Designing blockchain applications for construction project management

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Abstract

This paper describes the results of a study into the application of blockchain technology to construction and engineering (C&E) projects. Through design and simulation, the specification for an open source software framework and the architecture is provided that can support project governance through the use of a blockchain and extended modules. This work demonstrates that the technology is at a suitable stage of development to allow implementation to start for basic processes and that rapid progress of useful modules are expected to follow shortly.

Keywords: Blockchains, project management in construction

1. Introduction to the study

Many have written (Swan, 2015) and spoken[1] about blockchains as a revolutionary platform technology with numerous applications across industry, government and civil society (Glaser, 2017). The application of the technology to commercial activities promises to provide benefits far beyond its original purpose (Hultgren and Pajala, 2018; Turk and Klinc, 2017), including for construction and engineering (C&E) assembly and administration (Penzes 2018; Hultgren and Pajala, 2018) that could lead to automation. For example, secure payments made using smart contracts embedded in the blockchain software and triggered when all contractual conditions are met. These services can be provided independently of any central authority (López-Pintado, et. al., 2018), a feature particularly useful when trading partners are not entirely trusting of each other and when delays in payment introduces additional financial risk (Tapscott and Tapscott, 2017; Carroll and Bellotti, 2015). Indeed, further automation of a range of assembly and administration processes could provide broad benefits across an industry that is known for low productivity and profits (Barbosa et al., 2017). Additional features of the technology can provide similar functionality as Enterprise Resource Management (ERM) system, providing a low-cost alternative to these solutions.

Additionally, a good design of a blockchain system (Li, et. al., 2017) would help address heightened concerns about the safety of buildings (Brokenshire, 2018) as project governance and continuity have been identified as areas that need improvement. Indeed, any effort to further introduce digital technology would help achieve government industrial strategy for the sector (Cable et al., 2013). Solutions abound in other fields, such as an online voting system (Marella, et.al., 2017), systems for protecting personal data (Zyskind et al., 2015) and as a basis for interconnected and distributed services fundamental for the Internet of Things (Christidis and Devetsikiotis, 2016).

But despite these imperatives to adopt this new technology, there are several factors that are impeding implementation, the main one being the lack of fully featured commercial applications. There are an abundance of prototype systems, but most companies do not progress their projects beyond the pilot stage (Lacity, 2018), a fact that indicates some reluctance to adopt the new technology. Other factors are slowing widespread adoption. For example, many are sceptical about prospects of rapid-

[1] The Ted Talk by Bettina Warburg is a good introduction to the potential of the technology: www.ted.com/talks/bettina_warburg_how_the_blockchain_will_radically_transform_the_economy

scale destructive innovation and the hype (Pardolesi and Davola, 2019) associated with the technology, and with cryptography (that uses the same technology) which is associated with wild speculation (Fry and Cheah, 2016), quick fortunes won and lost (Decker and Wattenhofer, 2014) and illegal activities (De, 2019; Stroukal et al., 2016; Barone and Masciandaro, 2019; Buchanan et al., 2018). There is also the realisation that although adoption might help the industry as a whole, the direct benefits to individual companies may be illusive and investment therefore hard to justify. Evidence also shows that although many UK construction companies are favourable towards change (Waterhouse et al., 2017), such as by seeking out new technology (Waterhouse et al., 2019), engaging in collaborative relations with suppliers and clients (Akintoye and Main, 2007) and adopting Modern Methods of Construction (MMC) (Raynsford et al., 2016). The industry is still characterised as having low levels of trust (Cerić, 2015), for being adverse to change and slow to adopt innovation and for low profitability (Green, 2016; Davis et al., 2015). Construction is also known as a locus of crime (Warne, 2016) and for being associated with illegal and immoral business practices (Pontell and Geis, 2007). Despite these aspects, there is great enthusiasm for the promotion of blockchain technology and the field is progressing rapidly. Optimistically, there are few industries less likely to benefit from this innovation than construction the UK which is both driven-to and receptive-for change (Egan, 1998; Latham, 1994). This paper will explain how this technology can be introduced.

2. Aims and objectives of the technical paper and summary of the logic followed

The overall long-term aim of this research programme is to identify design, test, evaluate and plan for adoption of emerging technology to improve the management of C&E projects. The specific objectives of this paper are to:

(i) Define, through business process modelling, a suitable blockchain platform for use on C&E projects.
(ii) Propose a system architecture and configuration for a blockchain solution that is able to support C&E projects.
(iii) Discuss the relative merits on the use of blockchain technology for C&E projects based on criteria established through pilot studies.

3. Methods used in this study

This section describes the approach taken to accomplish the research objectives and make progress towards achieving the long-term aim. One of the main tasks is to define a blockchain application that is able to support C&E projects. There are several aspects of this. Firstly, at the time of writing, there are no full-featured, commercial systems on the market. Open source modular systems require a higher level of effort but with the added advantage that it forces a modular approach to problem-solving and creates the opportunity for creative innovation. The introduction of blockchains technology to construction management requires modelling of the business processes (García-Bañuelos et. al., 2017) in a similar manner to an ERM application. Thus business process mapping is a common approach to automation with a shift to customer interaction using mobile devices and as part of a distributed, client-side application (Viriyasitavat et al., 2018). The so-called artifact (sic) centric business process model (Nigam and Caswell, 2003) is a common method for modelling business processes. These are well documented in business literature (see Waller, 2003). Seebacher and Maleshkova (2018) helped to understand the graphical and model-driven tools for the blockchain business network. Grapical methods can help. For example, Damelio (2016) described the swim-lane chart that was helpful in modelling the individual chain of transactions that define ordering protocols of the process.

These and other aspects of the design and configuration for C&E projects requires a design for the system architecture that is optimised for the business process, including aspects such as the consensus and ordering protocols. To aid in defining these, Wang et al. (2018b) provides an understanding of how to configure a functioning consensus mechanism across networks and Cachin and Vukolić (2017) a practical guide to ensuring that the individual transactions are ordered correctly so that the trading record is accurate and reliable. This helps in the forensic analysis of a project and can help to determine if any accounting fraud or double payments occurred.

The approach taken to evaluate the relative merits on the use of blockchain technology for C&E projects based on criteria established through pilot studies. This is a long-term task as it also requires that some form of adoption plan be promoted. This plan will required a detailed evaluation of the current methods and a solid argument as to how blockchain technology can be used to either enhance or replace the existing systems. Separate evaluation is required to determine if the proposed system is robust enough to stand up to use in demanding industrial and commercial settings. A survey of the numerous pilot projects that have been reported helps with this evaluation as well as in-house testing using an open source system that was installed and configured as a simulated process.

4. Description of the blockchain technology suitable for project management

This section contains a description of a blockchain solution that would be suitable for use on C&E assembly and administrative processes[2]. This stage is essential in the study as it provides a working model to apply the new technology. As blockchains are considered a disruptive technology with applications and impact that have the potential to dramatically change normal working practice. Although this study focuses on a specific case where the blockchains are used to log transactions associated with the installation of series of offsite manufactured building components. Other process, such as the management of staff on site, or warranty conditions for installed M&E systems, might benefit from an application of the technology. Current practice for the management of component installation range from project to project and might include the use of standard paper or spreadsheet-based ledgers to record some (but not all) of the transactions. Additionally, commercial project management software (e.g. *Asta Powerproject* and *Microsoft Project*) have the capability record orders, deliveries, installations, inspects and so forth that can be used to update Gantt charts and to produce reports for Cost Value Reconciliations (CVR) and other methods to monitor and measure expenditures against budgets on construction projects.. But these systems lack certain features that blockchains could provide, most notably as a method to automate processes. These are:

(i) Transactions between members of a trading network are recorded and stored in an immutable ledger for later use or to trigger (with smart contracts) for actions such as communications or automatic payments.

(ii) The system, through extended modules can support realistic trading activities by providing services of the sort normally found in ERM applications[3].

(iii) That security and privacy are maintained to a level that is appropriate for a commercial operation.

In order to illustrate ow these features function and help, consider the diagram in Figure 1 which shows five (5) separate transactions of an *asset* (i.e. *a building component*) between members of a trading network (*Nodes* in this example).

[2] The ZeroToBlockchain practical and video series by Gill (2018) provides a template for a blockchain system that is suitable for use in project management.

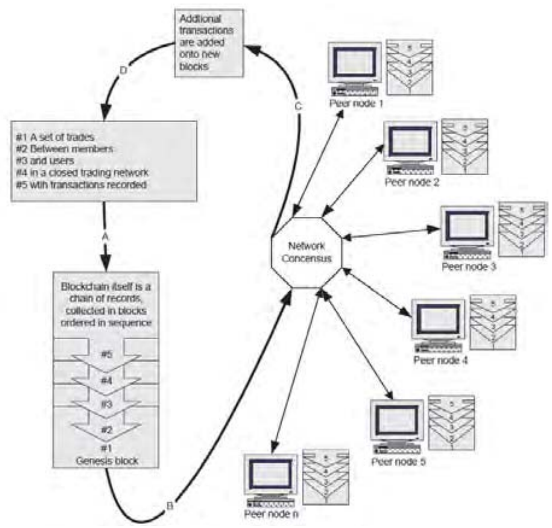

Figure 1: This diagram shows a simplified schematic of how the core blockchain functions. It is a flow chart describing how transactions are recorded on a blockchain. Arrows show the direction of the records of transactions as they are written on the blockchain, passing first through the central network consensus algorithm and on to the Peer nodes.

The arrow labelled **A** starts the process where transactions are sent to the *Peer nodes* for confirmation via a network consensus (arrow **B**) protocol, which is represented by the central octagonal box. The arrow labelled **C** shows how the process repeating cyclically with additional transactions recorded (arrow **D**). What makes the blockchain immutable is that each block of transactions is encrypted with a hash and the key is then stored in the block that follows. A cryptographic hash acts a one-way function that, once the blocks have been strung together, they can only be read by undoing them in sequence (Finck, 2018). The use of a cryptographic algorithm ensures a level of security (Szabo, 1997) that protects against hostile attempts to alter the record or obtain confidential data. If there is any attempt to alter or add data, then it will be impossible to reconstruct the data as it was before.

At the core of this system is a consensus and ordering algorithm, which is critical for the function of this business-oriented blockchain (Swanson, 2015). This ensures that partners engaged in a trade have a contract in place and that their right to trade is accepted and authorised by the other members of the network (even if they don't get to see the details of the trade) and that transactions are ordered sequentially. The consensus process, if properly configured, makes it difficult for fake, falsify or enter the same transaction. Although double-entry costs can sometimes occur by accident, fake ledger entries are hallmarks of organised crime[4]. For C&E projects, as in other commercial settings, a commonly used protocol is *Byzantine fault tolerance* (Lamport et al., 1982). This approach to consensus and ordering is based on the acceptance that one or more of the nodes might be out of service or, for some reason, contain false information (Cachin and Vukolić, 2017).

5. Digital ledger technology and the extended blockchain system

This section contains a description of the architecture of an extended blockchain system that to make it suitable for C&E projects. These additional elements make up a complete system (Xu et al., 2019; Wang et al., 2018a) that is collectively referred to as Digital Ledger Technology (DLT). Fortunately, a framework is available that can provide the features required. The Hyperledger Fabric (HLF) framework[5] is an implementation based on a series of projects (Androulaki et al., 2018) and

[4] See Beare (2007, p43) for a legal perspective of the issues around double-billing
[5] Hyperledger Fabric v1.4 can be downloaded at github.com/hyperledger/fabric.

published as part of the Hyperledger consortium (Hyperledger, 2017). This is an open software development community[6] managed by the not-for-profit Linux Foundation®. The requirements of the proposed system dictate an architecture of the HLF that is illustrated in Figure 2. This includes the following elements: (i) network designers that set up the initial configuration of endorsement and consensus algorithms, (ii) system administrators that manage deployment, membership management, smart contracts and system maintenance, (iii) a world state (i.e. a database) that contains the current status of the assets, (iv) a peer network, containing the distributed ledger and applications and (v) events management and notification system.

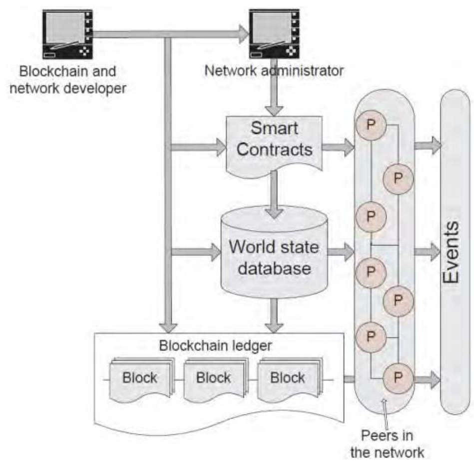

Figure 2 contains the basic system architecture of the DLT that includes the administrator and developer, smart contracts, world state database, peers and events based upon the HLF implementation. Peers are identified by the symbol 'P'.

The network developer and administrator, shown near the top of Figure 2 share a range of responsibilities in the deployment and administration of the DLT. Operating through a software development kit (SDK), they build and maintain the network, members and events. In HLF the membership manager can create, stop, change the configuration or, if required, delete the peers (Dunphy and Petitcolas, 2018). Members can extend beyond the Peers. 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.

What is not shown in Figure 2 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 blockchain or how the interface uses pull-down menus, check boxes and other forms of browser-based information exchange to interact with the DLT. Significantly, the system had the capability to manage separate sets of ledgers (i.e. blockchains) for each channel. Multiple channels are essential in that they that allow trading partners to maintain privacy. This protects confidential commercial data, but still allows mission-critical information such as the delivery date, warranty details and maintenance instructions, to be available for a wider audience. Membership profiles are controlled by the network administrator (López-Pintado et al., 2018). But this arrangement has the disadvantage in that some of the channel blockchains are saved on only two or three nodes. This could be a problem if any one of these nodes were to become unavailable, and could lead to a slowing down or bringing to a halt the project. One way around this is to host the DLT on a cloud computing system provided by a company that with mission-critical reliability and security.

[6] See Anon. (2016) and Söderberg (2015) for a general overview of the open source movement and Glaser (2017) for a discussion related to open source blockchains.

6. Business processes management in construction using blockchains

It is useful to consider added feature DLT when used in a commercial setting. Although primarily designed to record transactions, an added benefit of DLT is their ability to emulate an ERM. If configured properly, they can be used to monitor, record and control business and technical information, record critical dates and receive digital signatures for approval and implements complex contracts. DLT can (with some effort), be made to interact with relational databases, mobile sensors, hand-held devices, analytical machines, ERM systems and Building Information Models (BIM) (Swan, 2015). However, this integration requires that the business process is carefully mapped (Auberger and Kloppmann, 2017). This is done with the artifact (sic) centric business process model (Damelio, 2016; Nigam and Caswell), where multi-thread and multi-component processes are organised around service provision to online clients (Waller, 2003).

Design process to set up a distributed ledger system

Figure 3 demonstrates the flow chart associated with an example of a building component installation cycle. Modelling requires an iterative approach with modelling and optimisation to achieve an accurate representation (Garcia-Bañuelos et al., 2017) that is ultimately used to configure the DLT (Seebacher and Maleshkova, 2018). This example process starts when the Design Coordinator (DC) submits a set of drawings to a communal repository, accessible only to those who require it. This submission triggers the Network Administrator (NA) to *Deploy* the DLT so that the PM can *Invoke* the first transaction. This is shown in the left of Figure 3. In this flow chart, the process proceeds with the delivery of the component on site, then installation, inspection and finally, certification. The cycle then returns to the top with the delivery of another component.

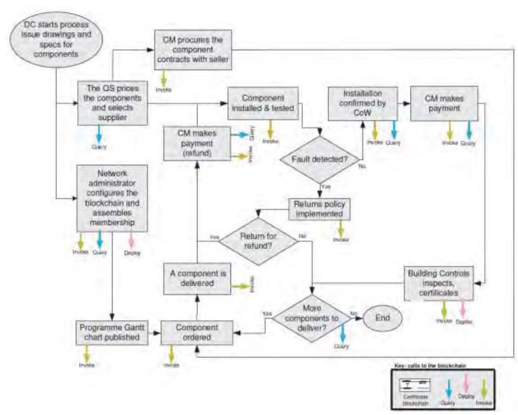

Figure 3 is a flow chart that shows the process of installation of the component that was made off-site. Those involved in this are the project manager (PM), Building Control (BC), Contract Administrator (CA), component supplier (SU), installer (IN) and Clerk of Works (CoW), who works for the client. Users are restricted to their access to the DLT to Deploy, Invoke or Query. These are represented by arrows extending from the task boxes.

Two sets of chaincode (smart contracts) are *Deployed* in separate blockchains in this example. The first one mirrors the paper contract between the component Supplier and the Client. The other one is *Deployed* by the Building Control (BC) regulator who uses a blockchain to save certificates required to authorise the safe occupancy of the building. The BC is responsible for confirming that each installation is done according to the building code and registers this by confirmation by invoking the blockchain to create a digital certificate that serves as an official mark of compliance. Certificates written to the blockchain and can be read by anyone with access privilege. Some members of the network receive signals (in the form of a text message, email or notification) when an event is triggered to indicate that action is required. For example, the Installer 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 play their roles.

The extended-function DLT is created using Hyperledger Composer and as the framework is extensible, modules and templates are used to provide the range of services required.

7. Conclusions, discussion and recommendations

These conclusions reflect on the research objective set out in the introduction. Further discussion is included on a range of questions raised as a result of the research and recommendations are made on how to further evaluate the technology and plan for its adoption. One of the key objectives of the study was achieved by reviewing currently available DLT systems. Based on this, it was determined that Hyperleger Fabric and Hyperledger Composer is a suitable platform. The system architecture is proposed that allows the DLT to be used in a commercial setting using a mixture of fixed computers to serve as nodes and mobile devices to enter data and receive communications. A system architecture is presented in this paper that is driven by the design of the business process and configuration for a blockchain solution that is able to support C&E projects.

The adoption of Modern Methods of Construction (MMC) involves off-site component manufacturing of bathroom and kitchen pods, door sets, and structural insulated panels (SIPS), precast concrete foundation, ceiling and floor slabs. This is further proof that this is a controlled industrial process (Pan and Goodier, 2011; Slaughter, 1998) and therefore suitable for automation using an enterprise IT system. Furthermore, HLF requires no licence fee payment.

Automation of the construction process is mostly about the coordination of components made off-site using MMC and Lean manufacturing. So far, there has been little interest shown in large-scale integration of processes in construction. This may be because of the high costs (and significant risk) of installing an IT system. One of the big advantages of DLT is that it can be installed piecemeal, with processes added on as they are needed. The rapid advances in finding solutions to sometimes obscure problems that open software frameworks offers, makes DLT ideal for this particular industry. This finding is based on the general requirements of C&E projects of the sort of modelled in this study that extends the recording, communication and data management as an improvement of the systems created for cryptocurrency trading.

One aspect of construction projects that cannot be neglected is that the trading environment, with multiple components, suppliers and subcontractors, is complex and risky. Traders would benefit from a shared database and permanent record that contains information from which members can read from and write to, depending on their requirements (Greenspan, 2015). These might be needed in the case of disputes or conflicts between trading partners, or in the event of a defective component, accidental double invoicing, or if there is a high likelihood of graft, fraud or untraceable expenses. It is unfortunate that in many C&E projects there exists a fundamental absence of trust amongst partners.

Prospects for adoption of the technology are promising and this research provides a basis for future work. Functions such as controlling access to a site, managing supply chains, recording deliveries and material handling is possible with current DLT and a number of pilot and proof-of-concept studies (Korpela et al., 2017), including a joint venture between IBM and Maersk (Hackius and Petersen, 2017), provide the promise of technically feasibility[7].

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[7] It has been reported that wider adoption of the technology by partners have been slow (Allison, 2018).

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