Revolutionising AEC financial system within project delivery stages: A permissioned blockchain digitalised framework

Sepehr Abrishami[1, *] and Faris Elghaish[2]

Senior lecturer at University of Portsmouth
Ph.D. Researcher at University of Portsmouth
email: Sepehr.Abrishami@port.ac.uk

Abstract

Extant literature accentuates the potential of blockchain in the Architectural, Engineering, and Construction (AEC) industry, and its prospective to be integrated into the construction projects to automate financial transactions; for better transparency, security, and controlling. Existing research highlights that permissioned blockchain can work as a platform to create a business network among project participants, due to its features being consistent with the construction industry nature. This paper introduces a framework to integrate permissioned blockchain, particularly Hyperledger fabric, into the construction delivery stages. The proposed framework includes specific steps, demonstrating the requirements to build a network within the pre-construction, construction, and closeout stages. Furthermore, the proposed framework reveals the flow of financial transactions throughout the proposed financial system. Due to the Building Information Modelling/Management (BIM) capabilities and cost planning, the proposed framework shows how the integration between blockchain and BIM processes can be achieved. Therefore, the framework identifies the required data from 4D/5D BIM to be entered into the blockchain financial system.

A systematic literature review was used to highlight the advantages of using blockchain in the construction industry, as well as, identifying the appropriate blockchain platform. The framework can be used by industry practitioners to identify the architecture of smart contracts (chaincode) in the construction industry, such as how endorsement and validation policies can be articulated. The outcome of this paper will be used to develop a proof of concept prototype to test and validate the applicability of the proposed conceptual framework through its application to a real case study.

Keywords: BIM, blockchain, AEC, Construction, Hyperledger

1. Introduction

Blockchain is defined as a distributed ledger for the bitcoin cryptocurrency (Swan, 2015), however, through the last few years, blockchain becomes a comprehensive technology to share and record data in high secure platforms (Andoni et al., 2019). Blockchain is widely recommended by many organisations to be exploited to enhance the entire construction projects ((ICE), 2018, Lamb, 2018, Kinnaird et al., 2018). Moreover, blockchain research becomes a trend during the last few years (Turk and Klinc, 2017, Li et al., 2018a). (Mason, 2017, Mason and Escott, 2018) highlighted the importance of implementing specific features of blockchain such as smart contracts to automate payments within the construction industry projects. Further to the researchers' recommendations, AEC companies such as Arup began to declare the high level of interest to integrate blockchain merits within the industry to enhance the construction industry performance in several services, such as automating the payment process, supply chain, and smart cities (Kinnaird et al., 2018). Moreover, BIM becomes a mandatory processes in many countries, and there have been several research to explore the integration of blockchain and BIM, i.e. Mathews et al. (2017) propose the mentioned integration for maximising trust among project participants in AEC industry. Besides, Blockchain and BIM are recommended for building a comprehensive smart milieu—digital built plan— for the construction industry ((ICE), 2018, Lamb, 2018, Kinnaird et al., 2018). Even though, there is a high level of declaration for the importance of blockchain, in terms of payment automation in construction industry, there has not been a real application developed/presented yet.

In this paper, literature review is used to investigate the current state blockchain/smart contracts implementation within the AEC sector, as well as, critically analysing the proposed potentials and the reality of revealed challenges. Thereafter, a conceptual framework will be developed to draw specific steps throughout project delivery stage such as how the blockchain consensus mechanism can be built during pre-construction stage, and how the close-out stage will be totally revolutionised by adopting blockchain.

In this essence, this research is an attempt to move forward the application of blockchain/smart contracts through articulating a conceptual framework, in which, it proposes how the smart contracts can be applied/exploited throughout the entire project delivery stages (Pre-construction, construction and close-out stage). In addition, the proposed framework considered as the interrelationship between the BIM process and the proposed workflow of the automated payment smart contract framework.

2. Overview of Blockchain and smart contracts

Tapscott and Tapscott (2016) define that blockchain is a distributed ledger that records all shared data amongst different members in a network. Each transaction represents a block in the network and subsequently new blocks are linked to previous in order to create a chain (Li et al., 2018b). The interrelationships between all blocks maximise the opportunity of security (Liang et al., 2017). Each block carries a data and hash for previous blocks, which reduce the chance of hacking (Nofer et al., 2017). Li et al. (2018b) mentioned that there are two categorises of Blockchain Networks (BCN), namely, Public BCN which can be accessed by the public, under generic consensus mechanism, and it remains secure due to its cryptography power such as Bitcoins (Andoni et al., 2019); and Consortium BCN, in which, its users should be pre-identified, therefore, the mechanism to get their consensus should be identified clearly and in advance (Li et al., 2018c). Even though, the private BCN represents a single BCN platform for specific organisation with centralised data within the organisation, it is decentralised between the network users.

Peters and Panayi (2016) define smart contract as a platform for enforcing and monitoring the entered data, by trusted source, in the BCN, based on the pre-identified contract terms. Smart contract is a result of evolving BCN ability to transfer cryptocurrency/data over the blockchain throughout the last decade (Christidis and Devetsikiotis, 2016). Andoni et al. (2019) assert that smart contracts uses peer-to-peer (PTP) network that enables multi-trusted parties to manage the data simultaneously, so that each chain in the BCN carries its own data and subsequently all data will be stored in the ledger according to agreed consensus mechanism (Watanabe et al., 2016). Additionally, smart contracts reduce the dependency on lawyers/ third persons in executing and monitoring the contract terms such as financial transaction, therefore, the accuracy and transparency of data could be enhanced (Mason and Escott, 2018). That is why, Christidis and Devetsikiotis (2016) contend that smart contracts gives an advantage for the user to have an automatic audit to the transferred data, as well as, once the data is valid, will be immutable which enhance the transparency and security. There are several platforms to develop a blockchain platform that smart contracts can be developed and integrated into the network. The most well-known platform is the Ethereum smart contract, which is a decentralised platform in cloud 2.0, where the data (i.e. Payments, penalties) can be shared (Wood, 2014). The process runs on Ethereum Virtual Machine (EVM) and can generate multi-smart contracts with the same characteristics (Hildenbrandt et al., 2017), therefore, there are the data sender and the petitioner. The shared information should be checked automatically to ensure there is no corrupted data, impartial payment, and etc. (Liu et al., 2018). Moreover, in smart contracts, it is ensured that the shared data, as business codes and information between different departments in an organisation, can be recorded confidently and protected from the competitors (Nakasumi, 2017), and each transaction requires an acceptance from the network core members in order to reach consensus (Andoni et al., 2019). Since Distributed ledger relies on cryptocurrencies, the linking between blockchain and traditional bank accounts is considered as a part of the fourth industrial revolution (Mason, 2017).

There are two types of blockchain, namely, Permissionless and Permissioned (Wüst and Gervais, 2018). The permissionless blockchain allows anonymous users to act in the blockchain and add new transaction based on generic consensus mechanism, such as Proof of Work (PoW) (Cachin, 2016). In permissioned blockchain participants are known, vetted and includes a governance approach that regulates the relationships among participants, which maximise the trust (Vukolić, 2017). Since all entities are well-defined in the chain, the permissioned blockchain can use consensus models such as crash fault tolerant (CFT) or byzantine fault tolerant (BFT), as the malicious opportunities are diminished (Baliga, 2017, Cachin, 2016).

According to Androulaki et al. (2018), the smart contract in hyperledger is called chaincode, which can be written in different programming language such as GO and Java script (Cachin, 2016). The program could be articulated separately and using API to interact with the blockchain (Androulaki et al., 2017). The user interacts with multiple nodes simultaneously through a channel, to create a business layer software development process (Vukolić, 2016). In any organisation, the channel could be used to share specific information to specific node, which keep the information private (Cachin, 2016). Transaction management is the philosophy of splitting transaction logs and the ordering process; thus, this allows to perform parallel transaction concurrently. Therefore, the ordering will be solely implemented for endorsing transactions (Androulaki et al., 2018).

Dhillon et al. (2017) and Hyperledger (2018) state that blockchain network comprises of several peer nodes, and each peer node includes different smart contracts and ledgers. The application is used to propose the transaction to perform a smart contract, thus, the proposed smart contract after the validation will be recorded in a specific ledger (Androulaki et al., 2018, Vukolić, 2016). In order to link mutual smart contracts for different peer nodes, a channel is used to send the proposed transaction as well as reflecting the response to the application (Benhamouda et al., 2018). The order of transaction is a pivotal task to package multiple transactions in a single block, and subsequently, record the block to its peer node (Dhillon et al., 2017, Hyperledger, 2018).

Xu et al. (2017) defines Consensus mechanism as a set of rules (algorithms) to ensure the correctness of performing set of transactions through a blockchain network. These specific algorithms are unified within a single function, and the consensus mechanism is responsible to order the transaction, check its validity via different endorsers, and allocate validated transaction to their ledger (Androulaki et al., 2018, Hyperledger, 2018). There are two main properties, namely, safety and liveness (Cachin and Vukolić, 2017, Hyperledger, 2018). Existing smart contracts use order-execute architecture, that requires all nodes to validate and execute every transaction, and the consensus should be completely identified/agreed upon (Androulaki et al., 2018).

In this essence, hyperledger works based on modular environment, which includes a pluggable consensus mechanism, management process, ordering approach, chaincode, and membership service (Androulaki et al., 2018, Benhamouda et al., 2018, Cachin, 2016). Therefore, each organisation could acclimatise the hyperledger in accordance with its hierarchy of data sharing, and the hyperledger can be configured by multiple users to provide a flexible platform for different industry purposes (Hyperledger, 2018).

Klaokliang et al. (2018) mentions the structure of hyperledger fabric comprises of (1) **Ledger**, which is a set of blocks that records multiple transactions, (2) **Peer**, that is a pool containing ledgers and smart contracts, (3) **Chaincode** is the smart contract to perform transaction according to the hyperledger concept, (4) **Channel**, which it is the path that the transaction and blocks take to be allocated amongst different peers, (5) **Endorsement policy**, which is a set of instructions that provide specific metrics to the peer to decide whether the received transaction valid or invalid (Hyperledger, 2018), (6) **Ordering service,** which is a node (Ordering Service Node (OSN)) that is exploited to order the transactions and blocks based on the agreed consensus mechanism, such as Kafka. This node should include specific information regarding the size of blocks, maximum time, and number of allowed transaction for each block before assigning it to the peer through the channel (Androulaki et al., 2018, Hyperledger, 2018).

Implications of blockchain/smart contracts in the construction industry:

Despite Blockchain does not creep into the construction industry like some other technologies, there are several attempts to adopt it by emerging business models (Tozzi, 2018), as an instance, Bimchain is a proof of concept to integrate BIM into Blockchain as a plug-in into the BIM platforms (Bimchain, 2018, Lamb, 2018). Fox (2019) states that there are several benefits of adopting smart contracts in the construction industry, such as; delivering the agreed contracts automatically with enabling parties to update any variations, enhancing the copyright for the project documentations, automated payments amongst project parties, and potentially it can works as a claim submission platform (Lamb, 2018, Tozzi, 2018). As such, smart contracts will be valuable, in terms of automation of some construction processes that traditionally relies on multi-interactions and contribution from project participants to make a decision (Mason, 2017, Mason and Escott, 2018).

Uncertainties in construction payments are a challenge in developing reliable cash flow and subsequently leads to several claims that affect the business growing (Carmichael and Balatbat, 2010, Elghaish et al., 2019). Since the construction trust account is recommended (Cardeira, 2015), Smart contracts can work as a trust account that hold the money and transferred automatically to the party who warranted it (Cardeira, 2015). That is because, the project participants will trust the smart contracts outputs, as all embedded data is immutable and decentralised (Christidis and Devetsikiotis, 2016, Lamb, 2018, Mason and Escott, 2018, Watanabe et al., 2016).

Koutsogiannis and Berntsen (2019) argue that digital construction is an integrated process, thus when a building's real-time digital will be implemented, the smart contracts will be more effective and applicable. Exploiting smart contracts with cryptocurrencies supports articulating a contract draft that specific funds can be embedded to avoid the common insolvency issues or late payment in the construction industry (Cardeira, 2015). In addition, the cross verifications by several references lead to acquiring an efficient, robust, secure and reliable system, which build a trust environment amid project parties (Mason, 2017, Mason and Escott, 2018).

3. Previous research on blockchain and Smart contracts in Construction Industry:

Through using Scopus, Web of Since (WoS) and google scholar research repository, researchers have used relevant keywords to find the relevant papers in implementing blockchain and smart contracts in the construction industry/built environment. The used keywords were, namely; "blockchain in construction" and "blockchain and smart contracts in built environment". The output of the search was 13 papers, the table below shows the contribution of each paper to raise the awareness of implementing blockchain and smart contracts in the construction industry, whether thorough addressing it directly or indirectly in different disciplines.

Table 1. Previous research in the field: Analysis of core drivers

Discipline	Contributions	Authors
Construction management and built environment	• Highlighting the potential of blockchain in construction management, as well as providing a map to direct potential users to select the suitable type of blockchain based on the nature of the data and the hierarchy of the organisation. • Illustrating the blockchain interoperability with other systems (data storage)	Turk and Klinc (2017)
	• Highlighting the challenges that face implementing smart contracts in the construction industry. • Articulate specific steps that should be considered by industry participants.	Mason and Escott (2018)
	• Providing an emergent framework that considers multi-dimensions, namely social, political and technical. This is in order to enable potential developers/users of blockchain in construction to highlight the potentials and challenges.	Li et al. (2019b) and Li et al. (2018a)
	• Asserting the importance of intelligent contract (smart) for the construction industry through saving the cost of	Mason (2017)

	employing third party. And, minimising needed time to perform new transactions. • Highlighting the importance of integrating smart contracts into BIM in order to automate the construction process.	
	• Presenting an outlook for implementing blockchain to revolutionize the persist issues in managing the supply chain, contract management and resource management, particularly leasing equipment. • Providing a taxonomy of blockchain implementation challenges in the AEC industry.	Wang et al. (2017)
	• Linking the current challenges that face construction industry to the potential benefits of blockchain to provide reliable solutions. • Researchers articulated a framework—Presenting the socio-technical dimensions— this could facilitate implementing blockchain in seven areas of the built environment as categorised by researchers. • Identifying decision making criteria in terms of adopting blockchain.	Li et al. (2019a)
Blockchain and Internet of Things	• Providing a model to show the possibility of integrating Blockchain into IoT and highlighting the potentials of this integration. • Further with the mentioned model, the authors present a detailed list of blockchain usages in different sectors. Moreover, authors underpin the new concepts of chain of things, and blockchain of things.	Reyna et al. (2018)
	• Authors articulated a decentralised blockchain based supply chain management model to overcome the current challenges of supply chain. • The proposed Supply chain via blockchain MAS uses the smart contracts into blockchain.	Casado-Vara et al. (2018)
	• Pointing out the benefits of blockchain and IoT to support a shared economy such as Uber. • Presenting examples of shared economy applications such as AutoPay, which is used to pay car parking fee.	Huckle et al. (2016)
Data movement in the Energy sector	• Highlighting the potential benefits of using blockchain in the energy sector, such as price discovery, logistics, identify customers, reconcile any problem and reporting it. • Presenting a MicroGrid based blockchain to manage and control energy demands.	Andoni et al. (2019)
Generic application of blockchain and smart contracts	• Providing a study map to point out the needed future research to implement blockchain and smart contracts. • The authors concluded (n=16) issues in implementing smart contracts. Therefore, the findings of this paper could be used by researchers and developers to try to find remedies for mentioned problems.	Macrinici et al. (2018)

4. Methodology:

Since, structured literature review is highly recommended to draw a comprehensive understanding about a specific topic, on other words, a literature review should be concept-centric (Webster and Watson, 2002). Langley (1999) states that "review articles may draw from both variance and process research to develop conceptual models to guide future". Thus, the literature review is utilised to define the research gap and explore all possible solutions to approach/fill the revealed gaps, in terms of previous attempts to adopt blockchain (automated payment) in the construction industry, as well as, existing recommendations/directions to exploit the blockchain potential in different industries. (Gregory and Watson, 2008). Afterwards, a conceptual framework will be developed to provide robust solutions regarding implementing smart contracts, in terms of the automated payment, throughout the entire construction delivery stages.

4.1. Development Framework:

The construction process comprises of three main stages, namely; pre-construction, construction, and closeout. Throughout all mentioned stages, there are a huge number of transactions of moving information among project participants, which requires a platform to record all these data, particularly the payment transactions between the owner and non-owner parties. Since BIM became mandatory in the UK, the needed payment platform should be compatible and interoperable with BIM process/applications. The extant literature review demonstrates the blockchain's ability to record the transaction and make it immutable. Therefore, the blockchain is adopted to develop an automated platform to automate the payment between project participants. The mechanism of using this platform is designed to be workable in parallel with the construction stages.

4.2. Pre-construction stage:

Throughout the pre-construction stages, the parties agree upon the project contractual conditions that include the mechanism of payments, retentions, etc. These conditions will be coded in order to be used as a validation data in blockchain platform, the validation process is called consensus mechanism, which is defined as a set of algorithms to ensure the validity of invoked and recorded data on the blockchain network (Baliga, 2017, Cachin and Vukolić, 2017, Wang et al., 2018). As critically discussed in the literature review, permissioned blockchain must fits with the construction context due to its ability to limit the adversarial consequences of general blockchain, such as the privacy, private membership and legality of the network, accordingly, a privileged party should be appointed to allocate the responsibilities and roles during using the blockchain platform (i.e. data sender and receiver). Thereafter, the consensus mechanism should be agreed by all parties before deploying the blockchain (construction process). Since the permissioned blockchain has pre-defined counterparts, which requires an automated consensus mechanism, this mechanism should include a quantified data that can work as validation points to automate the consensus mechanism. Once the construction process begins, the blockchain developer can deploy it, and it can be used to share the information, particularly the payment data. BIM can play a significant role in this stage through providing the proposed prices for each package (5D BIM) and linking these prices to the timeline (4D BIM) in order to provide constant payment milestones for all non-owner parties.

4.3. Construction stage

During the construction process, the privileged party could start to assign who is the data sender/receiver at each payment milestone. Similar to the conventional financial system in the construction industry, the contractor works as a data sender (i.e. invoice), and the client representative could be the data receiver. Therefore, the endorsement policy should include the client and architect as the main endorser for any invoked transaction, and this should be listed in the generic endorsement policy (i.e. Hyperledger fabric's consensus mechanism relies on two stages to validate the transaction, first is the endorsement policy that includes who should accept the transaction, and the second stage is the data-blocks allocation through specific channel as described in the theoretical background section). The agreed consensus mechanism will be applied to each block (transaction) automatically, to check its validity based on agreed terms and conditions, such as payment timeline and maximum value of each invoice. Therefore, once the transaction is validated, the data will be sent to the parties' ledger. On the contrary, if the sent data is invalid (whether by the consensus mechanism or the receiver) the privileged person (voter) check the nature of the transaction and explore the source of invalidity, subsequently, insert the transaction again as a new block, which should meet all consensus criteria and pass through the same process. One of the most important advantage of blockchain is the internal validation amongst blocks themselves, that enable automated checking of the sequence of payments between all parties. For instance, one party could act as a data sender for several times during the construction process, so all recorded transactions could be identified and check each other, so not to exceed the maximum value of the contract and inform the parties about any significant cost overrun for any party.

Concerning BIM role in the construction stage with blockchain, the contractor (Data sender) should check the production output against planned (4D and 5D BIM) to prepare the invoice values and obtain the deserved value. Whilst, the client representative uses BIM to check the invoice value. Since all the data are centralised in the federated BIM model, it enables all parties to obtain the same information at the same time.

In permissioned blockchain, the privileged party is able to make some parties silent once their work has been accomplished, and parties can follow the progress of the project from different geographical locations. This confirms the ability of blockchain to support the future of collaborative delivery approaches, such as Integrated Project Delivery (IPD), so that the party is not necessarily available throughout the entire project timeline but can follow all progress through checking all new blocks in the blockchain. The silent parties will be able to check the uploaded data on the Common Data Environment (CDE) to raise the degree of transparency between all parties. As such, the entered data into blockchain could be checked whether using federated BIM model by parties or by the client representative.

4.4. Close out stage

Once the project is completed, the blockchain can play a key role in closeout stage as the inherent issue in preparing the historical cost data for the construction projects. Even though using blockchain enables users to export all recorded data, the client can evaluate all parties' progress throughout the construction process, in order to have a clear vision regarding selecting future parties in new projects. As such, the owner and non-owner parties get several benefits of the final output of blockchain during the close out stage, so that the owner can evaluate other parties and non-owner parties can follow their remaining rights, such as receiving their accumulative retentions, which can be highlighted on the blockchain records to enable detecting the monetary values.

To conclude the mechanism of the proposed framework, it is an automated platform to receive, validate, record and display immutable payments data throughout the entire construction process, once the block becomes valid, it cannot be amended, therefore, all non-owner parties' rights will be kept, which potentially reduces the payment claims. Regarding receiving the remaining rights for non-owner parties after handing the project, such as receiving retention money, the blockchain remains active to send a request based on recorded retention values, and the once the client accepts these values, it will be transferred directly to their accounts. Moreover, the proposed framework enhances the estimation process in the future projects, through providing a reliable historical cost data. As such, the cost data will be sustainable inside the consortium or the business organisation.

4.5. Model interoperability

Figure (1) shows the tasks that should be implemented at each stage. The ordered tasks could facilitate the implementation process; therefore, it can be used as a departure point for the industry user in terms of determining needed resources and capabilities to employ permissioned blockchain. BIM conceptually embedded into the proposed blockchain adoption process in order to build a robust and applicable proposal.

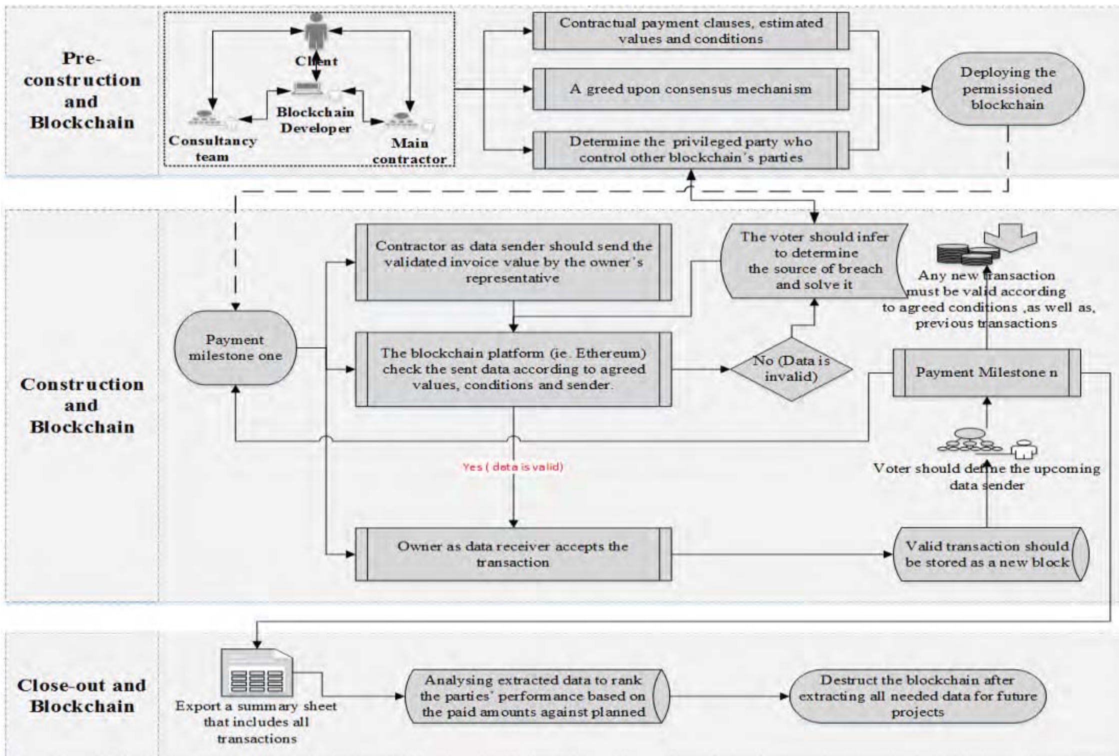

Figure 1. The automated payment conceptual framework

5. Research significance and conclusion

From the literature review survey, the hyperledger fabric is the most suitable blockchain platform to automate the payment through the entire construction delivery stages, that is because; (1) its consensus mechanism is modular that enables project parties to build a consistent mechanism according to the project conditions (Androulaki et al., 2018, Brandenburger et al., 2018, Dhillon et al., 2017), (2) the applicability due to the several cooperation between hyperledger (Linux), IBM, Oracle and SAP, which facilitates its implementation (Van Mölken, 2018, Vukolić, 2016).

Through critical analysis of the previous researches in blockchain within the AEC industry, most of these researches focused on building a theoretical foundation that can be used as a departure point in order to move forward the application, or developing prototypes to validate proposed researchers' themes and conceptual frameworks.

As such, this research is an attempt to draw a realistic application to smart contracts through defining the requirements before the construction stage such as building the consensus mechanism. In addition, the construction stage has been carefully considered within the proposed framework, and the flow of data is highlighted (i.e. who is the data sender and receiver). The closeout stage is not enough investigated regarding financial issues (Kiprotich, 2014), and most claims raised at this stage, thus, the proposed framework includes a list of tasks that should be implemented with smart contracts, whether minimising potential claims, or to be used as a mean to resolve the disputes. This could come to the reality through exploiting the functionality of smart contracts in order to add more functions and to record all types of financial issues (i.e. advanced payments, regular payments and retentions).

References

(ICE), I. O. C. E. 2018. BLOCKCHAIN TECHNOLOGY IN THE CONSTRUCTION INDUSTRY Digital Transformation for High Productivity.

ANDONI, M., ROBU, V., FLYNN, D., ABRAM, S., GEACH, D., JENKINS, D., MCCALLUM, P. & PEACOCK, A. 2019. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable and Sustainable Energy Reviews,* 100**,** 143-174.

ANDROULAKI, E., BARGER, A., BORTNIKOV, V., CACHIN, C., CHRISTIDIS, K., DE CARO, A., ENYEART, D., FERRIS, C., LAVENTMAN, G. & MANEVICH, Y. Year. Hyperledger fabric: a distributed operating system for permissioned blockchains. *In:* Proceedings of the Thirteenth EuroSys Conference, 2018. ACM, 30.

ANDROULAKI, E., CACHIN, C., DE CARO, A., KIND, A. & OSBORNE, M. Year. Cryptography and protocols in hyperledger fabric. *In:* Real-World Cryptography Conference, 2017.

BALIGA, A. 2017. Understanding blockchain consensus models. *Persistent.*

BENHAMOUDA, F., HALEVI, S. & HALEVI, T. Year. Supporting private data on Hyperledger Fabric with secure multiparty computation. *In:* 2018 IEEE International Conference on Cloud Engineering (IC2E), 2018. IEEE, 357-363.

BIMCHAIN. 2018. *Accelerating BIM through the Blockchain* [Online]. Available: https://bimchain.io/ [Accessed 14/04/2019 2019].

BRANDENBURGER, M., CACHIN, C., KAPITZA, R. & SORNIOTTI, A. 2018. Blockchain and trusted computing: Problems, pitfalls, and a solution for hyperledger fabric. *arXiv preprint arXiv:1805.08541*.

CACHIN, C. Year. Architecture of the hyperledger blockchain fabric. *In:* Workshop on distributed cryptocurrencies and consensus ledgers, 2016.

CACHIN, C. & VUKOLIĆ, M. 2017. Blockchain consensus protocols in the wild. *arXiv preprint arXiv:1707.01873*.

CARDEIRA, H. 2015. Smart contracts and their applications in the construction industry. Romanian Construction Law Review.

CARMICHAEL, D. G. & BALATBAT, M. C. 2010. A contractor's analysis of the likelihood of payment of claims. *Journal of Financial Management of Property and Construction,* 15**,** 102-117.

CASADO-VARA, R., PRIETO, J., DE LA PRIETA, F. & CORCHADO, J. M. 2018. How blockchain improves the supply chain: Case study alimentary supply chain. *Procedia computer science,* 134**,** 393-398.

CHRISTIDIS, K. & DEVETSIKIOTIS, M. 2016. Blockchains and smart contracts for the internet of things. *Ieee Access,* 4**,** 2292-2303.

CUCCURU, P. 2017. Beyond bitcoin: an early overview on smart contracts. *International Journal of Law and Information Technology,* 25**,** 179-195.

DHILLON, V., METCALF, D. & HOOPER, M. 2017. The hyperledger project. *Blockchain enabled applications.* Springer.

ELGHAISH, F., ABRISHAMI, S., ABU SAMRA, S., GATERELL, M., HOSSEINI, M. R. & WISE, R. 2019. Cash flow system development framework within integrated project delivery (IPD) using BIM tools. *International Journal of Construction Management*, 1-16.

FOX, S. 2019. *Why construction needs smart contracts* [Online]. https://www.thenbs.com/knowledge/why-construction-needs-smart-contracts. [Accessed 13/04/2019 2019].

GREGORY, A. & WATSON, T. 2008. Defining the gap between research and practice in public relations programme evaluation–towards a new research agenda. *Journal of Marketing Communications,* 14**,** 337-350.

HILDENBRANDT, E., SAXENA, M., ZHU, X., RODRIGUES, N., DAIAN, P., GUTH, D. & ROSU, G. 2017. Kevm: A complete semantics of the ethereum virtual machine.

HUCKLE, S., BHATTACHARYA, R., WHITE, M. & BELOFF, N. 2016. Internet of things, blockchain and shared economy applications. *Procedia computer science,* 98**,** 461-466.

HYPERLEDGER. 2018. *A Blockchain Platform for the Enterprise (Transaction Flow)* [Online]. Available: https://hyperledger-fabric.readthedocs.io/en/release-1.3/txflow.html [Accessed 2019].

KINNAIRD, C., GEIPEL, M. & BEW, M. 2018. Blockchain technology: how the inventions behind bitcoin are enabling a network of trust for the built environment.

KIPROTICH, C. J. K. 2014. *An investigation on Building Information Modelling in Project Management: challenges, strategy and prospects in the Gauteng Construction Industry, South Africa.*

KLAOKLIANG, N., TEAWTIM, P., AIMTONGKHAM, P., SO-IN, C. & NIRUNTASUKRAT, A. Year. A novel IoT authorization architecture on hyperledger fabric with optimal consensus using genetic algorithm. *In:* 2018 Seventh ICT International Student Project Conference (ICT-ISPC), 2018. IEEE, 1-5.

KOUTSOGIANNIS, A. & BERNTSEN, N. 2019. *Blockchain and construction: the how, why and when* [Online]. Available: http://www.bimplus.co.uk/people/blockchain-and-construction-how-why-and-when/ [Accessed 14/04/2019 2019].

LAMB, K. 2018. Blockchain and Smart Contracts: What the AEC sector needs to know.

LANGLEY, A. 1999. Strategies for theorizing from process data. *Academy of Management review,* 24**,** 691-710.

LI, J., GREENWOOD, D. & KASSEM, M. Year. Blockchain in the built environment: analysing current applications and developing an emergent framework. *In*, 2018a. Diamond Congress Ltd.

LI, J., GREENWOOD, D. & KASSEM, M. 2019a. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction,* 102**,** 288-307.

LI, J., GREENWOOD, D. & KASSEM, M. 2019b. Blockchain in the construction sector: a socio-technical systems framework for the construction industry. *Advances in Informatics and Computing in Civil and Construction Engineering.* Springer.

LI, Z., BARENJI, A. V. & HUANG, G. Q. 2018b. Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. *Robotics and Computer-Integrated Manufacturing,* 54**,** 133-144.

LI, Z., KANG, J., YU, R., YE, D., DENG, Q. & ZHANG, Y. 2018c. Consortium blockchain for secure energy trading in industrial internet of things. *IEEE transactions on industrial informatics,* 14**,** 3690-3700.

LIANG, X., SHETTY, S., TOSH, D., KAMHOUA, C., KWIAT, K. & NJILLA, L. Year. Provchain: A blockchain-based data provenance architecture in cloud environment with enhanced privacy and availability. *In:* Proceedings of the 17th IEEE/ACM international symposium on cluster, cloud and grid computing, 2017. IEEE Press, 468-477.

LIU, K., DESAI, H., KAGAL, L. & KANTARCIOGLU, M. 2018. Enforceable Data Sharing Agreements Using Smart Contracts. *arXiv preprint arXiv:1804.10645*.

MACRINICI, D., CARTOFEANU, C. & GAO, S. 2018. Smart contract applications within blockchain technology: A systematic mapping study. *Telematics and Informatics*.

MASON, J. 2017. Intelligent contracts and the construction industry. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction,* 9**,** 04517012.

MASON, J. & ESCOTT, H. Year. Smart contracts in construction: views and perceptions of stakeholders. *In:* Proceedings of FIG Conference, Istanbul May 2018, 2018. FIG.

MATHEWS, M., ROBLES, D. & BOWE, B. 2017. BIM+ blockchain: A solution to the trust problem in collaboration?

NAKASUMI, M. Year. Information sharing for supply chain management based on block chain technology. *In:* 2017 IEEE 19th Conference on Business Informatics (CBI), 2017. IEEE, 140-149.

NOFER, M., GOMBER, P., HINZ, O. & SCHIERECK, D. 2017. Blockchain. *Business & Information Systems Engineering,* 59**,** 183-187.

PETERS, G. W. & PANAYI, E. 2016. Understanding modern banking ledgers through blockchain technologies: Future of transaction processing and smart contracts on the internet of money. *Banking beyond banks and money.* Springer.

REYNA, A., MARTÍN, C., CHEN, J., SOLER, E. & DÍAZ, M. 2018. On blockchain and its integration with IoT. Challenges and opportunities. *Future Generation Computer Systems,* 88**,** 173-190.

SWAN, M. 2015. *Blockchain: Blueprint for a new economy*, " O'Reilly Media, Inc.".

TAPSCOTT, D. & TAPSCOTT, A. 2016. *Blockchain revolution: how the technology behind bitcoin is changing money, business, and the world*, Penguin.

TOZZI, C. 2018. *How Blockchain Innovation Can Help Cost-Efficiency in the Construction Industry* [Online]. Available: https://www.nasdaq.com/article/how-blockchain-innovation-can-help-cost-efficiency-in-the-construction-industry-cm956525 [Accessed 2019 14/04/2019].

TURK, Ž. & KLINC, R. 2017. Potentials of blockchain technology for construction management. *Procedia engineering,* 196**,** 638-645.

VAN MÖLKEN, R. 2018. *Blockchain across Oracle: Understand the details and implications of the Blockchain for Oracle developers and customers*, Packt Publishing Ltd.

VUKOLIĆ, M. 2016. Hyperledger fabric: towards scalable blockchain for business. Tech. rep. Trust in Digital Life 2016. IBM Research, 2016. URl: https://www ….

VUKOLIĆ, M. Year. Rethinking permissioned blockchains. *In:* Proceedings of the ACM Workshop on Blockchain, Cryptocurrencies and Contracts, 2017. ACM, 3-7.

WANG, J., WU, P., WANG, X. & SHOU, W. 2017. The outlook of blockchain technology for construction engineering management. *Frontiers of engineering management,* 4**,** 67-75.

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*.

WATANABE, H., FUJIMURA, S., NAKADAIRA, A., MIYAZAKI, Y., AKUTSU, A. & KISHIGAMI, J. Year. Blockchain contract: Securing a blockchain applied to smart contracts. *In:* 2016 IEEE International Conference on Consumer Electronics (ICCE), 2016. IEEE, 467-468.

WEBSTER, J. & WATSON, R. T. 2002. Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly***,** xiii-xxiii.

WOOD, G. 2014. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum project yellow paper,* 151**,** 1-32.

WÜST, K. & GERVAIS, A. Year. Do you need a Blockchain? *In:* 2018 Crypto Valley Conference on Blockchain Technology (CVCBT), 2018. IEEE, 45-54.

XU, X., WEBER, I., STAPLES, M., ZHU, L., BOSCH, J., BASS, L., PAUTASSO, C. & RIMBA, P. Year. A taxonomy of blockchain-based systems for architecture design. *In:* 2017 IEEE.