Handbook of Research on Driving Transformational Change in the Digital Built Environment

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Chapter 8
Blockchains for Use in Construction and Engineering Projects

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ABSTRACT

This chapter describes blockchains and illustrates this explanation using the results of a prototype project for an industrial application for a construction project. The chapter describes the application and how modular software components can be used to assemble a blockchain solution. The chapter concludes with a design of the system architecture. The background to blockchain technology includes a description of the evolving nature due to communal, open software consortia and an accelerated prototyping of systems. Four recommendations are made in the chapter. These include the need to form consortia for prototyping applications, encouraging government involvement, the need for engagement with the open software development community, and the suggestion that systems should be designed to support Lean production. A final section offers a range of discussion topics on the current state of the technology and where to expect area of increased interest. These are summarized in three areas: Lean management, Industry 4.0 and smart cities, and topics around privacy and security.

INTRODUCTION

Perspectives of The Research and a Summary Of The Contents Of The Chapter

This chapter describes the technology behind blockchains and how, in conjunction with a suite of inter-related modular components, they can be used for a variety of tasks in construction and engineering (C&E) projects (Darabseh & Martins, 2020; Yang, et al., 2020; Hargaden, et al., 2019). There are a number of applications of blockchains that, irregardless of skepticism (Perera, et al., 2020), and the difficulty in scaling-up in size, could provide advantages over current solutions. This is because blockchains provide something novel: the ability to hold critical data that, once written, are immutable, protected,

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can reside on a distributed network of computers. Immutability provides the data with authenticity, the use of distributed networks allows independence of a central hosting authority (Berg, et al., 2018; Zheng, et al., 2018; Pilkington, 2016), and security of valuable data is made possible by cryptography. Smart contracts, embedded in the blockchains, can help automate processes, most notably, payments. In other words, blockchains enable mutually distrustful parties to transact safely without the intervention of a trusted third party. This, most distinguishing attribute, is a mechanism that institutionalizes trust (Werbach, 2018; Berg, et al., 2017; Weber, et al., 2016; Anon., 2015b).

These features and capabilities are increasingly in demand as mobile arrays of interconnected devices produce volumes of data that can be valorized by artificial intelligence, big-data analytics, and advanced visual displays. Proponents of blockchain technology have been quick to propose applications to support concepts such as the Internet of Things (IoT) (Delgado-Mohatar, et al., 2020; Panarello, et al., 2018), Industry 4.0 (Lee, et al., 2019), smart cities (Swan, 2018; Huckle, et al., 2016), digital twins (Yaqoob, et al., 2020), and edge computing (Xiong, et al., 2018), and BIM. What all these concepts require is reliable machine to machine communications (Afanasev, et al., 2018) on a secure data-layer that is able to overcome the segmentation caused by multiple sources. It was the work of insightful and futuristic thinkers that envisioned the broader application of blockchains across industry (Al-Jaroodi & Mohamed, 2019), government and civil society (Swan, 2015). -

The novelty of the technology has prompted proposals in C&E for: energy management and carbon accounting (Petri, et al., 2020; Wang, et al., 2017), transport monitoring (Knirsch, et al., 2018), contract and document flow automation, and supply chain synchronization. The hope is that the use of blockchains can lead to improved project workflow, time and cost savings, increased transparency and trust amongst stakeholders (Turk and Klinc, 2017).

But there are impediments to the smooth adoption of this new technology, notably the difficulty in scaling up in size, in the management of the networks, and in getting the systems to function correctly in the first place. But there are significant trends that inspire continued interest in this area. Firstly, leading technology companies offer blockchain hosting and partnering solutions. Secondly, start-up companies are developing innovative technology that makes developing and deploying blockchains systems easier and finally, a growing community of enthusiast are collaborating to provide solutions.

For use in C&E projects, systems can be divided into two categories: (1) blockchains for holding critical data such as certificates, authorisations, payments and tokens and (2) blockchains optimised for enacting smart contracts within complex trading environments. Both of these categories would be classified as *industrial blockchains.* They use the same core engineering elements as those in cryptocurrencies such as Bitcoin (Nakamoto, 2008), but have added capabilities that allow for smart contracts and a choice of algorithms for ordering and confirming the authenticity of the data. The following sections will explain these features and describe how they work.

Who is This Chapter for and How Will the Contents Assist in Technology Implementation and Adoption?

Users of the chapter are likely to be those who are faced with a deluge of data emanating from devices in buildings and cities and want to use the properties of the blockchain to obtain improved analysis and problem solving. Amongst this group are likely to be managers who have an interest in automating certain aspects of their administrative, assembly or manufacturing processes and want to be able to integrate these with their suppliers, customers, banks, insurance companies and government regulators.

It is with some optimism that blockchain technology is described in this chapter as there is often hesitance shown by managers working in C&E to adopt new technology (Waterhouse et al., 2019) or for engaging in the level of collaboration required to adopt radical change (Akintoye and Main, 2007). However, there are encouraging signs, particularly if we consider how BIM and project management software, after initial hesitation, are now being used in many projects. Indeed, the adoption of Modern Methods of Construction (MMC) (Raynsford et al., 2016; Pasquire & Connolly, 2002) by contractors is a sign of the changing requirement for more sophisticated approaches to supply chain management, logistics and automation, all of which could be supported by the use of blockchains.

Aims and Objectives of the Chapter and a Summary of the Contents

The long-term aim of the research is to enable authenticity and independence of data in smart cities and to facilitate their use in delivering useful services. The short-term objectives of this chapter are as follows:

Objective 1: To explain private permissioned blockchains and associated modules, collectively referred to as digital ledger technology (DLT).
Objective 2: To illustrate the design principles and implementation process for a DLT using a prototype example.
Objective 3: To show how DLT can be applied to facilitate services in C&E projects.
Objective 4: To propose a system architecture for a DLT solution for C&E projects.
Objective 5: To provide a set of recommendations for those with an interest in seeing blockchains develop further.
Objective 6: To introduce a set of discussion topics on the future technical developments and expanded applications.

BACKGROUND

Basic Description of A Blockchain

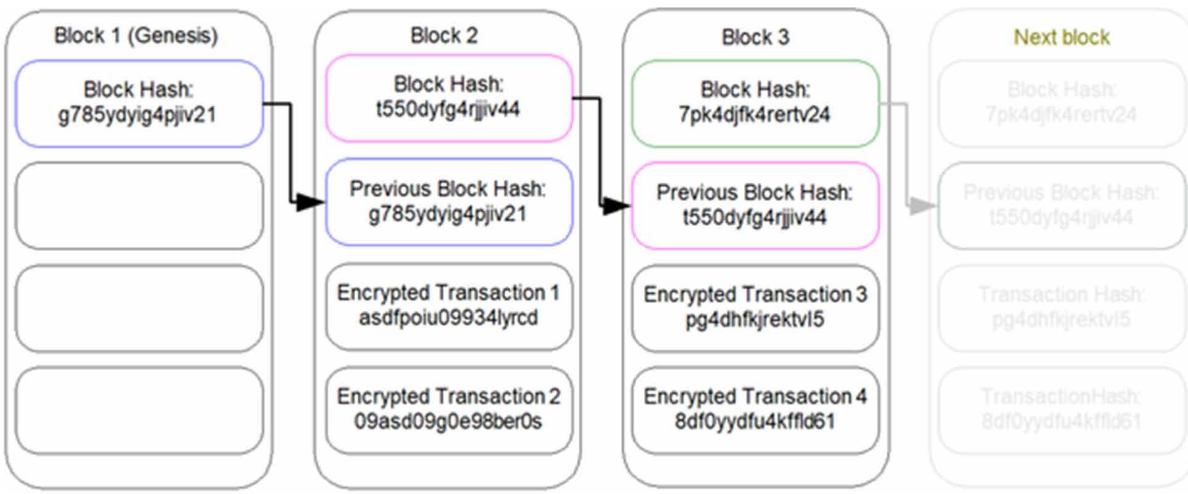
Blockchains achieve their unique characteristics by the application of three technologies. These are: cryptography (Kosba, 2016), distributed systems on networks, and consensus algorithms (Wang et al., 2018b).

In its most basic form, a blockchain is a computer file that resides in multiple nodes of a computer network. An example of a fragment of a blockchain file is shown in Figure 1.

In this diagram, the three large vertical rectangles represent the *blocks* from which the blockchain derives its name. At the core of the blockchain is the cryptographic hash function (CHF), a mathematical algorithm that is very useful as it converts data of an arbitrary size (for example, a message or a password) to a string (or *hash*) of a fixed length. There are no passwords involved and, as a one-way (i.e. irreversible) function, it is nearly impossible to reverse. Hashes have useful properties, for example, miniscule difference in the original text makes for significant differences in the hashed versions.

The CHF is used to ensure that the chain of records contained in a blockchain cannot be altered as it would interfere with the propagation of hashes that are used to link one block to the next (Finck, 2018). An example of this is shown in the sixteen-digit hexadecimal hash (representing 64-bit encryption) shown in Figure 1. In addition to the hash of the previous block, each block also contains a schema referred to as the Merkle Tree (not shown in Figure 1), a structure in which historic hashed data are stored to ensure ordering is conserved.

Figure 1. Contains a schematic diagram of a typical blockchain file. In this example, three (3) completed blocks of data, ordered sequentially, are shown. The leftmost (the so-called Genesis block) is the first, with the blocks to the right added on later. The fourth block (shown as the rightmost rectangle that is shaded out) is represented as incomplete, and will only be finalized once the information has been authorised by the consensus algorithm.



Cryptography, in the form of *asymmetrical key* (see Singh, 2000), is used elsewhere on the blockchain to ensure the security and privacy (Banerjee, et al., 2018; Szabo, 1997) of individual records. This helps protect against attempts to alter the details of the records as is required by current standards for computer security in the built environment (PAS 1192-5., 2015). Users are issued with a unique pair of numbers by a trusted certificate authority (CA). One – the private key – is kept secret, while the other, the so-called public key, is visible to all. The public key of the pair is used to encode a message that can only be decoded with the private key (Rivest, et al., 1978), thus ensuring a level of individually tailored privacy on the data in a shared ledger or blockchain.

Figure 1 illustrates how the blockchain file is constructed, but to determine which records are permitted to be written to the blockchain requires the use of an ordering and consensus algorithm.

Consensus and Ordering Algorithms in Digital Ledger Technology

The second technology needed to make blockchains work is the ordering and consensus algorithm (Cachin and Vukolić, 2017; Swanson, 2015), the main purpose of which is to ensure only legitimate records get added to the blockchain and that they are added in the correct order. This is necessary as data can arrive via any of the nodes in the network.

For cryptocurrencies, like bitcoin, the most common form of consensus algorithm is proof-of-work (Anon., 2015a), a time and energy intensive operation where self-selected members of the network race to perform a routine that confirms the authenticity and order of the transactions. In these blockchains, there can be thousands of nodes, each with their own copy of the blockchain and each recording thousands of transactions per hour. Members who do the computation the fastest are rewarded with cryptocurrency credits.

Fortunately, proof-of-work is not required for industrial blockchains, such as those designed for C&E projects. In these systems, the number of traders is likely to be less than one hundred and a transaction rate less than a hundred per day. In these cases, the ordering and consensus algorithm must ensure that basic trading rules are enforced between members, so that transactions are legal.

More importantly the system must be robust and dependable. This can be achieved by incorporating *Byzantine fault tolerance* (BFT)(Lamport et al., 1982) into the ordering and consensus algorithm. Using BFT, data will be preserved if one or more of the nodes goes out of service or is interrupted.

For example, transaction records can be confirmed as legitimate using a small, embedded programmes called smart contracts. These are configured to verify a if a set of pre-determined requirements, such as entering a digital signature, have been fulfilled. An effective consensus algorithm will reduce the ability to fake, falsify or enter a transaction more than once. In real trading environments, this double entry can be costly and are hallmarks of organized crime (Beare 2007, p43).

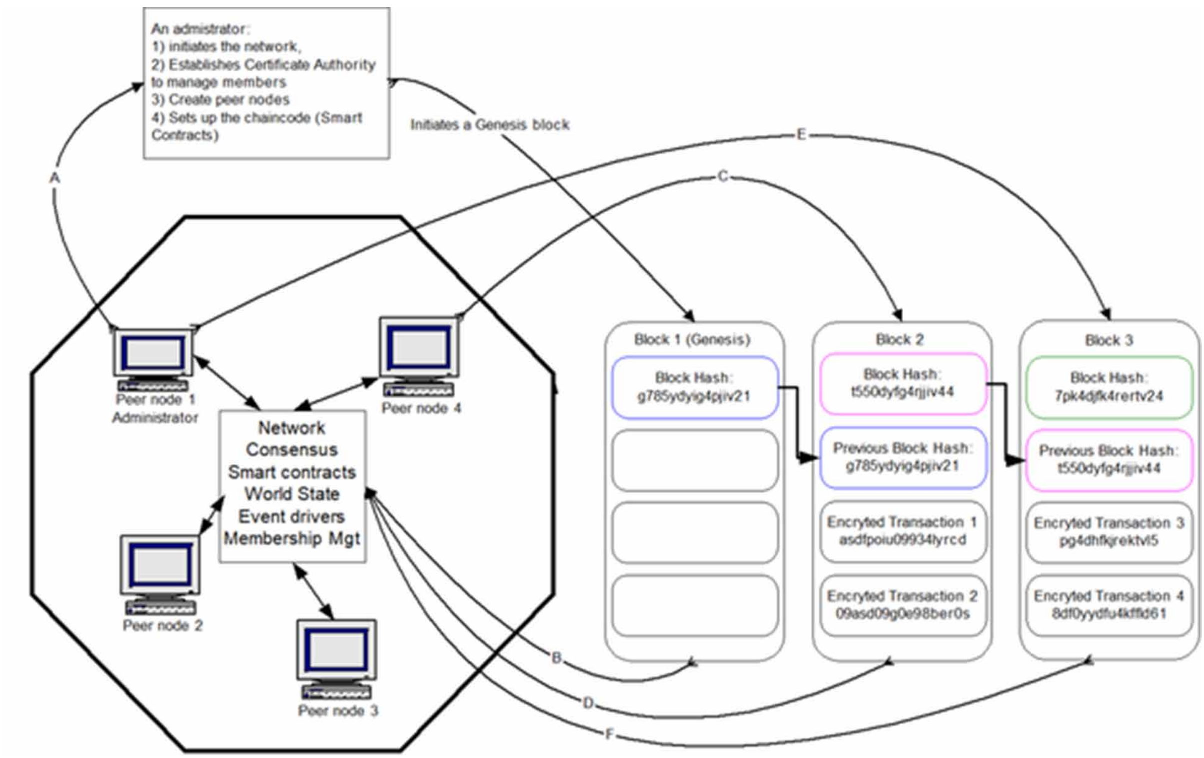
Distributed Systems and Digital Ledger Technology

Distributed systems are the final technology that makes blockchains workable. Unfortunately, it is also what makes them so difficult to deploy, maintain and upgrade. Blockchains exist only because they can be shared by nodes across a network using a peer-to-peer application (see Steinmetz & Wehrle, 2005). Key to these working is, of course, the internet, which provides the language and physical systems that permits communication and coordination.

To illustrate these concepts further, consider the diagram in Figure 2. This flowchart maps the transactions of an *asset* between members of a trading network (referred to as *Nodes* in this example). The *asset* traded could be any entity that is able to be represented by digital data, for example, a quantity of material, a confirmation of delivery or a building component.

The initiation of the network starts when Peer node 1 establishes the network and performs a series of tasks, such as setting up a certificate authority for public/private key encryption on the network. This closed, permissioned network is represented by the central octagonal box. In this scenario, the system administrator also sets up a world state database, configures the consensus algorithm and invites members to join the network. This action is represented by the arrow labelled **A** in the figure. The act of establishing a network starts the process where transactions can be recorded. Trading records are sent to the Peer nodes (represented by the arrow labelled **B**) for confirmation via a network consensus and protocol to create the Genesis block. The arrow labelled **C** shows Peer Node 3 writing two separate transactions to the network. Included in this newly written Block 2 includes the hash of the previous block. Block 2 is created only after it has been confirmed and verified by the consensus algorithm. This is shown by the arrow labelled **D**. This process is repeated when Peer node 1 sends 2 transactions to peers to await the creation of Block 3 (**E**). This, in turn, includes the hash of the previous Block 2, again only after consensus confirmation has been confirmed (**F**). At each stage of this process, the nodes within the network contain identical versions of the blockchain file and will continue to do so until the next transaction is proposed.

Figure 2. This diagram shows a simplified schematic of how the core blockchain functions. It is a flowchart describing how transactions are recorded on a blockchain. Arrows show the direction of the records as transactions proceed and are written to the blockchain. The sequence in this flowchart follows alphabetical order starting with A and culminating with the final block being written at F.



In this example, the basic elements that characterize an industrial blockchain are described. In summary these are:

Item 1: A replicable ledger with the history of all transactions that are added sequentially and have an immutable past held on files that are replicated across a network.
Item 2: Business logic, in the form of embedded smart contracts, are executed along with the transactions.
Item 3: A consensus and ordering service that ensures a decentralized protocol that can be used to control inevitable disruptions and to allow the transactions to be validated.
Item 4: In all these elements, cryptography is used to ensure the integrity of the ledger, the privacy and authenticity of transactions and the identity of participants.

These requirements are best fulfilled by a *private* and *permissioned* blockchain, which requires a central organization to manage the home node of the blockchain, where the administrator can deploy, upgrade, and maintain the network. This doesn't reduce any of the robustness of the systems. Hyperledger Fabric (HLF), developed as an open source project, is ideally suited for industrial applications requiring private, permissioned blockchains (Hyperledger Foundation, 2017; Dhillon, et al., 2017; Vukolić, 2016). HLF is modular and allows tailored and additive solutions. For example, the ordering and consensus algorithm is configurable to allow the business model to be programmed into the smart contracts. This includes a multi-level security setup that ensures transactions are legitimate and ordered correctly.

BLOCKCHAINS USED FOR SECURE RECORDING

The secure handling of data has operational as well as legal requirements (see Yue, et al., 2016, for an example in healthcare). What makes storing information on the blockchain different from hosting it on a secure database is that its storage and retrieval are controllable, but not dependent on a central authority. Case studies of prototype systems have been published, for instance, for digital diplomas and educational qualifications (Jirgensons & Kapenieks, 2018) and other certificate-centered activities, such as commercial debt obligations, could also be accomplished using DLT (Cheng et al., 2018).

Of particularly interest for C&E projects are:

- Building regulations completion certificate,
- Certificate of occupancy,
- Defects certificate,
- Energy performance and carbon reduction certificates,
- Established use certificate,
- Planning permission and,
- Practical completion certificate.

Obtaining approvals represents a burdensome and bureaucratic aspect of commercial life and DLT has the potential to provide considerable cost savings. Indeed, this and other types of non-productive work are noted in Government industrial strategy documents for the sector (see Cable et al., 2013 for an example).

Certification is particularly important in the construction industry due to the inherent risks to the public from dangerous buildings. A good example of this is the heightened concerns about the safety of buildings due to the risk of fire (see Brokenshire, 2018 or Hackitt, 2018). In automated buildings, smart contracts operating on blockchains could act to invalidate a certificate of occupancy should there be a failure to properly monitor or repair safety devices. To provide an idea of what a digital certificate looks like, Figure 3 contains the decrypted version and demonstrates the essential information required for certification.

The certificate represented in Figure 3 is maintained on the blockchain and is readable by anyone with the link and the password. The consensus algorithm validated the certificate using a smart contract to verity the digital signatures of responsible officials.

BLOCKCHAINS USED FOR MANAGING TRADING NETWORKS

Blockchains can also be used to record transaction details (see Chapron, 2017) in complex trading environments that contain multiple layers of suppliers and customers who require a digital paper trail (Hultgren and Pajala, 2018; Penzes 2018). With further enhancement, the system could also be made to allow automation, for example, by making a secure payment (Wang et al., 2018a). Payments could be made independently of any central authority, a feature particularly useful when trading partners are not entirely trusting of each other (Tapscott and Tapscott, 2017; Carroll and Bellotti, 2015) and when delays in payment introduces additional financial strain (Das, et al., 2020). Indeed, further automation of a range of assembly and administration processes could provide broad benefits across the construction industry and to help improve issues of low productivity and profitability (Heiskanen, 2017; Barbosa et al., 2017). These additional elements make up a modular DLT system (Syed, et al., 2019; Xu et al., 2019). Existing technology, such as enterprise resource planning (ERP) software can do the same thing but is expensive and lacks an element of impartiality that the blockchains can provide.

Figure 3. Shows a certificate encrypted and written to a blockchain. This record contains a certification written and authorised by Building Control (a governmental office) to the Clerk of Works that confirms that the component is safe to operate. Further details of this example are provided in this and following sections. The format is consistent with the new IEEE data standard (Li & Sond, 2020).

Unique certification number:	223
Address:	25 Mill Street, Oxford
Time of certification:	14:52:23
Date of certification:	June 6, 2020
State of asset:	Certified
Location:	A46P
Drawing number:	BGH58091
Certification authority:	Building Control
Custodian of certification:	Clerk of Works

Transaction *asdfpou09934yrcd* decoded with key

To clarify the utility of automated data recording systems, consider for a moment the example of an autonomous vehicle moving across a conurbation carrying paying passengers and cargo. As it traverses the city, it uses a combination of public and private toll roads along which it picks up and discharges passengers and cargo. Near the end of the trip, the battery powered vehicle sells its excess power at a favorable rate. What characterizes this imaginary journey is a series of transactions which are shown in Table 1. In this table, the type of asset is listed along with the transactor (or seller) and custodian (the buyer). These transactions are recorded on different blockchains depending on the type of asset.

As a rule, assets can be any tradable entity, such as units of transport, or energy or a measure of work performed. If it can be represented in digital form, then a trade of an entity can be recorded in a blockchain. In the terminology of DLT, transactions would all possess a *state* and the blockchain records *state changes* to the assets. Examples of *state* would be *issued, assigned, sold, rejected* or other qualification that describes the asset. The advantage of this type of recording is that data can be easily streamed for collection and analysis.

Table 1. Contains a list of transactions performed between an autonomous vehicle (numbered 1 in this example) and several clients and customers represented on the blockchain as a transactor and custodian of an asset.

Transaction	Asset:	Transactor of asset:	Custodian of asset:
Vehicle 1 picks up a passenger	Unit human transport	Passengers 1	Vehicle 1
Vehicle picks up cargo	Unit cargo transport	Customer 1	Vehicle 1
Vehicle pays toll on Road 1	Unit use of road	Vehicle 1	Municipality 1
Vehicle 1 picks up a passenger	Unit human transport	Passengers 2	Vehicle 1
Vehicle pays toll on Road 2	Unit use of road	Vehicle 1	Municipality 2
Vehicle discharges excess energy	Unit of electrical energy	Vehicle 1	Local energy collective

Design Principles for Industrial Applications

This section provides a glimpse into the design principles required to integrate data collection via blockchains with databases, messaging systems and websites. The design principle required to implement systems and introduce automation to the process (see Li, et al., 2018 and Li & Sond, 2020 for the data standards) are:

Item 1: The recording of transactions between traders in a way that eliminates data discrepancies and allows simultaneous multi-party collaboration with data accessible to all parties in real-time.
Item 2: The ability to establish multiple trade channels or sub-networks to maintain data privacy.
Item 3: The capability that transactions can trigger events such as sending email messages, automatic invoice creation, payments, and for providing proof of delivery.
Item 4: To support the deployment of smart contracts that can aid in the modelling of business processes.
Item 5: To provide a data streaming service to allow the flow of transaction data with analytical systems, such as an ERP that might use artificial intelligence and business analytics and to maintain control of production and performance.
Item 6: To enable a high degree of security and privacy at a level appropriate for commercial operations. This includes the adherence to General Data Protection Regulation (GDPR) (Trong, et al., 2020).
Item 7: Provide membership management and a certificate authority to ensure that members and peers' identity is authentic and that they are authorized to invoke transactions within a channel in a blockchain network.
Item 8: That it provides a high degree of reliability to guarantee robust operation in industrial settings.

Business Process and Data Modelling

In this example, a scenario is described where building components are designed, ordered, delivered, installed, inspected, certified, and paid for with all transactions recorded by a blockchain. This scenario requires that the business process and the data models are codified. One approach to formulating this mapping process is to use a combination of flow and swimlane charting (Chang, et al., 2019; Auberger and Kloppmann, 2017). In this example, this is done using the artifact-centric business process model

(Damelio, 2016; Nigam and Caswell), where multi-thread and multi-component processes are organized around service provision to online clients (Waller, 2003). Business process mapping (BPM) is seen as one of the fast-growth technology areas as it is an enabling technology underpinning the IoT (Miller, 2019). It is also a process useful in the automation of commercial sites that are accessed by distributed, client-side applications (Viriyasitavat et al., 2018). These use graphical and model-driven tools to design the blockchain business network (Seebacher and Maleshkova, 2018).

Figure 4. Is a flowchart that shows the process of installation of the component that was made off-site. Those involved in this, project manager (PM), Building Control (BC), Contract Administrator (CA), etc are listed in the membership table.

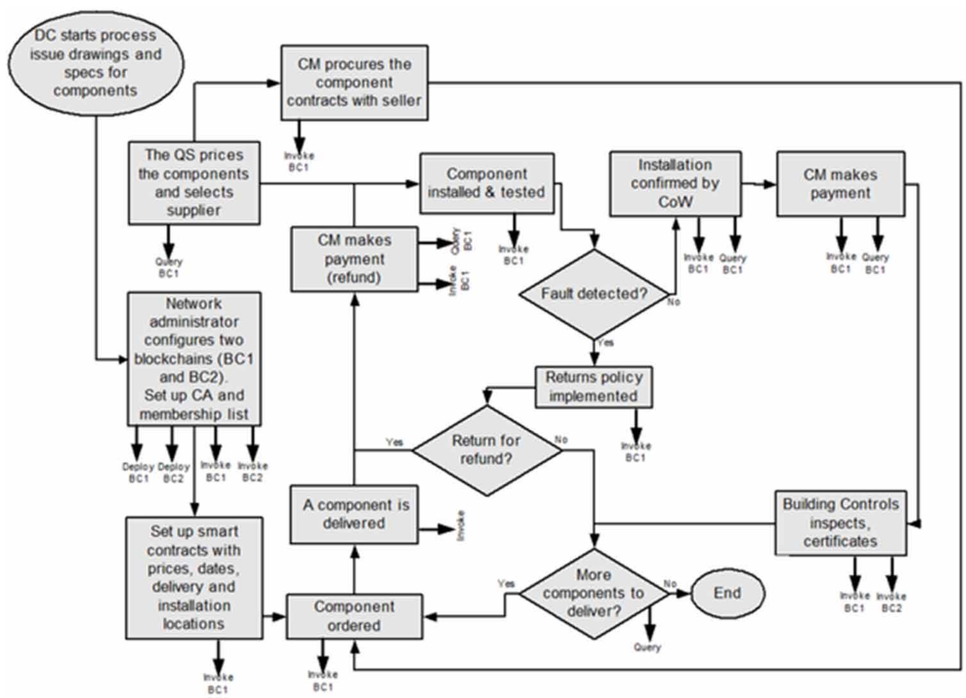
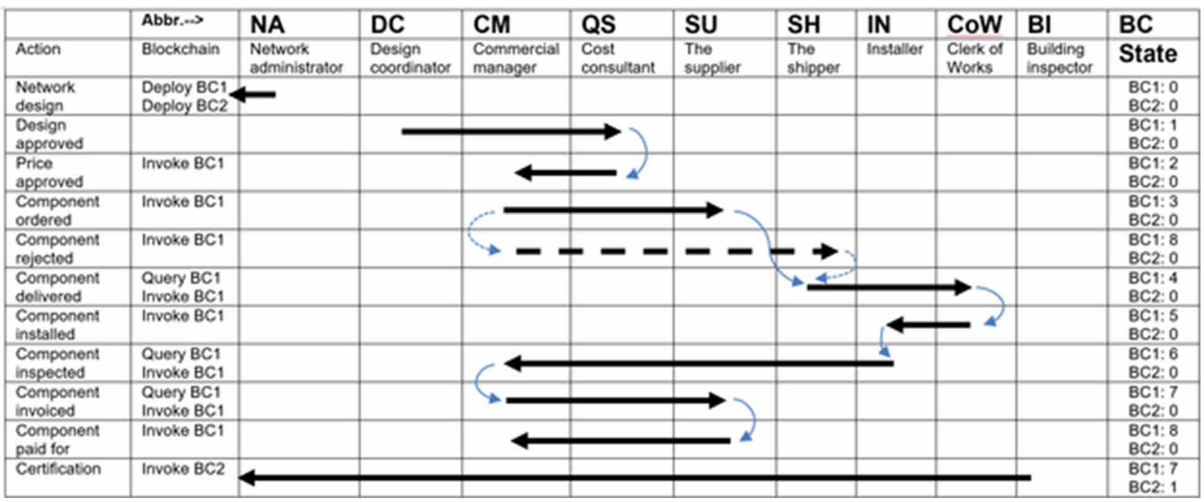


Figure 4 contains a flowchart of a business process describing a building component installation cycle. The flowchart shown here is a simplification of the typical real-life ordering, installation cycles. There are branches not included, for example if the component fails during the warranty period. However, one of the main advantages of DLT is that the transaction variables (or states) can be easily added to cover all eventualities. This amounts to a democratization of the data collection process. In the simplified scenario shown in Figure 4, the *states* of transaction for Blockchain 1 (BC1) are as follows:

State 1: Design approved
State 2: Price agreed
State 3: Component ordered
State 4: Component delivered
State 5: Component installed

State 6: Component inspected
State 7: Component Invoiced
State 8: Component paid for
State 9: Component rejected

Figure 5. Contains a swim-lane chart for the example of a DLT in a C&E project that involves the cycle of transactions required to install a series of building components. The rightmost box on the top of the figure represents the blockchain and the arrows indicate that the members of the network, who are also identified in the boxes across the top, write to the blockchain.



Other states of the BC1 transaction exist in more completely modelled systems, for example, *component failure*, *warranty period exceeded*, *payment delayed*, *delivery delayed*, *invoice greater than quote*, for example. Any of these states could trigger automatic action in invoking the blockchain. For example, if the *payment delayed* variable exceeds 5 days, then a penalty is automatically added to the invoice.

For Blockchain 2 (BC2), which contains the installation certificate, there are only two states which are:

State 1: Not certified
State 2: Component certified

To help design the business logic required for this example system, a swim-lane chart (after Damelio, 2016), shown in Figure 5, is used to display a chain of transactions that describe the progressively evolving state of the blockchain. Using this in conjunction with the flowchart (Figure 4) allows an iterative approach to modelling to achieve an accurate representation (Garcia-Bañuelos et al., 2017) of the business process leading to the schedule for the DLT coding.

In this swimlane chart, the process proceeds downwards with the state changing at every invocation of the blockchain until the component is invoiced, then paid for. The sequence of transactions starts with the blockchain being *deployed* by the Network Administrator (NA). From this initial stage, the Design Coordinator (DC) submits a set of drawings to a communal repository so that the QS can price the component and set up the terms of the contract. Approval by the Commercial Manager (CM) *Invokes* the transaction to the supplier (SU) to order the component. Once received and confirmed by the Clerk of Works (CoW), the Installer (IN) completes the installation of the component, with the blockchain recording the transaction and informing the Commercial Manager (CM), who in turn informs the SU that the order is ready to be invoiced. Once this is done an automatic payment is made.

Note that two independent blockchains are *Deployed* in this example. The first one mirrors the contracts between the client, shipper, and supplier. The other blockchain (BC2) is used to store official certification documentation. Finally, the Building Inspector (BI) provides certification, a transaction that is stored on another blockchain (BC2, in this example).

To add a record to this the Building Control (BC) regulator *invokes* a transaction to the blockchain with a record that contains certification information that is required for the safe occupancy of the building. This digital certificate is repeated for each component installed done in accordance to the building code and serves as an official mark of compliance. Certificates written to the blockchain can be read by anyone with access privilege.

Using a modular system approach, it should be possible for transactions in the network to trigger signals in the form of a text message or email. This would greatly facilitate automation and communication. The Installer (IN) would receive notification on his mobile device when a component is ready for fixing into place. The exact location (floor and room number) for each component would also be conveyed in the DLT, so that, for example, the crane operator, plumber, and other technicians can ensure the accuracy and timing of their activities.

In the Conclusion of this chapter, the elements that make up an industrial blockchain using modular DLT technology are explained along with the development framework that is used for testing and for prototype systems.

CONCLUSION

This section concludes the chapter with a description of a suitable development framework and architecture for the application of DLT to C&E projects. The first part of this conclusion introduces the HLF framework, describing the open source development environment where professionals in academia, industry and the not-for-profit sector collaborate to advance this complex and novel technology. Essential aspects of the design, such as membership management and the system architecture are detailed and illustrated with the same example as in previous sections. The section finishes with a list of recommendations for readers of this chapter and a brief discussion on future topics for research.

The Hyperledger Fabric Software Framework and Open Source Development Environment

The Hyperledger Fabric (HLF) is a framework implementation based on a series of projects (Androulaki et al., 2018) by the Hyperledger consortium (Hyperledger, 2017) and developed with open software principles. This development was coordinated and partially financed by the Linux Foundation®, which set up the Hyperledger Project in 2015. See Söderberg (2015) for a general overview of the open source movement and Glaser (2017) for a discussion related to open source blockchains. The Consortium is organized around the development of software for use in industrial settings, characterized by the need to reliably record in complex trading environments such as supply chains. The Consortium management has stated that it would not develop applications for a bitcoin-type cryptocurrency.

Consortium members are from a wide range of organizations. These include technology platform companies (such as Cisco, Hitachi, and IBM), banks (ABN AMRO, BNY Mellon, and others), software companies (SAP, IBM, and others) and academic institutions (Columbia, UCLA, and others). In open software development communities' members are often collaborating with each other at one level and then competing on another. The main advantage of open source collaboration is that it speeds up development time, spreads the risk inherent in software projects, encourages a modular approach to problem-solving and spurs innovation.

Ironically, it is the private permissioned DLT development that requires broad collaboration between industry, academic and not-for-profit organizations. Whereas, the widely used and familiar public blockchains (like *Bitcoin, Altcoin,* and *Ethereum*) are developed and maintained by small groups, working mostly with proprietary systems.

Another open source software company, and an original member of the Hyperledger Consortium, is Digital Assets LLC. It contributes to projects using their high-level programming language known by its acronym, DAML for Digital Asset Modeling Language (Kfir, & Fournier, 2019). DAML makes programming of DLT systems easier and cheaper with a language that is specifically designed to model complex and multi-faceted transactional environments. The most significant project to date employs DAML to provide large-scale clearing facilities for the financial services industry (Tsai, et al., 2020).

Membership of Private Permissions Blockchains

Industrial blockchains are permissioned and therefore require that membership is managed. In HLF, membership profiles are controlled by the system administrator (López-Pintado, et al., 2018) who grants access to independent members and to large consortia, who can then control access to their node. Operating through a software development kit (SDK), the system administrator can initiate, build, and maintain the network by adding members and controlling events. The system administrator can create, stop, change the configuration or, if required, delete the peers (Dunphy and Petitcolas, 2018). Members in HLF do not need to be attached to a Peer. For example, the shipper, responsible for delivering components on site would be able to query the DLT (or be prompted by a message) for the expected time of delivery, then once one site, register the delivery with a countersign by the site foreman. This could all be done using RFID tags, digital signatures, drop down menus and tick-boxes on module devices. Indeed, the functionality and intelligence embedded in the system is based on the user interfaces which can limit the choices of how a member interacts with the blockchain.

To understand the basics of membership management, consider again the example project. A description of members, their roles in the project and how they interact with the blockchain is shown in Table 2.

The members shown in Table 2 are linked to the business process as outlined in the flowchart shown in Figure 4 and the swimlane chart in Figure 5. The full logic of this trading network requires hundreds of lines of computer code and extends to define all possible states of the process.

Digital Ledger System Architecture

The example system described in this chapter sets the requirements that dictate a system architecture that is illustrated in Figure 6. This architecture includes the following elements:

Table 2. Showing the members in the network with their roles, activities, and transactions on the blockchain. These are associated with the mobilisation of building projects using a blockchain to record transactions and chaincode in a commercial setting.

Role	Abbr.	Task(s) in the project	Actions on the blockchain
System administrator	SA	Models business and processes, maintains membership, and ensures network operates as designed.	Deploys network, creates channels & smart contracts.
Design coordinator	DC	Delivers as-built design, ensures that drawings are up to date and complete	Evokes BC1: State 1: Design and price approved.
Commercial manager	CM	Procures and orders components, delivery schedule, price, warranty period and other contract details.	Evokes BC1: State 2: Component ordered
Cost consultant	QS	Produces costs and suppliers for procurement	Confirm payment Evokes BC1: State 7: Paid for.
Supplier	SU	Produces the components in accordance with the contract and schedule as provided.	Evokes BC1: State 3: Component delivered
Shipper	SH	Delivers components in accordance to the schedule.	Queries BC1: Times for delivery.
Installer	IN	Receives the building plans from the dc and program from the PC and a signal from the SF when the component is ready for installation.	Queries BC1: to sync with the program, then evokes blockchain to confirm installation.
Clerk of Works	CoW	Confirms and inspects installation of the components.	Evokes BC1: State 5: Component inspected.
Building inspector	BI	Issues certificate of compliance for Building Control.	Deploys BC2. Evokes BC2: certification of compliance.

Item 1: A system administrator that can design and establish the initial configuration of the system, manage deployment of smart contracts, define and set the endorsement, configure the consensus and ordering algorithm, invite members and ensure that the integrity of the data is maintained in a secure private server.

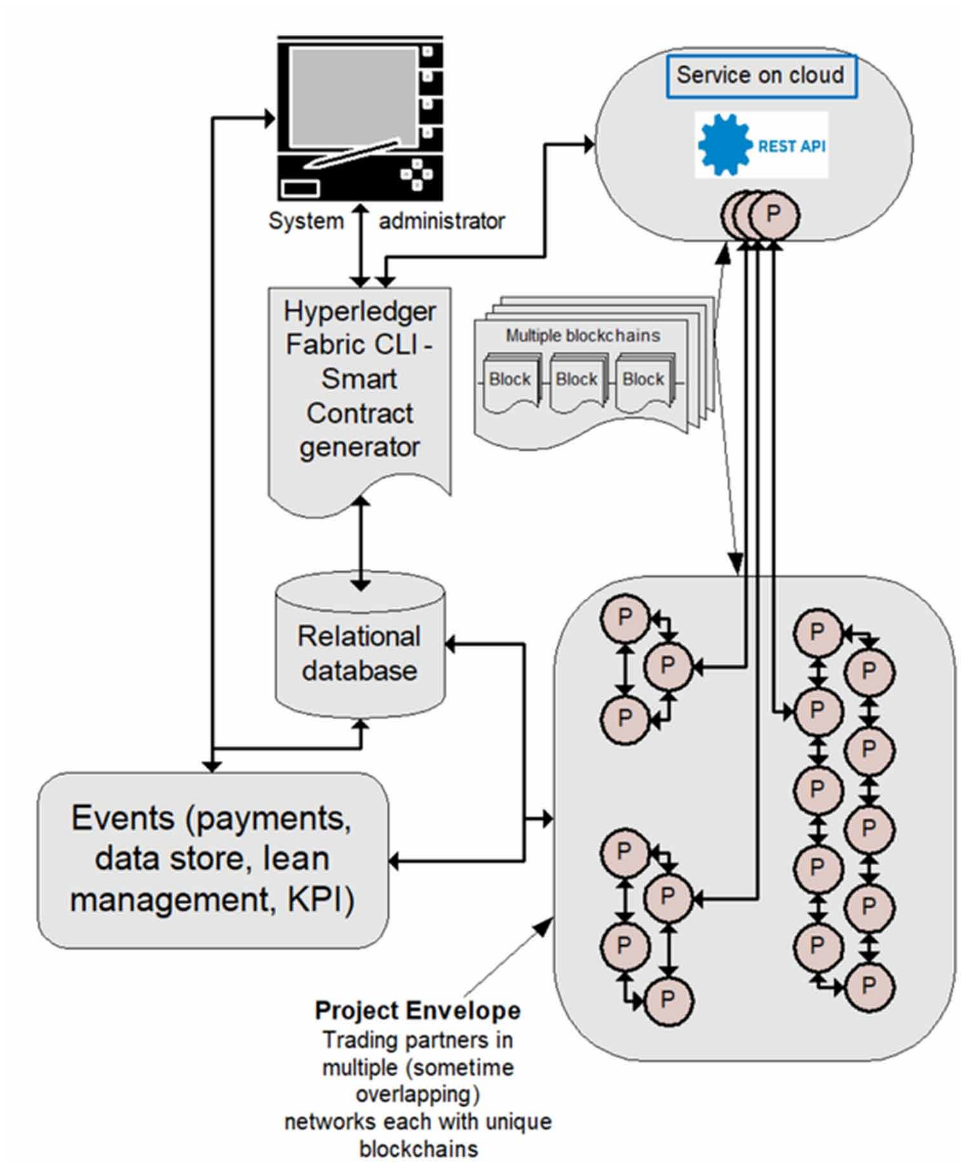
Item 2: An ordering and consensus algorithm to manage the recording of accepted transactional data to the blockchain and to be able to convert sequential data to a more convenient relational format so that is can be used to write reports and other structured documents that are necessary for operational purposes (such as reconciliation, invoicing, and general accounting).

Item 3: Maintain the peer network, through membership recruitment, so that they can hold copies of the distributed ledgers and associated smart contracts.

Item 4: Implement and maintain an events management system as a modular component of the DLT to provide communication and notification.

Item 5: Ensure that a suitable cloud service is maintained so that it can perform the role of a secure data and system repository.

Figure 6. Contains the basic system architecture of the DLT that includes the administrator and developer, smart contracts, database, peers, and events based upon the HLF implementation. Peers are identified by the symbol 'P'. Other components of the system are described in the text.



The system administrator, shown near the top of Figure 6, has the responsibility for the deployment and administration of the DLT, which may include multiple channels. These are essential in allowing trading partners to maintain privacy. This protects confidential commercial data but would still allow mission-critical information such as the delivery date, warranty details and maintenance instructions, to be made available for a wider audience. Including in this figure is a representation of a relational database, which is accessed with the standard query language (SQL).

What is not shown in Figure 6 are some of the finer features of the DLT, notably how the consensus algorithm works, and the way that smart contracts are embedded into the core of the blockchain, or how the interface uses pull-down menus, check boxes and other forms of browser-based tools.

Summary of the Objectives of the Chapter

This conclusion fulfils the objectives set out at the start of the chapter. By first describing the three technologies underlying an industrial blockchain and then providing a varied set of applications, a system architecture is described. The rationale for using private permissioned blockchains, with a limited form of centralized control, is demonstrated as necessary in complex, supply-chain based trading networks. This and a set of factors on engineering requirements point to a modular architecture. Hyperledger Fabric provides a good framework for this, but it is the introduction of high-level language implementation, such as DAML, which will make programming of DLTs easier.

Business process and data modelling are needed based on a set of design principles (see Eynon, 2013). These tasks are exemplified by a flowchart and a swimlane graph. To fulfil the additional objectives of the chapter, recommendations are made in the interest in progressing the technology and to ensure engagement with the data-rich and highly interconnected digital future that is predicted to revolutionize manufacturing, commerce and the built environment. Finally, to complete this chapter, a set of discussion topics on areas of active research interest is included.

RECOMMENDATIONS

The recommendations that are included in this section are based on experience gained in designing a prototype system based on HLF, on observations on the state of the technology and its use in other industries. These are:

Recommendation 1: DLT can be promoted by forming consortia to encourage collaboration for data integration along supply chains. These would help to develop the value of digital assets.
Recommendation 2: That efforts should be made to encourage governments and financial institutions to support the use of DLT and that innovative services be approved for use.
Recommendation 3: Support the open source software community in building complex applications through collaborative efforts.
Recommendation 4: Encourage the use of a data rich DLT environment to support Lean management. Lean requires abundant process data of the sort available in a well-monitored trading and supply-chain network.

FUTURE RESEARCH DIRECTIONS

This section provides a brief survey on future research directions that are likely to lead to commercialization for industrial blockchains and is intended to provide a basis for discussion. The following topics are summarized in the following sections:

- Issues around adoption of innovative technology,
- Blockchains for financial services,
- The use of DLT for ERP and Lean management,
- The role of the blockchain in the Industry 4.0, smart cities, and Internet of Things paradigms and
- Issues on privacy, security, and on autonomous data control.

Adoption of Innovative Technology

Ultimately, the adoption of any new system such as DLT by an organization is a commercial decision that is likely to be influenced by the desire to maximize their return on investment on innovation (Christensen & Raynor, 2013). For example, adoption could augment knowledge enhancement and gain a competitive advantage. It could also be used to improve the corporate image as a partner or employer or to provide a basis for carbon accounting. Companies might also be strategizing for brand reinforcement, an approach that could lead to a higher reputational profile. They might also experiment with DLTs to enter new technological ecosystems, a foray that would put them into contact with others who also want to see change. Whatever the motivation is, the introduction of any modern technology, especially one as revolutionary as DLT, is bound to lead to changes inside the organization itself.

Whatever the costs and expected benefits, any adoption must be done with a well-thought-out business justification (Carson et al., 2018) using the standard approach as used in manufacturing industries (Warszawski, 2003). There is also the realization that although adoption might help the industry, the direct benefits to individual companies may be illusive.

For example, the construction industry, prone as it is to sudden downturns and disruptions, renders managers naturally conservative and often reluctant to contemplate introducing technology that might disrupt operations (Waterhouse et al., 2017). Managers in the construction industry get fired for missing deadlines, not for missing out on the promise of a digital revolution.

But the industry could surely use a boost as it is characterized as having low levels of trust (Cerić, 2015) and for being averse to change. It is also known for low profitability (Green, 2016; Davis et al., 2015) and as a locus of crime (Warne, 2016) and questionable business practices (Pontell and Geis, 2007). Optimistically, the industry is so large and strategically important, that it is both driven-to and receptive-for change (Egan, 1998; Latham, 1994).

Blockchains, despite the advantages presented here, may not be the most favored solution and managers need to weigh up the pros and cons of the various alternatives. To begin with, there are alternatives, including doing nothing at all and simply using existing accounting and administrative methods. Other software systems perform similar functions as DLTs, for example, Infrastructure as a service (IaaS), like those offered by Amazon AWS, Google, Oracle, Microsoft Access or open source systems such as MySQL) or ERP systems that can be configured to suit the company. Hand-held devices, of the sort used to track packages (Navon and Berkovich, 2005) could also be integrated into back-office control and management systems that could keep track of supply chain materials and components.

One promising possibility is for governments to offer incentives and other forms of encouragement for firms to accept novel technology that promises to modernize industry. A good example of this is the UK government's strategic plans to implement Building Information Modelling (BIM) (Eadie, et al., 2015; Cable et al., 2013). In the same way that BIM requires a new level of cooperation, installing DLTs could help with collaborative assembly and process improvements (Walasek & Barszcz 2017).

Blockchains and Financial Services in the Built Environment

There are highly publicized projects in the financial services industry that make use of blockchains (McWaters, et al., 2016, McKinsey & Company 2017). The most impressive of these so far is for the clearing (or reconciliation) of international transactions (Meszaros, et al., 2016; CBA-Media, 2016). The advantages of using blockchains in this area are significant (Attaran & Gunasekaran, 2019) as it would help reduce administration costs and speed up the transfer of money. For example, in the age of globalized trade, cross-border payments total around $600 billion annually, with transaction costs somewhere between 2% to 3% percent (and as high as 10% in extraordinary cases). McKinsey and Co. (Higginsonm, et al., 2019), estimate that if blockchains are used for the settlement of cross-border transactions, savings on transaction fees could be on the order of 30% or $4B/year. In 2016, the Canadian ATB Financial Bank successfully used blockchain technology to send 1000 Canadian dollars to Germany in about 20 seconds. Far quicker than the two to three working days that it normally takes to complete using standard methods. Security as well as speed are amongst the benefits of DLT use in financial services (Wüst, et al., 2019; Zhong, et al., 2019).

The provision of novel financial services may attract construction companies and developers into using blockchain technology, for example, by making it easier to raise funding for projects using a cryptocurrency-based approach or by using blockchains to hold commercial debt obligations.

Enterprise Resource and Lean Management

ERP is based around the implementation of enterprise-wide integrated control systems. Lean management (Lean) is a managerial paradigm commonly used in car manufacturing, but increasingly, in other industries (Binder, 2007; Liker and Meier, 2006; Liker, 2004; Womack and Jones, 2003; Womack et al., 1990).

In Lean, data is the driver for continuous improvements, most notably in the coordination of component delivery and assembly. In the C&E industry, the paradigm of Modern Methods of Construction (MMC) calls for off-site production and just-in-time delivery for bathroom and kitchen pods, door sets, and structural insulated panels (SIPS), and precast concrete panels. This gives contractors using MMC all the appearances of a controlled industrial process (Pan and Goodier, 2011; Slaughter, 1998).

Data such as the timing of operations, delivery details, individual costs per item, warranty periods, and aspects of transactional information, are essential for both ERP and Lean systems. These are needed to support a range of organizational–wide business processes, such as payroll, quarterly accounting and reporting, process, and commercial analysis (Morabito, 2017).

Little enthusiasm has been shown by construction managers in implementing large-scale ERP or Lean management of the sort common in automotive, pharmaceutical, or other manufacturing industries. The reason for this is the risk associated with installing large enterprise-wide IT systems. One of the potential advantages of DLT is that it can be installed piecemeal, from the ground up, with minimal risk to the organization. The hidden promise of DLT is that it might provide the capability of a much larger system at a lower cost.

Blockchains in the Industry 4.0, Smart Cities, and the Internet of Things

Automation of construction and other manufacturing forms the core of the Industry 4.0 paradigm (Lee, et al., 2019). This involves the integration of data supplied by IoT devices, such as sensors and RFID tags with operational control. Embedded in this environment, DLT is the keystone technology that provides a secure and immutable data-layer that is accessible from both inside and out of the enterprise (Christidis and Devetsikiotis, 2016).

Automation in this area is needed as IBM, Cisco, and IDC, amongst others, have estimated the number of (partially) connected devices already in use to be in the billions (International Data Corporation. 2020) and that numbers are likely to double within a decade.

As it has been established that construction projects are an industrial process (Koskela, 1992), it is reasonable to think that automation will lead to higher productivity and hence, higher profits (Enshassi et al., 2007). This makes them suitable for computer-based management as called for by Industry 4.0.

Research and development in this area is likely to cover a broad range of topics, for example novel forms of internet-connected digital sensors, analytical engines accessible from the cloud, various forms of autonomous vehicles, better development environments and so forth. There is promise of use. For example, the New York based, DLT Labs implemented an HLF blockchain for Walmart of Canada (Hamilton & Srivastava, 2020) to help manage complex supply chains.

Privacy, Security and Autonomous Data Control

Issues of privacy and security of data abound in data-rich environments such as smart cities, in IoT applications, and in distributed systems. Additionally, it is critical to have control of digital identities and personal data (Zyskind et al., 2015). Not only is the collection and use politicized, it is also controlled by law. Research on the social impacts of privacy and security of data are of great interest to developers of DLTs.

One of the most interesting areas of research is the move away from the centralized control of data towards self-regulating systems. In other words, systems where the data itself can control who has permission to read or write it. This feature could help, for example, to preserve identity in the event of accidental (or intentional) release of confidential information. Blockchains have the potential, with their multi-layer encryption capability, to provide a component in self-regulated data, a feature that would be particularly useful in complex trading environments, such as those encountered in construction projects.

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REFERENCES

Afanasev, M. Y., Fedosov, Y. V., Krylova, A. A., & Shorokhov, S. A. (2018). *An application of blockchain and smart contracts for machine-to-machine communications in cyber-physical production systems. In 2018 IEEE Industrial Cyber-Physical Systems*. ICPS.

Akintoye, A., & Main, J. (2007). Collaborative relationships in construction: The UK contractors' perception. *Engineering, Construction, and Architectural Management*, *14*(6), 597–617. doi:10.1108/09699980710829049

Al-Jaroodi, J., & Mohamed, N. (2019). Blockchain in Industries: A Survey. *IEEE Access: Practical Innovations, Open Solutions*, *7*, 36500–36515. doi:10.1109/ACCESS.2019.2903554

Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., ... Yellick, J. (2018). Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains. In *Proceedings of the Thirteenth EuroSys Conference* (pp. 30:1–30:15). New York, NY: ACM. 10.1145/3190508.3190538

Anon. (2015a, Jan. 9). How do bitcoin transactions work? How a bitcoin transaction is processed. *The Economist Magazine*.

Anon. (2015b, Oct. 31). The promise of the blockchain. The trust machine. The technology behind bitcoin could transform how the economy works. *The Economist Magazine*.

Attaran, M., & Gunasekaran, A. (2019). Financial Services: The Largest Blockchain Market. In Applications of Blockchain Technology in Business (pp. 21-26). Springer.

Auberger, L., & Kloppmann, M. (2017). *Combine business process management and blockchain*. IBM Tutorial on Blockchain implementation. Available online and accessed on June 15, 2020 at https://www.ibm.com/developerworks/library/mw-1705-auberger-bluemix/1705-auberger.html

Banerjee, M., Lee, J., & Choo, K.-K. R. (2018). A blockchain future for Internet of Things security: A position paper. *Digital Communications and Networks*, *4*(3), 149–160. doi:10.1016/j.dcan.2017.10.006

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., . . . Brown, S. (2017). *Reinventing construction through a productivity revolution.* Tech. rep., McKinsey Global Institute.

Beare, M. E. (2007). The devil made me do it: Business partners in crime. *Journal of Financial Crime*, *14*(1), 34–48. doi:10.1108/13590790710721792

BergC.DavidsonS.PottsJ. (2017). Blockchains industrialise trust. Available at SSRN 3074070.

BergC.DavidsonS.PottsJ. (2018). Ledgers. Available at SSRN 3157421.

Binder, A. K. (2007). *Ward's Automotive Yearbook 2007*. Wards Communications.

Brokenshire, J. (2018). *Building a Safer Future: An Implementation Plan.* Presented to Parliament, Secretary of State for Housing, Communities and Local Government, APS Group on behalf of the Controller of Her Majesty's Stationery Office.

Cable, V., Fallon, M., & Higgins, D. (2013). Construction 2025. Industrial Strategy: Government and Industry in Partnership. In *Industrial Strategy: Government and Industry in Partnership*. Department for Business, Innovation & Skills.

Cachin, C., & Vukolić, M. (2017). *Blockchain consensus protocols in the wild.* arXiv preprint arXiv:1707.01873.

Carroll, J. M., & Bellotti, V. (2015). Creating Value Together: The Emerging Design Space of Peer-to-Peer Currency and Exchange. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing* (pp. 1500–1510). New York, NY: ACM. 10.1145/2675133.2675270

Carson, B., Romanelli, G., Walsh, P., & Zhumaev, A. (2018). *Blockchain beyond the hype: What is the strategic business value?* McKinsey & Company.

CBA-Media. (2016). *Commonwealth Bank, Wells Fargo and Brighann Cotton pioneer landmark blockchain trade transaction*. Retrieved July 25, 2020, from https://www.commbank.com.au/guidance/newsroom/CBA-Wells-Fargo-blockchain-experiment-201610.html

Cerić, A. (2015). *Trust in construction projects*. Routledge. doi:10.4324/9781315747675

Chang, P.-Y., Hwang, M.-S., & Yang, C.-C. (2018). A Blockchain-Based Traceable Certification System. In S.-L. Peng, S.-J. Wang, V. E. Balas, & M. Zhao (Eds.), *Security with Intelligent Computing and Big-data Services* (pp. 363–369). Springer International Publishing. doi:10.1007/978-3-319-76451-1_34

Chang, S. E., Chen, Y. C., & Lu, M. F. (2019). Supply chain re-engineering using blockchain technology: A case of smart contract-based tracking process. *Technological Forecasting and Social Change*, *144*, 1–11. doi:10.1016/j.techfore.2019.03.015

Chapron, G. (2017). The environment needs cryptogovernance. *Nature*, *545*(7655), 403–405. doi:10.1038/545403a PMID:28541332

Cheng, J.-C., Lee, N.-Y., Chi, C., & Chen, Y.-H. (2018). *Blockchain and smart contract for digital certificate. In 2018 IEEE international conference on applied system invention*. ICASI.

Christensen, C., & Raynor, M. (2013). *The innovator's solution: Creating and sustaining successful growth*. Harvard Business Review Press.

Christidis, K., & Devetsikiotis, M. (2016). Blockchains and smart contracts for the Internet of Things. *IEEE Access: Practical Innovations, Open Solutions*, *4*, 2292–2303. doi:10.1109/ACCESS.2016.2566339

Damelio, R. (2011). *The basics of process mapping*. CRC (Taylor & Francis) Press.

Darabseh, M., & Martins, J. P. (2020). Risks and Opportunities for Reforming Construction with Blockchain: Bibliometric Study. *Civil Engineering Journal*, *6*(6), 1204–1217. doi:10.28991/cej-2020-03091541

Das, M., Luo, H., & Cheng, J. C. (2020). Securing interim payments in construction projects through a blockchain-based framework. *Automation in Construction*, *118*, 103211. doi:10.1016/j.autcon.2020.103284

Davis, R., Wilen, A., Crane, T., Bryer, L., Ward, D., Pottier, F., & Blackwell, M. (2015). UK Industry Performance Report-2015. *Construction Industry Key Performance Indicators*.

Delgado-Mohatar, O., Tolosana, R., Fierrez, J., & Morales, A. (2020). *Blockchain in the Internet of Things: Architectures and Implementation.* arXiv preprint arXiv:2004.05817.

Dhillon, V., Metcalf, D., & Hooper, M. (2017). The hyperledger project. In *Blockchain enabled applications* (pp. 139–149). Springer. doi:10.1007/978-1-4842-3081-7_10

Dunphy, P., & Petitcolas, F. A. (2018). A first look at identity management schemes on the blockchain. *IEEE Security and Privacy*, *16*(4), 20–29. doi:10.1109/MSP.2018.3111247

Eadie, R., Browne, M., Odeyinka, H., McKeown, C., & McNiff, S. (2015). A survey of current status of and perceived changes required for BIM adoption in the UK. *Built Environment Project and Asset Management*, *5*(1), 4–21. doi:10.1108/BEPAM-07-2013-0023

Egan, J. (1998). *Rethinking Construction (the Egan Report).* Tech. rep., Department of the Environment, Transport and the Regions, HMSO.

Enshassi, A., Mohamed, S., Mustafa, Z. A., & Mayer, P. E. (2007). Factors affecting labour productivity in building projects in the Gaza Strip. *Journal of Civil Engineering and Management*, *13*(4), 245–254. doi:10.3846/13923730.2007.9636444

Eynon, J. (Ed.). (2013). *The design manager's handbook*. John Wiley & Sons. doi:10.1002/9781118486184

Finck, M. (2018). Blockchains and data protection in the european union. *Eur. Data Prot. L. Rev.*, *4*(1), 17–35. doi:10.21552/edpl/2018/1/6

García-Bañuelos, L., Ponomarev, A., Dumas, M., & Weber, I. (2017). Optimized Execution of Business Processes on Blockchain. In J. Carmona, G. Engels, & A. Kumar (Eds.), *Business Process Management* (pp. 130–146). Springer International Publishing. doi:10.1007/978-3-319-65000-5_8

Glaser, F. (2017). *Pervasive decentralisation of digital infrastructures: a framework for blockchain enabled system and use case analysis*. Academic Press.

Green, B. (2016). *Productivity in construction: creating a framework for the industry to thrive*. Chartered Institute of Building.

Hackitt, D. J. (2018). *Building a Safer Future. Independent Review of Building Regulations and Fire Safety: Final (Hackitt) Report.* Tech. rep.

Hamilton, S., & Srivastava, N. (2020). *Member Webinar: DLT Labs & Walmart Improve Margins, Visibility & Transparency in the Supply Chain*. Video recording accessed on July 17, 2020 on https://www.youtube.com/watch?v=XqXL3kPsBj8

Hargaden, V., Papakostas, N., Newell, A., Khavia, A., & Scanlon, A. (2019). The role of blockchain technologies in construction engineering project management. In *2019 IEEE International Conference on Engineering, Technology and Innovation ICE/ITMC*. IEEE. 10.1109/ICE.2019.8792582

Heiskanen, A. (2017). The technology of trust: How the Internet of Things and blockchain could usher in a new era of construction productivity. *Construction Research and Innovation*, *8*(2), 66–70. doi:10.1080/20450249.2017.1337349

Higginsonm, M., Nadeau, M.-C., & Raigopal, K. (2019). *Blockchain's Occam Problem. McKinsey Quarterly*. Insights on Financial Services.

Huckle, S., Bhattacharya, R., White, M., & Beloff, N. (2016). Internet of things, blockchain and shared economy applications. *Procedia Computer Science*, *98*, 461–466. doi:10.1016/j.procs.2016.09.074

Hultgren, M., & Pajala, F. (2018). *Blockchain technology in construction industry: Transparency and traceability in supply chain*. Academic Press.

Hyperledger. (2017). Hyperledger Announces Production-Ready Hyperledger Fabric 1.0. *Hyperledger Announces Production-Ready Hyperledger Fabric 1.0*. Retrieved from https://www.hyperledger.org/news

International Data Corporation. (2020). IDC FutureScape: Worldwide IT industry 2020 predictions. *IDC FutureScape: Worldwide IT industry 2020 predictions*. Online and accessed on June 20, 2020 from www.idc.com/getdoc.jsp\?containerId=US45599219

Jirgensons, M., & Kapenieks, J. (2018). Blockchain and the future of digital learning credential assessment and management. *Journal of Teacher Education for Sustainability*, *20*(1), 145–156. doi:10.2478/jtes-2018-0009

Kfir, S., & Fournier, C. (2019). DAML: The contract language of distributed ledgers. *Communications of the ACM*, *62*(9), 48–54. doi:10.1145/3343046

Knirsch, F., Unterweger, A., & Engel, D. (2018). Privacy-preserving blockchain-based electric vehicle charging with dynamic tariff decisions. *Computer Science-Research and Development*, *33*(1), 71–79. doi:10.100700450-017-0348-5

Kosba, A., Miller, A., Shi, E., Wen, Z., & Papamanthou, C. (2016). Hawk: The blockchain model of cryptography and privacy-preserving smart contracts. In 2016 IEEE symposium on security and privacy (SP) (pp. 839-858). IEEE.

Koskela, L. (1992). *Application of the new production philosophy to construction* (Vol. 72). Stanford University.

Lamport, L., Shostak, R., & Pease, M. (1982). The Byzantine generals problem. *ACM Transactions on Programming Languages and Systems*, *4*(3), 382–401. doi:10.1145/357172.357176

Latham, S. M. (1994). *Constructing the Team.Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry. Final Report.* Tech. rep., HMSO.

Lee, J., Azamfar, M., & Singh, J. (2019). A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems. *Manufacturing Letters*, *20*, 34–39. doi:10.1016/j.mfglet.2019.05.003

Li, J., Greenwood, D., & Kassem, M. (2018). *Blockchain in the built environment: analysing current applications and developing an emergent framework*. Academic Press.

Li, M., & Sond, W. (2020). IEEE standard for data format for blockchain systems. IEEE Std 2418.2-2020, Developed by the Standards Activities Board, IEEE Computer Society.

Li, X., Jiang, P., Chen, T., Luo, X., & Wen, Q. (2017). A survey on the security of blockchain systems. *Future Generation Computer Systems*.

Li, Z., Barenji, A. V., & Huang, G. Q. (2018). Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. *Robotics and Computer-integrated Manufacturing*, *54*, 133–144. doi:10.1016/j.rcim.2018.05.011

Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw–Hill.

Liker, J. K., & Meier, D. (2006). *The Toyota Way Fieldbook: A practical guide for implementing Toyota's 4Ps*. McGraw–Hill.

López-Pintado, O., Dumas, M., García-Bañuelos, L., & Weber, I. (2018). *Dynamic Role Binding in Blockchain-Based Collaborative Business Processes.* arXiv preprint arXiv:1812.02909.

McKinsey & Company. (2017). Blockchain technology in the insurance sector. Quarterly Meeting of the Federal Advisory Committee on Insurance (FACI). *Blockchain technology in the insurance sector. Quarterly Meeting of the Federal Advisory Committee on Insurance (FACI)*.

McWaters, R. J., Galaski, R., & Chatterjee, S. (2016). The future of financial infrastructure: An ambitious look at how blockchain can reshape financial services. In *World Economic Forum* (Vol. 49). Academic Press.

Meszaros, R., Adachi, D., Dharamsi, H., Yetiskin, B., & Thomas, P. (2016). *Blockchain Technology: How banks are building a real-time global payment network*. Accenture Mobility.

Miller, R. (2018). *Camunda hauls in $28M investment as workflow automation remains hot*. Published online in *Tech Crunch* on 5 December 2018. Retrieved June 25, 2020 from https://techcrunch.com/2018/12/05/camunda-hauls-in-28m-investment-as-workflow-automation-remains-hot/

Morabito, V. (2017). Blockchain and Enterprise Systems. In *Business Innovation Through Blockchain* (pp. 125–142). Springer. doi:10.1007/978-3-319-48478-5_7

Nakamoto, S. (2008). *Bitcoin: A peer-to-peer electronic cash system*. Academic Press.

Navon, R., & Berkovich, O. (2005). Development and on-site evaluation of an automated materials management and control model. *Journal of Construction Engineering and Management*, *131*(12), 1328–1336. doi:10.1061/(ASCE)0733-9364(2005)131:12(1328)

Nigam, A., & Caswell, N. S. (2003). Business artifacts: An approach to operational specification. *IBM Systems Journal*, *42*(3), 428–445. doi:10.1147j.423.0428

Pan, W., & Goodier, C. (2011). House-building business models and off-site construction take-up. *Journal of Architectural Engineering*, *18*(2), 84–93. doi:10.1061/(ASCE)AE.1943-5568.0000058

Panarello, A., Tapas, N., Merlino, G., Longo, F., & Puliafito, A. (2018). Blockchain and IoT integration: A systematic survey. *Sensors (Basel)*, *18*(8), 2575. doi:10.339018082575 PMID:30082633

PAS 1192-5. (2015). *Specification for security-minded building information modelling, digital built environments and smart asset management*. Tech. rep., BIM Task Group's security working group of the British Standards Institute.

Pasquire, C. L., & Connolly, G. E. (2002). Leaner construction through off-site manufacturing. *Proceedings IGLC*, 263–266.

Penzes, B. (2018). *Blockchain technology in the construction industry.* Technical report, Institution of Civil Engineers.

Perera, S., Nanayakkara, S., Rodrigo, M., Senaratne, S., & Weinand, R. (2020). Blockchain technology: Is it hype or real in the construction industry? *Journal of Industrial Information Integration*, *17*, 100125. doi:10.1016/j.jii.2020.100125

Petri, I., Barati, M., Rezgui, Y., & Rana, O. F. (2020). Blockchain for energy sharing and trading in distributed prosumer communities. *Computers in Industry*, *123*, 103282. doi:10.1016/j.compind.2020.103282

Pilkington, M. (2016). Blockchain technology: principles and applications. In Research Handbook on Digital Transformations (vol. 225). Edward Elgar Publishing. doi:10.4337/9781784717766.00019

Pontell, H. N., & Geis, G. (2007). *International handbook of white-collar and corporate crime*. Springer. doi:10.1007/978-0-387-34111-8

Raynsford, N., Briginshaw, J., Burke, A., Cook, R., Curtis-Thomas, C., Davies, H., . . . Smith, N. (2016). *Modern methods of construction: Views from the industry.* Technical report based on primary research. Online publication retrieved on 3 Apr 2019 from: www.nhbcfoundation.org/publications/

Rivest, R. L., Shamir, A., & Adleman, L. (1978). A method for obtaining digital signatures and public-key cryptosystems. *Communications of the ACM*, *21*(2), 120–126. doi:10.1145/359340.359342

Seebacher, S., & Maleshkova, M. (2018). A model-driven approach for the description of blockchain business networks. *Proceedings of the 51st Hawaii International Conference on System Sciences*. 10.24251/HICSS.2018.442

Singh, S. (2000). *The Code Book: The Code Book: The Science of Secrecy from Ancient Egypt to Quantum Cryptograph*. Anchor Books.

Slaughter, E. S. (1998). Models of construction innovation. *Journal of Construction Engineering and Management*, *124*(3), 226–231. doi:10.1061/(ASCE)0733-9364(1998)124:3(226)

Söderberg, J. (2015). *Hacking capitalism: The free and open source software movement*. Routledge. doi:10.4324/9780203937853

Steinmetz, R., & Wehrle, K. (Eds.). (2005). *Peer-to-peer systems and applications* (Vol. 3485). Springer. doi:10.1007/11530657_2

Swan, M. (2015). *Blockchain: Blueprint for a new economy*. O'Reilly Media, Inc.

Swan, M. (2018). Blockchain enlightenment and smart city cryptopolis. In *Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems* (pp. 48-53). 10.1145/3211933.3211942

Swan, M. (2018). Blockchain Economics: "Ripple for ERP". *Eur. Financ. Rev*, 24–27.

Swanson, T. (2015). *Consensus-as-a-service: a brief report on the emergence of permissioned, distributed ledger systems*. Retrieved from http://www.ofnumbers.com/wp-content/uploads/2015/04/Permissioned-distributed-ledgers.pdf

Syed, T. A., Alzahrani, A., Jan, S., Siddiqui, M. S., Nadeem, A., & Alghamdi, T. (2019). A comparative analysis of blockchain architecture and its applications: Problems and recommendations. *IEEE Access: Practical Innovations, Open Solutions*, *7*, 176838–176869. doi:10.1109/ACCESS.2019.2957660

Szabo, N. (1997). *The God Protocols.* Satoshi Nakamoto Institute. Retrieved from nakamotoinstitute.org/the-god-protocols/

Tapscott, D., & Tapscott, A. (2017). How blockchain will change organizations. *MIT Sloan Management Review*, *58*, 10.

Truong, N. B., Sun, K., Lee, G. M., & Guo, Y. (2020). GDPR-Compliant Personal Data Management: A Blockchain-Based Solution. *IEEE Transactions on Information Forensics and Security*, *15*, 1746–1761. doi:10.1109/TIFS.2019.2948287

Tsai, W. T., Luo, Y., Deng, E., Zhao, J., Ding, X., Li, J., & Yuan, B. (2020). Blockchain systems for trade clearing. *The Journal of Risk Finance*, *21*(5), 469–492. doi:10.1108/JRF-02-2017-0022

Turk, Ž., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. *Procedia Engineering*, *196*, 638–645. doi:10.1016/j.proeng.2017.08.052

Viriyasitavat, W., Da Xu, L., Bi, Z., & Sapsomboon, A. (2018). Blockchain-based business process management (BPM) framework for service composition in industry 4.0. *Journal of Intelligent Manufacturing*, 1–12.

Vukolić, M. (2016). *Hyperledger fabric: towards scalable blockchain for business.* Tech. rep., Tech. rep. Trust in Digital Life 2016. IBM Research. Recovered 1 Apr 2019 from trustindigitallife.eu/wp-content/uploads/2016/07/marko_vukolic.pdf

Vukolić, M. (2017). Rethinking Permissioned Blockchains. *Proceedings of the ACM Workshop on Blockchain, Cryptocurrencies and Contracts*, 3–7. 10.1145/3055518.3055526

Waller, D. L. (2003). *Operations management: a supply chain approach*. International Thomson Business Press.

Wang, J., Wang, Q., Zhou, N., & Chi, Y. (2017). A novel electricity transaction mode of microgrids based on blockchain and continuous double auction. *Energies*, *10*(12), 1971. doi:10.3390/en10121971

Wang, S., Yuan, Y., Wang, X., Li, J., Qin, R., & Wang, F.-Y. (2018). An overview of smart contract: architecture, applications, and future trends. *2018 IEEE Intelligent Vehicles Symposium (IV)*, 108–113. 10.1109/IVS.2018.8500488

Wang, W., Hoang, D. T., Xiong, Z., Niyato, D., Wang, P., Hu, P., & Wen, Y. (2018). *A survey on consensus mechanisms and mining management in blockchain networks.* arXiv preprint arXiv:1805.02707.

Warne, L. (2016). Crime in the Construction Industry. CIOB Policy Document, Chartered Instute of Building.

Warszawski, A. (2003). *Industrialized and automated building systems: A managerial approach*. Routledge. doi:10.4324/9780203223697

Waterhouse, R., Bew, M., Parkinson, K., Malleson, A., May, I., Matthews, A., . . . Hamil, S. (2017). *NBS National BIM Report 2017*. Academic Press.

Waterhouse, R., Highfield, B., Hamil, S., Malleson, A., Kell, A., Tate, G., . . . Ainscough, N. (2019). *NBS Construction Technology Report 2019*. Academic Press.

Weber, I., Xu, X., Riveret, R., Governatori, G., Ponomarev, A., & Mendling, J. (2016). Untrusted business process monitoring and execution using blockchain. *International Conference on Business Process Management*, 329–347. 10.1007/978-3-319-45348-4_19

Werbach, K. (2018). *The blockchain and the new architecture of trust*. MIT Press. doi:10.7551/mitpress/11449.001.0001

Womack, J. P., & Jones, D. T. (2003). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Simon and Schuster.

Womack, J. P., Jones, D. T., & Roos, D. (1990). *Machine that changed the world*. Simon and Schuster.

Wüst, K., Kostiainen, K., Čapkun, V., & Čapkun, S. (2019). PRCash: Fast, private and regulated transactions for digital currencies. In *International Conference on Financial Cryptography and Data Security* (pp. 158-178). Springer. 10.1007/978-3-030-32101-7_11

Xiong, Z., Zhang, Y., Niyato, D., Wang, P., & Han, Z. (2018). When mobile blockchain meets edge computing. *IEEE Communications Magazine*, *56*(8), 33–39. doi:10.1109/MCOM.2018.1701095

Xu, X., Weber, I., & Staples, M. (2019). *Architecture for blockchain applications*. Springer. doi:10.1007/978-3-030-03035-3

Yang, R., Wakeeld, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G., & Chen, S. (2020). Public and private blockchain in construction business process and information integration. *Automation in Construction*, *118*, 103276. doi:10.1016/j.autcon.2020.103276

Yaqoob, I., Salah, K., Uddin, M., Jayaraman, R., Omar, M., & Imran, M. (2020). Blockchain for digital twins: Recent advances and future research challenges. *IEEE Network*, *34*(5), 290–298. doi:10.1109/MNET.001.1900661

Yue, X., Wang, H., Jin, D., Li, M., & Jiang, W. (2016). Healthcare data gateways: Found healthcare intelligence on blockchain with novel privacy risk control. *Journal of Medical Systems*, *40*(10), 218. doi:10.100710916-016-0574-6 PMID:27565509

Zheng, Z., Xie, S., Dai, H.-N., Chen, X., & Wang, H. (2018). Blockchain challenges and opportunities: A survey. *International Journal of Web and Grid Services*, *14*(4), 352–375. doi:10.1504/IJWGS.2018.095647

Zhong, L., Wu, Q., Xie, J., Li, J., & Qin, B. (2019). A secure versatile light payment system based on blockchain. *Future Generation Computer Systems*, *93*, 327–337. doi:10.1016/j.future.2018.10.012

Zyskind, G., Nathan, O., & Associates. (2015). Decentralizing privacy: Using blockchain to protect personal data. Security and Privacy Workshops (SPW), 2015 IEEE, 180–184.

KEY TERMS AND DEFINITIONS

Block: Is the basic unit that describes how files are organized in a blockchain. Blocks contain an ordered set of transactions that are cryptographically linked to the preceding block, and in turn it is linked to subsequent blocks. Blocks are assembled by the ordering service and then validated and committed to the blockchain by peers that reside on nodes.

Blockchain: A file linked in a block structure that takes the form of a sequential database. It is ubiquitous, immutable, and traceable, and can record transactions with transparent and trusted rules in a peer-to-peer network.

Certification: Is defined as secure data in the form of a signed document that is held on a blockchain. These records can have controlled access through multiple layers of cryptography.

Certificate Authority (CA): Is a modular component of the DLT with the role of issuing encryption keys to network members and other users. The CA issues one root certificate to each member and one enrollment certificate to each authorized user. This should not be confused with using the blockchain to hold official certification by an authority.

Chaincode: Is an alternative name for smart contracts used in the Hyperledger Fabric framework. Using modular features of HFL, smart contracts can be programmed into the system in diverse ways, such as the client interface or through an associated database.

Channel: A name given to an enhanced feature of a DLT that allows a degree of privacy to exist within a subset of a larger trading network.

Consensus Algorithm: Is the process by which the members of a network determine which transaction get recorded onto the blockchain.

Custodian: This is the term used to describe the holder of the asset, receiving it from the Transactor.

Distributed Ledger Technology (DLT): Is the term given to the collection of services, interfaces, software, and associate systems that allow blockchains to be used in industrial settings.

Endorsement: Is defined as the process where specific peer nodes execute a chaincode transaction and return a proposal response to the client application. Endorsement is based on a policy that defines which peer nodes on a channel can execute transactions.

Genesis Block: Is defined as the first block on a chain and represents the configuration that initializes and defines the ordering service.

Hyperledger Fabric: Is primarily aimed at industrial blockchains. It is a quickly evolving framework that contains commands and modules to allow the blockchains to be developed, evaluated, deployed, and initiated.

Invoke: Is when a call is made via chaincode to alter the state (i.e. write) to the blockchain. This requires that the transaction is sent as a proposal to a Peer, which must be endorsed, ordered, and committed to become a permanent record.

Ledger: Is a document that contains records of transactions held in chronological sequence. In modern terms, a digital ledger is defined as containing two distinct parts: the blockchain and the Current State database (or World State). The term Distributed Ledger Technology (DLT) describes copies held by multiple computers (or nodes) across a network.

Membership Service Provider (MSP): Is a set of tasks within the system that provides credentials to clients, and peers that allow them to participate in a HLF network. HLF supports dynamic membership, where members, peers, and ordering service nodes can be added and removed without compromising the integrity of the network.

Orderer Nodes: Are specific nodes on the network that are tasked with ordering the transactions. They ensure the consistency of the blockchain and deliver the endorsed transactions to the peers of the network. The orders provide the Ordering Service that sort the transactions into blocks and then distributes these blocks to peers for validation. The ordering service is independent of the peer processes and orders transactions and in HLF, it supports modular implementations so that the system can be extended and configured.

Organization: Is a collective term used to describe users who can read and write to the blockchain. They are also referred to as members and managed by the MSP, which defines how other members of the network may verify their digital signatures when transacting or reading the ledger access rights of identities within an MSP are governed by policies which are also agreed upon when the organization joins the network. There is no size limit to the organization if they have access to a Peer (the main trading point). If they exist, collections of organizations form a Consortium.

Peer: A network entity that maintains a ledger and runs chaincode containers in order to perform read/write operations to the ledger. Peers are owned and maintained by members and make up the principle nodes in a blockchain network. Peers host ledgers, chaincode and participate in consensus.

Permissioned Blockchain: Infrastructure that is based on a principle of modular architecture. Permissioned describes a DLT that has a controlled and limited membership. This allowed a great deal of flexibility in designing systems as it permits the separation of roles between the nodes in the infrastructure, execution of chaincode and a configurable consensus and membership service.

Permissioned ledger: Is a blockchain network where each entity or node is required to be a member of the network. Anonymous nodes are not allowed to connect.

Policies: Are part of the language used for constructing the layers of encryption in the data blockchain. They are used to control access to data and other resources in a blockchain network, notably who or who cannot read and write to a channer, evoke, query, or deploy chaincode. Policies are defined in the configuration files prior to deploying the network, setting up an ordering service or creating a channel. They can also be specified with instantiating chaincode.

Privacy: Is required by the chain transactors to conceal their identities on the network. While members of the network may examine the transactions, the transactions can't be linked to the transactor without special privilege. Data as well as transaction details can also be held privately.

Private Data: Are confidential information stored by peers on the blockchain but kept separate from other data. Access to this data is restricted to members with permission, while unauthorized organizations will only see a hash of the private data on the channel ledger as evidence of the transaction For an additional level of privacy, these hashes of private data go through the Ordering Service, which keeps it hidden from the Orderer.

Query: Is a call (or invocation) to read from the blockchain ledger. In HLF, chaincode is used to unwrap the blockchain to read certain keys or other data. Queries do not change the ledger state, although the client application can choose to submit a read-only transaction for ordering, validation, and commit, to provide an auditable proof that the blockchain has been read.

Quorum: Is the minimum number of members of the cluster that need to affirm that a transaction is acceptable to write to the ledger. For networks with few members, the central authority may make up the majority vote for acceptance.

Smart Contract: A simple computer program that resides in compiled format within the block data structure across a peer-to-peer network that runs whenever the chain is re-written. A set of instructions in the form of a checklist, executes the instructions held in the blockchain.

Software Development Kit (SDK): Provides a structured environment where the System Administrator can design, deploy, and manage the network. In HLF, the SDK is modular and configurable using standard software tools. Modules, such as the cryptographic algorithms, logging frameworks and others, can be switched in and out by the SA using the SDK. Through the SDK, transaction processing, membership services, node traversal and event handling are deployed. HLF currently uses both Node.js and Java, with two more: Python and Go, in development.

Transactions: Are the official term used to describe the addition of a record to a blockchain. Members cannot write directly but must submit transaction proposals to the consensus and ordering algorithm.

Transactors: Can be either human or a device, for example a shipper delivering a package and registering the transaction with a smartphone, that sends a transaction proposal to the consensus and ordering algorithm.

Validating Peers: All transactions must be validated by Peers. These are networked computer nodes owned either by one of the participant organizations or hosted by a professional service provider. Nodes hold a copy of the blockchains and are responsible for ensuring consensus used to validate transactions. Once validation is complete when all nodes receive an updated version of the blockchain.

World State Database: (also called the *Current State*) is a data store that is permanently attached to the blockchain where the latest and most complete records of transactions are stored. It is more efficient to read and query the blockchain through the World State.