart contracts for integrated building management.
Accelerating the business case for renovation and reuse	Supports integration of existing and new buildings for sustainability goals, promoting circular economy concepts.	Developing business models such as renovation passports and servitisation in building management, tailored for energy efficiency and resource optimisation.
Enabling new P2P business models	Facilitates innovative digital business models and decentralised marketplaces across the building lifecycle.	Examining transformations in business models and governance through blockchain, focusing on P2P interactions and efficiency in the AEC industry's value chain.
Improving existing legal structures	Challenges existing legal frameworks with its novel approach, emphasising data security and multi-jurisdictional operations.	Creating toolkits for legal adaptation to blockchain technologies, enhancing data confidentiality and developing standard legal protocols for smart contract operations.
Fostering new governmental policies, incentives and regulations	Encourages adoption of sustainable practices and compliance through blockchain-enabled transparency and accountability.	Exploring how stakeholder engagement shapes policies for DBL adoption, analysing the effectiveness of governmental incentives for sustainable practices in the built environment.
Moving towards a more circular Europe	Promotes sustainability by enabling more efficient resource use and supporting circular practices in the building sector.	Investigating the impact of DBLs on European Green Deal goals, enhancing resource management and resilience in the AEC sector, assessing the environmental performance of blockchain technologies and addressing concerns about the energy consumption of blockchain technologies.
Enabling better security and privacy of data	Enhances data protection with robust cryptographic security and privacy-centric features, fostering user trust and engagement.	Advancing the integration of privacy-preserving technologies like zero-knowledge proofs in blockchain frameworks and assessing their impact on user confidence and system adoption.

6.3.1 Enabling a new information 'self-infrastructuring' backbone

The proposed blockchain-based DBL can act as a new information infrastructure backbone for the data of a building, consolidating disparate sources of information, from BIM to drawings, material passports and energy performance certificates. But how can this come about? We think the concept of Web3 as 'self-infrastructuring' is a key future research direction [44]. Self-infrastructuring occurs when relevant actors have the ability to place boundaries around their own actions in relation to shared purposes or goals, that are then expressed in technical and institutional infrastructure [44]. Future research can better identify how such actors can organise decentralised data networks can act as the information layer for a circular economy for the built environment and also can assist in integrating a fragmented industry such as the architecture, engineering and construction (AEC) industry. This will increase the visibility and trustworthiness of blockchain technologies as a decentralised information system for use in Architecture Engineering construction. The open-source nature of smart contracts on the logic layer can both educate and empower researchers and professionals to find integrated approaches to building management that emphasises carbon and energy performance.

6.3.2 Accelerating the business case for renovation and reuse

The AEC industry encompasses diverse market segments, including manufacturing, design, construction and software development such as BIM. These segments not only operate independently but also collaborate, sharing data, services and resources. As industry moves towards embracing a circular economy, the concept of treating the built environment as an urban mine becomes crucial. This involves using digital tools like material passports, energy certificates and digital twins throughout the lifecycle of buildings to support sustainability goals such as reducing resource extraction and achieving net-zero emissions.

The EU estimates that there are about 131 million buildings, with a significant portion built before the latest thermal standards [45]. This is also reflected in the fact that, across the EU, most residents still live in buildings that are at least half a century old – which are inadequate for today's energy efficiency demands [45]. The buildings' low energy efficiency can negatively impact their occupants' quality of life, while their suboptimal environmental microclimate can have a strong economic and ecological impact [14]. To address this, EU's Energy Performance of Buildings Directive (EPBD) EU/2010/31 and the new EED EU/2023/1791 are emphasising the renovation of existing buildings, as constructing new dwellings is getting increasingly more difficult, especially in densely populated areas: usable empty sites within cities are fewer, and demolishing and dismantling older buildings may have an even worse environmental impact [1,46]. A salient example of a national context affected by these EU demands could be found in Sweden: Nearly 933,000 (45%) of one- or two-dwelling buildings were built between 1961 and 1990, 20% of one- or two-dwelling buildings were built before 1931 and 51% of multi-dwelling buildings were built between 1951 and 1980 [47] –

which showcases a massive buildings stock in need of renovation. According to Sveriges Allmännytta [48], aligning the renovation needs of such an aging building stock with EPBD, along with the general goal of attaining a carbon-neutral construction sector in Sweden until 2045 [49], would be crucial but also very expensive – with early calculations pointing to a cost of many billion Euros.

Examples like that of Sweden and the general EU regulatory framework showcase a large opportunity for energy retrofits, which can be efficiently managed using a blockchain-based DBL. The proposed system supports the easy integration of both new and existing buildings into its system. For new constructions, it allows data to be entered at the design phase, while a 'legacy bridge' enables the inclusion of older buildings by updating and integrating their data. This process supports the creation of new business models like building renovation passports and servitisation, where companies manage installations and are incentivised to maintain them.

6.3.3 Enabling new peer-to-peer business models

The logic layer offers the opportunity to facilitate novel digital business models, considering the creation, maintenance and interoperability of DBL along the building's lifecycle. Those novel digital business models will comprise added value for the network (value constellation) and value offered to stakeholders or customers (value proposition) through the application of DBL. Both values will be combined through blockchain. One advantage of decoupling data storage from the logic layer, is that blockchain-based DBL remains flexible with regards to the types of logics proposed at the service layer. This enables local and regional markets to develop new business models that best fit the local markets and regulatory conditions. In other words, using our proposed conceptualisation, technical infrastructure and approach, various implementers can then create their own user interface and marketplace layers that are interoperable with our architecture. This allows the concept of DBL to scale while still accounting for local and regional building considerations.

The novelty here includes the necessary transformation of processes/activities and traditional (contractual and relational) governance mechanisms into new cooperation and coordination modes enabled by blockchain/smart contracts governance and the creation of new decentralised marketplaces and incentive mechanisms (cryptoeconomic; non-monetary) for participation in the DBL and exchange of information. Hence, future research of the expected business model transformation could investigate how changes in P2P transactions occur across the NICE framework [14] adapted from [50–52] *Novelty* (adoption of new activities, structures, approaches), change in *Lock-in effects* (attracting stakeholders to become business model participants), *Complementariness* (bundling of activities for the generation of added value, along the value chain) and *Efficiency* (reorganising and reshaping activities in order to reduce tacitness/transaction costs).

6.3.4 Improving existing legal structures

The implementation of blockchain-based DBLs confronts existing legal structures and frameworks that have yet to evolve to match the technology's novelty and data security demands. The challenges are amplified by blockchain's international and multi-jurisdictional nature, complicating the identification of applicable laws and enforcement of legal frameworks. The issue here is not the absence of a legal framework that can regulate the DBL environment but the adequacy and or adaptability of such framework to the changing socio-legal landscape. Legal systems (whether based on the common law or civil law) are often adaptable and are able to address challenges posed by technological innovations such as the DBL concept. Fundamentally, much of the processes outlined here will be underpinned by contract law in one form or the other and statutory provisions around data handling and privacy as reflected in the GDPR (see EU Document 32016R067). However, more work still remains in terms of adapting these existing frameworks to the DBL concept specifically. This necessitates a thorough investigation into current and prospective regulations concerning DBLs to address critical issues such as data confidentiality and to prepare for future legal developments. Future research could include the development of toolkits that outline consensus-building protocols and enhance data security are pivotal for navigating the legal landscape.

Furthermore, existing legislation could inadvertently impede the adoption of blockchain technology, posing significant barriers to implementation. Thus, there is an imperative for ongoing research into legal structures tailored to blockchain-based DBLs. Legal scholars are encouraged to develop toolkits that elucidate legal rights across jurisdictions, laying the groundwork for smart contract operations and the creation of standard protocols that will underpin internal governance structures. Such foundational work will clarify how the law interacts with blockchain's innovative incentive mechanisms, fostering a more profound understanding and smoother integration of blockchain within the AEC industry's regulatory environment.

Finally, however, DBLs, tailored appropriately, could provide a vehicle for the collation, distribution and analysis of the information which is required by regulatory bodies in various jurisdictions. Justified in the name of transparency, accountability and information sharing, different regulatory regimes - such as those which protect health and safety or the environment, require those involved in construction projects to provide specific information in terms of the activities being undertaken and with a view to meeting the particular regulatory requirements. Such regulations often also require there to be regular updates to these documents. The ability to record and update the necessary information in real time and to secure it on the blockchain, is therefore a potentially valuable avenue for the DBLs and one where the legal structures provide a positive additional use-case, assuming the DBLs are appropriately calibrated.

6.3.5 Fostering new governmental policies, incentives and regulations

If a blockchain-based DBL is shown to be technically feasible, future market adoption will depend on a series of orchestrated events such as adoption of standards by international commissions and national governments, as well as local regional and municipal authorities. Future research would need to look at how a proactive engagement with a broad spectrum of stakeholders – from large-scale building owners to municipal and national environmental authorities – could shape favourable conditions for the widespread adoption and effective implementation of DBLs.

A blockchain-based DBL enables third-party access to building logbooks across Europe. This could foster new approaches to governmental incentive systems that support a more circular and sustainable economy in the built environment. For example, city authorities can use blockchain to offer tax reductions to building owners who show that their buildings have a minimal environmental impact. These tax incentives can be managed and monitored through smart contracts, ensuring transparent and automatic enforcement of environmental standards.

Additionally, the DBL could allow for the integration of recycled and reused building materials during the design phase of new projects. Access to the DBLs makes it easier for city authorities and builders to verify that reclaimed materials are used correctly, adhering to sustainability practices.

6.3.6 Moving towards a more circular Europe

The adoption of DBLs is set to support the European Green Deal [45] by enhancing sustainability throughout the lifecycle of buildings. This improvement may help reduce net carbon emissions in the building sector by promoting more efficient resource use and lessening reliance on raw materials, which are core tenets of European Green Deal.

The use of DBLs will promote circular practices in design, construction and operation within the AEC industry. For instance, the transfer of ownership of building components can be simplified through Product-Ownership-Tokens on the blockchain, facilitating easier and more transparent transactions – even if the component is still in use. These transactions can occur directly or via the DBL marketplace using methods like auctions or set pricing, ensuring the new owner gains all associated rights and data.

Implementing digital logbooks more broadly can improve security by providing more reliable data, which makes buildings easier to update and adapt, increasing their resilience. It encourages sustainable practices such as designing for recycling and supports the use of environmentally friendly building materials. Moreover, it allows for the tracking of materials globally, enhancing the industry's ability to manage resources effectively and respond to crises with greater agility. This comprehensive approach not only reduces waste but also boosts the overall environmental performance of buildings, contributing to a more sustainable future for Europe's built environment.

As a short note, there are many rightful concerns about the current environmental performance of blockchains. While we share these concerns, we also want to note the ongoing momentum in blockchain development to solve this problem. Specifically, the current consensus mechanism for many blockchains (e.g. the bitcoin blockchain) is known as proof of work, which requires the solving of a cryptographic puzzle using energy-expensive algorithms. There are alternative approaches that can be used for a DBL, such as a proof of stake where consensus is ensured by participants risking some of their own stake. Proof of stake consumes much less energy. For example, the Ethereum blockchain reduced its energy footprint by 99.9% when it made the transition to proof of stake in September 2022 [53].

6.3.7 Enabling better security and privacy of data

Blockchain technology, recognised for its robust cryptographic security, plays a crucial role in enhancing data protection and privacy. Incorporating zero-knowledge proofs within blockchain frameworks, which allow the verification of data without exposing the actual data, further strengthens this approach. This combination ensures that personal data remains private even as it is used to verify transactions or interactions within a network.

By deploying these advanced security measures, blockchain technology supports the safe participation of stakeholders in shared data environments such as the decentralised data marketplace proposed above. This secure setup is critical for fostering trust among users, as it guarantees that their private information is not compromised while still allowing them to benefit from the system. The privacy-centric features of blockchain not only protect data but also enhance user confidence and willingness to engage with the platform.

The continued development and integration of these technologies are likely to accelerate the societal and commercial acceptance of blockchain-based systems. As stakeholders recognise the dual benefits of robust security coupled with strict privacy controls, the adoption of blockchain for managing sensitive information in a transparent yet secure manner is expected to increase. This will play a significant role in transforming how data is shared and utilised across industries, driving innovation while safeguarding user privacy. In this vein, it is encouraged that future empirical studies will be conducted to test the proposed impacts and validate the expounded conceptual model.

6.4 Conclusion

The exploration of a blockchain-based DBL as detailed in this chapter could represent a significant advancement in the AEC industry, particularly in fostering sustainable and efficient practices within Europe's built environment. By deploying blockchain technology for DBLs, it can be possible to enable a robust, secure and transparent framework for managing extensive data across a building's lifecycle. This approach not only supports the operational needs of building management but also aligns with strategic environmental goals such as those outlined in the European Green Deal. The integration of blockchain ensures that all changes, from construction through maintenance to demolition, are recorded immutably, enhancing trust and reliability in building documentation.

Moreover, the proposed architecture for DBLs incorporates decentralised data storage, smart contract functionality and the creation of a decentralised data marketplace, which together improve interoperability, reduce administrative burdens and enhance user engagement. These technological advancements facilitate more accurate tracking of material usage, energy consumption and overall building performance, contributing to the circular economy objectives. As the chapter concludes, it calls for ongoing research to refine these blockchain applications, ensuring that they can meet future demands and continue to evolve with the industry's technological landscape. This future-focused approach underscores the necessity for continuous improvement and adaptation in the implementation of blockchain technologies within the AEC sector.

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