A proof of concept of a project bank account (PBA) blockchain payment application for the construction industry

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Declaration

I, Denis Scott, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Denis Jame Scott

London, United Kingdom

25th of March 2025

Contents

Author’s Published and Unpublished Work

Below is a list of five academic papers this dissertation’s author published alongside his research supervisors, written during the four-year duration of his PhD.

Scott, D. J., Broyd, T., & Ma, L. (2020). Archival Study of Blockchain Applications in the Construction Industry From Literature Published in 2019 and 2020. Exploring the mutual role of BIM, Blockchain and IoT in changing the design, construction and operation of built assets, Northumbria University. https://itc.scix.net/paper/ADW-2020-05

Scott, D. J., Broyd, T., & Ma, L. (2021). Exploratory literature review of blockchain in the construction industry. *Automation in Construction*, *132*, 103914. https://doi.org/10.1016/j.autcon.2021.103914

Scott, D. J., Broyd, T., & Ma, L. (2022). Conceptual framework of a Project Bank Account (PBA) blockchain payment application for the construction industry. Proceedings of the European Conference on Computing in Construction, 10.35490/EC3.2022.188

Scott, D. J., Broyd, T., & Ma, L. (2022). Conceptual model utilizing blockchain to automate project bank account (PBA) payments in the construction industry. In *Blockchain for Construction* (1 ed., pp. 141–165). Springer, Singapore. https://doi.org/10.1007/978-981-19-3759-0_8

Scott, D. J., Ma, L., & Broyd, T. (2024). Project bank account (PBA) decentralised application for the construction industry. *Construction Innovation*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/CI-04-2023-0067

Below is a list of two academic papers currently under review.

Scott, D. J., & Broyd, T. (2024). Investigating hosting project bank accounts on the blockchain and its potential value contribution to the construction industry. *Journal of Information Technology in Construction*.

Scott, D. J., & Broyd, T. (2024). Knowledge transfer from computer science to construction: Exploring the technical concerns of using blockchain for payments in the construction industry. *Journal of Information Technology in Construction*.

The UCL research declaration form associated with the author’s published unpublished works is documented in Appendix 1 and Appendix 2 in the Appendices chapter.

Abstract

In 2012, the UK Government created a goal to use project bank accounts (PBAs) to deliver £4 billion worth of public-sector projects by 2015. The ambition of this goal was to restrict main contractors from exercising cash farming and to mitigate the risk of government money being lost when main contractors become insolvent (i.e., when a PBA is used, a project's cash is partitioned from the main contractor's business account; therefore, if the main contractor files for bankruptcy, the project's cash is protected). Cash farming is a strategy contractors use to increase their working capital to invest in large-scale projects, which involves withholding supply chain liabilities. However, this withholding of cash comes at the cost of subcontractors enduring unethical working practices, such as prolonged overdue payments that lead to high levels of insolvencies. This thesis explores the cash flow problem from the technology perspective, particularly whether the programmability of smart contracts and the general-purpose protocol layer of the blockchain (BC) can be used to increase systems integration cash flow automation. This research proposes a PBA BC application and tests its hypothesis through proof of concept. Data is collected from two groups of study participants: (1) construction practitioners with working experience of PBAs and (2) blockchain engineers with technical expertise in BC to validate the proposal from the organisational and technical perspective. The author's PhD studentship was sponsored by a UK main contractor that uses PBAs in most of the construction projects they deliver. Furthermore, this contractor was interested in exploring blockchain as a potential solution to improve their business performance. Therefore, the researcher leveraged the opportunity of extracting construction company insight by engaging in a knowledge-transfer study, by pulling information from industry and presenting it in this thesis. The findings of this thesis suggest: (1) blockchain (BC) and smart contract (SCs) can reduce the management workload of processing PBAs in the current climate; (2) BC and SCs include the potential to democratise PBAs across a broader percentage of supply chain tiers, (3) a BC-based PBA can be set-up within a day (as opposed to weeks using normal banking procedures), and finally, (4) BC provides a trusted data layer for improving the granularity and traceability of cash flow in payment performance reports.

Impact Statement

Throughout the duration of this four-year research program, Denis (author of this thesis) was the senior author of five scholarly publications on the topical area of this research. He published those articles with his principal and secondary research supervisors at UCL. Extracts from those articles were used in this dissertation. Furthermore, during this research, Denis presented his work at three conferences in Switzerland, Greece, and China, and attended many academic workshops that expanded his knowledge in the research field of construction technology, and allowed him to network and exchange ideas with scholars from various international universities. Throughout his time as a researcher, Denis also participated as a candidate in questionnaires, interviews, and focus groups as part of the data collection of other PhD students.

From an academic perspective, Denis's research method included a knowledge-transfer study which extracted critical insight from computer scientists and software engineers, which brought new ideas and concepts into construction research. Since Denis's research was focused on applications of technologies in construction, extracting insights from other, more technical subject areas was valuable in expanding the knowledge base of construction technology research.

Furthermore, Denis's research method also included collecting data from industry by working directly with a construction main contractor who was interested in exploring his ideas. He participated in industry meetings and provided technology consultancy to the main contractor in exchange for having crucial access to their business data and contacts. For example, he was invited to participate in calls with company directors and large public sector clients to discuss ideas on how to leverage new technologies to improve construction performance. This engagement with the industry allowed him to gain insight into the inner workings of how construction companies operate and their appetite for using technology to improve their business workflows. This enabled Denis to think more practically in terms of how technology could be adopted by various tiers of the construction supply chain (e.g., tier-one contractors and tier-two subcontractors). Engagement with industry had a strong influence on the direction of Denis's research, and the technology application he developed and tested in this thesis was in direct response to a problem the main contractor was facing regarding fragmented business processes.

Overall, the data Denis collected from his engagement with industry and his knowledge-transfer study with the computer science subject area provided valuable insight that was lacking in current construction research. In this thesis, he proposed a conceptual framework of a technology application that responds to a problem main contractors face in the existing environment, and gained feedback on the technical issues of developing that application in a practical, real-world context. To test the hypothesis of the framework proposed in this research, Denis developed a test application, simulated it, and presented the work to software engineers and construction practitioners to test its viability as a solution in construction.

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1 Introduction

The construction industry suffers from high data flow fragmentation caused by outdated systems (Jaskula & Papadonikolaki, 2021). This research investigates system fragmentation from the technology perspective and whether blockchain can integrate management flows with cash flows to improve systems integration and workflow automation. This research conducts a proof of concept (PoC) of a blockchain payment application using project bank accounts (PBAs) as its test case. The PBA system investigated in this research is delimited to that of the UK. The UK Government published the PBA guidance document in 2012, instructing the partitioning of project funds into an escrow account to prevent cash farming (i.e., withheld payments) and contractor insolvency risk (UK Cabinet Office, 2012b, p. 2). When a PBA is used in a project, the employer/client would make all project payments to the PBA instead of to the contractor, and the PBA would be used for all liabilities payments to the supply chain (UK Government, 2012a). The proposed PBA blockchain application was tested across two dimensions: (1) organisational and (2) technical to validate its potential for managing PBAs. The proposed application was inspired by and builds upon ideas from existing academic publications to fill research gaps in the topical area of blockchain for cash flow management in construction. Main contractors are disadvantaged when using standard PBAs because they are solely responsible for their set-up, operations, and management; however, it does not provide them with any direct benefits (which will be discussed in greater detail in later chapters). Nevertheless, main contractors are mandated by the UK Government to use PBAs in public sector projects (Biddell, 2015, p. 3). The primary beneficiaries of PBAs are (1) subcontractors due to their payments being processed within 30 days and (2) clients due to them having greater cash flow auditability and contractor insolvency protection. In contrast, supply chain payments in standard, non-PBA projects are typically processed over 30 days late (Cowton & San-Jose, 2021)). Despite the PBA guidance document stipulating that all supply chain tiers are paid from the PBA, the Chapter Five (Data and Analysis) suggested that this was not the reality and that payments to tier-three subcontractors and below are excluded. This is due to the increased workload PBA processes impose on projects (Macaulay, 2019). The proposed application addresses this problem through systems integration and payment automation, with its potential long-term value contribution being PBA democratisation across the entire supply chain and various project types (i.e., using PBAs on private-sector and small projects rather than just large public-sector projects). The immediate benefits of the proposed application to the supply chain are time and cost savings for managing PBAs and faster payment processing.

Research suggests that “fear of reprisal” is the number one factor preventing subcontractors from requesting PBAs in projects, followed by “legal expenses” and “culture” of the industry to resist change (Griffiths et al., 2017, p. 331). Subcontractors are disadvantaged in projects that do not use PBAs due to them not having late payment protection. Research suggests that subcontractors in the UK spend billions annually chasing overdue payments (Swai et al., 2020). This is because PBAs are only used on large public-sector projects rather than all project types. PBAs are the best defence subcontractors have against cash farming (i.e., withheld payments); thus, making PBAs accessible for a more significant percentage of the supply chain would improve payment performance and reduce supply chain insolvencies. Data from the Office for National Statistics, based on figures from 2016 to 2020, suggest that an average of seven construction companies file for bankruptcy daily in the UK (Office For National Statistics, 2016, 2017, 2018, 2019a, 2020). Furthermore, since the 1970s, the UK construction industry has continually maintained pole position for the industry that contributes to the highest levels of insolvencies vs all other industries, averaging 20% of the total insolvent population (Lowe & Moroke, 2010). Furthermore, the two primary suggested causes of insolvencies are (1) lack of project profitability and (2) poor cash flow management (Lowe & Moroke, 2010). PBAs in their current form reduce the main contractor’s project profitability and increase their cash flow management complexity, leading to the partial adoption of PBAs, which this research attempts to mitigate by programming blockchain smart contracts to semi-automate the management of PBAs. The term “semi-automation” was used because project participants are still required to interact with the proposed application to insert data and approve works. Nevertheless, complete automation of PBA cash flows is not achievable in the current climate, and a transition from manual-based to automated must occur in gradations. This research provides a framework, tested through a PoC, demonstrating how PBA workflows can be semi-automated using blockchain and smart contracts.

1.1 Background

This section was organised into three subsections: (1) *Fragmentation*, which summarises the workflow and data fragmentation aspects of construction; (2) *Innovation*, which outlines the current state of digitisation in construction; and (3) *Decentralised Systems*, which overviews decentralisation from the economic and technological spectrum.

1.2 Fragmentation

Construction fragmentation has several dimensions, such as policy (e.g., lack of compliance to payment legislations), process (e.g., siloed construction workflows) and socio-technical (i.e., lack of data and systems interoperability among project parties). In the 1980s, the UK transferred most of its construction and infrastructure projects to the private sector, creating a frenzy of construction companies competing for work (Infrastructure Client Group, 2017, p. 11). Some of the problems this caused was as inadequate addressing of project requirements, over-emphasis on low cost over value, and over-competition between contractors (Infrastructure Client Group, 2017, p. 11). This results in increased process flow fragmentation. Process flow fragmentation is defined by the compartmentalisation of activities, such as when procurement, design, construction management, and payments are performed in isolation and with no collaboration (Riazi et al., 2022). Research from 2021 also suggests that fragmentation in construction remains a significant problem (Brandín & Abrishami, 2021).

The fragmented nature of the construction industry makes it difficult for external authorities to check the standards compliance of construction companies due to the non-standard methods (e.g., scanned copies of paper documents) of recording information (Adel et al., 2022). Unfortunately, the auditing of regulations compliance only becomes a serious matter after a tragic event occurs, such as the Grenfell Tower fire that caused many casualties (Hackitt, 2018, p. 19). In response to that fire, the UK government commissioned the Hackitt report, which identified a severe lack of transparency in health and safety compliance certificates that deemed the building's cladding material and fire escape routes safe for residential occupancy (Hackitt, 2018, p. 5).

Project participants in the construction industry conduct critical day-to-day operations using fragmentary software systems that do not interoperate (Safa et al., 2019). Furthermore, construction over-relies on fragmentary communication channels, such as using e-mail for project-critical document exchanges, resulting in increased data processing delays, errors, and cybersecurity risk (Safa et al., 2019). Despite this, the industry is pushing towards greater data standardisation to reduce systems fragmentation through bodies such as the International Standard Organisation (ISO), BuildingSmart's Industry Foundation Class (IFC), and governmental mandates that enforce BIM (Hargaden et al., 2019b). Nevertheless, despite these, data fragmentation remains widespread in construction management.

The construction industry is known for having bad payment practices, such as overextended periods of delayed payments (Ali, 2006). Furthermore, the industry is still recuperating from the effects of the 2008 financial crisis, which left many construction companies with elevated capital expenditure, increased competition, and greater exposure to economic uncertainty (Purnus & Bodea, 2016). Commercial solutions to mitigate this include parent-company guarantees and collateral warranties (Cheng et al., 2010). However, these do not address the primary concern of reducing withheld payments. Solving the late payment problem would increase the stability of the industry by increasing cash liquidity (Kenley, 2003, p. 251). Data from the UK Office for National of Statistics (ONS) in 2019 suggests that for every large company in the construction industry, there is an average of 1,000 SMEs (small and medium enterprises) (Office for National Statistics, 2019b). This imbalance creates over-competition and forces subcontractors to accept unfair contractual conditions, such as high-risk work for less pay and protracted payment durations (Gruneberg & Ive, 2000, p. 132).

Across ten years spanning 2011 to 2021, the UK Government published six (four new and two revised) legislations on fair payment practices for the construction industry (Scott et al., 2022b, p. 145). These include the 2011 part two of the Housing Grants Construction and Regeneration Act, which is an amendment, with the original published in 1996 (GovUK, 2011); the 2012 Supply Chain Finance Scheme (UK Government, 2012c); the 2012 Guide to the Implementation of Project Bank Accounts (PBAs) (UK Government, 2012a); the 2013 revised Late Payments of Commercial Debts regulation (UK Government, 2013a); the 2014 Construction Supply Chain

Payment Charter (ConstLeaderCouncil, 2018); and 2021 revised Prompt Payment Code (UK Government, 2021a). Despite this, from 2008 to 2013, the average delay in late payments in construction increased by 22%, while bank lending for construction projects was reduced by 38% (Constructing Excellence, 2019, p. 3). This places small and medium enterprises (SMEs) in a challenging financial position because banks refuse to provide them finance. Obtaining bank finance is the most common approach companies use for increasing cash flow; however, banks are hesitant to offer construction projects competitive rates due to their high-risk profile (Maritz, 2011). This causes construction companies to struggle to obtain the financial services they need to run daily operations efficiently (Offei et al., 2019). Even though the Supply Chain Finance scheme helps subcontractors obtain loans to cover project expenses, the scheme is also available to other industries; thus, it suffers slow processing times (Wu et al., 2019). Governments struggle to enforce payment legislation because compliance auditing is an administratively intensive task (Maritz & Robertson, 2010). For example, the payment performance data published by construction companies are highly private, opaque, prone to errors, and prone to processing delays. Governmental authorities would need to invest more resources into legislation compliance bodies to meet the workload requirement for conducting thorough audits unless a more transparent and traceable system becomes standardised. Bank finance is another solution for improving cash liquidity in construction projects; however, banks charge high fees/rates due to construction being a high-risk industry (Maritz, 2011). Furthermore, bank loans can take many months to approve and process, making them inadequate at mitigating unfair withholding of payments (Wu et al., 2019).

1.2.1 Innovation

The lack of profitability in construction is a primary reason it spends insufficiently on innovation (Oesterreich & Teuteberg, 2016). The lack of innovation in construction is a contributor to projects being 80% over budget and 40% behind schedule; furthermore, productivity in construction has been in slow decline since the 1990s (Agarwal et al., 2016, p. 2). Digital innovation is important for improving efficiencies in the construction industry (Ahad et al., 2020). Other sectors, such as manufacturing, have achieved gradual and measurable improvements year after year for many decades; however, construction continues to lag due to its lack of digitisation (Nawari & Ravindran, 2019b). One article commented how “the built environment industry has not yet embraced new digital technologies” and that “R&D spending in construction runs well behind that of other industries, less than 1% of revenues, versus 3.5% to 4.5% for the auto and aerospace sectors” (Gupta et al., 2020). The construction industry faces the ongoing dilemma of trying to increase innovation while reducing costs (Nawari & Ravindran, 2019b).

The increasing global population has put additional pressure on the construction industry to build more with less whilst in a skills shortage (Woodhead et al., 2018). Skills shortage was also mentioned in the Egan Report as a contributor to poor project performance (Egan, 1998, p. 7). According to Egan, trainees in the construction industry had halved since the 1970s, reducing the ability for technical and managerial knowledge to pass on to the next generation (Egan, 1998, p. 7). Digital reform is required to meet the demands of the modern economy (Kypriotaki et al., 2015). Innovation remains a perpetuating problem despite efforts in digitisation through building information modelling (BIM). While BIM is a construction industry-focused innovation, blockchain developments in other industries are adaptable to construction (Di Giuda et al., 2020, p. 30). This was supported by another researcher who claimed that solutions from other sectors are transferable to construction due to blockchain's general-purpose and multi-sectoral properties (Al-Jaroodi & Mohamed, 2019). For example, the proposed application was created using the codebase templates of a general-purpose decentralised application (Atra, 2019).

The UK construction industry's total revenue was estimated at £325 billion in 2022; furthermore, over the next five years (i.e., 2022 to 2027), it was projected to increase 46% to an estimated £475 billion (Statista Research Department, 2022). Therefore, increasing efficiencies through digitisation have substantial practical implications for contributing to current and future GDP (Wu et al., 2008). Despite the industry’s projected growth, its lack of investment in innovation and aversion to risk/change stagnates its ability to improve performance (Autodesk, 2019, p. 4). For example, the problems, such as poor cash flow management, highlighted in the 1964 Banwell Report continue to persist today (Hardcastle et al., 2003, p. 63). This is one of many factors why construction clients are hesitant to undertake new work (McDermott et al., 2005).

1.2.2 Decentralised Systems

Decentralised systems have existed for many decades before blockchain. For example, a 1967 publication by the American Journal of Economics and Sociology discussed the socio-economic and political problems with centralised management structures and how decentralised systems are frequently overlooked (Winthrop, 1967). Furthermore, according to an economics publication in 2006, decentralised systems are more robust in dealing with adversity because problems are localised to a particular region rather than affecting the entire system (Paganelli, 2006). Late payment is one of the construction industry's most significant problems; however, it is a multifaceted problem that overlaps with several factors, such as economic (cash flow and access to finance), organisational (management structures), policy/political (standards and legislation), and technology. This research focuses on the technology factor, particularly the role decentralised technologies, such as blockchain, can play in providing services/tools to integrate management and cash flow processes in the construction industry, resulting in cost and time savings for payment processing.

Blockchain is the technology that enables triple entry accounting, which allows multiple parties to transact across a shared synchronous ledger. Each transaction is substantiated with a digital signature to provide proof of its authenticity (Grigg, 2005). Blockchain includes several key features, such as decentralised, distributed, and consensus (Chen et al., 2020). A typical public blockchain comprises thousands of computer nodes connected through a decentralised network, and it does not require a central power of authority to manage the system (Foti et al., 2020). Blockchain is a self-sustaining network that rewards users for participating in validating, processing, and reconciling transactions across all computer nodes on the blockchain network (Wang, Chen, et al., 2020). Whenever a transaction is sent to the blockchain, it is placed into a pool of unverified transactions, where they are periodically collected and validated by blockchain miners (computer nodes that process transactions on the blockchain) (Karale & Ranaware, 2019). Blockchain miners use a consensus algorithm to reconcile the correctness of the transactions to ensure that only one version of the ledger exists at any moment (Hribernik et al., 2020). Bitcoin was the first blockchain and came into existence in 2009; since then, its protocol has proved immutable to hacks and has not suffered accounting errors, such as double spending (Perera et al., 2020). Ethereum was the second blockchain to come into existence, which emerged in 2015 and introduced smart contracts, allowing transacting parties to codify and deploy peer-to-peer agreements without relying on a trusted third party (Han et al., 2020). Smart contracts are unique because their codified terms and conditions cannot be changed once deployed, mitigating users unfairly withdrawing from signed agreements (Ye & König, 2021). Smart contracts also prevent external entities from interfering with peer-to-peer agreements or charging service fees for escrows. The codified terms of smart contracts are transparent and open for auditing, allowing transacting parties to audit and verify agreements for consistency.

1.3 Research Gap

Only three academic publications are returned when querying the Scopus and Web of Science databases for “blockchain” “and” “project bank accounts”. From these, Li et al., (2019) published a systematic review assessing the potential of using blockchain for PBAs. Ahmadisheykhsarmast & Sonmez (2020) provided an alternative to PBAs, whereby the client’s project payments get frozen in a smart contract one month before liabilities are due. Lastly, Tezel (2021) presented a blockchain application; however, it lacked sophistication in terms of adapting to project variations and change orders, and the system did not consider how various project participants, such as the client, project manager, and main contractor would interact with the application to perform user-specific tasks (Tezel et al., 2021). This research builds upon these earlier works by developing the proposed PBA blockchain application that uses smart contracts to integrate various construction management and PBA systems, such as interoperating cash flow scheduling, approvals, and executions. The research is significant because the UK Government mandates the use of PBAs in public-sector work (Abrahams, 2019). The research’s data collection was structured into two parts: (1) Since main contractors are solely responsible for setting up and managing PBAs, they were targeted for the organisational aspect of the data collection; and (2) since blockchain applications are built and maintained by blockchain engineers, they were targeted for the technical aspect of the data collection.

1.4 Research Aim and Questions

Existing literature suggests that PBAs suffer from improper adoption due to the additional workload they impose on main contractors. PBAs are also hampered by the same technological challenges of construction projects: System fragmentation that causes unnecessary data duplication and lack of process flow automation. The research aim is to thoroughly investigate, through a proof of concept (PoC), whether the cited benefits of blockchain and smart contracts, such as disintermediation, programmability, and automation, can contribute to mitigating the abovementioned problems concerning the management and operations of PBAs. To test the PoC, the author proposed a PBA blockchain application and proposed an application readiness (ARL) scale for analysing its maturity for commercial adoption. Commercial adoption is beyond the scope of this research, but the ARL scale provides context to its developmental stage in conjunction with other developmental stages the application would need to pass through to achieve commercial adoption. Based on the abovementioned, the research questions were devised around developing a PBA blockchain application, collecting data to verify the results of the PoC, and analysing its maturity. With this in mind, this thesis is structured around answering the following research questions (RQs):

1. How can a blockchain application improve the delivery of PBAs through systems integration and process flow automation, and how would end-users interact with the system?
2. By collecting data from construction practitioners experienced in PBAs, what are the potential advantages and disadvantages of using blockchain and smart contracts for managing PBAs?
3. By collecting data from blockchain engineers experienced in developing decentralised applications, what are the technical challenges for developing the proposed application further?
4. Through analysing the data collection, how mature is the proposed application for commercial adoption in the construction industry?

Chapter Six (Discussion) evaluated the research findings in greater detail in conjunction with how the RQs were answered.

1.5 Significance

Blockchain is investigated in construction research on whether it can provide the infrastructure that enables better data interoperability between various software systems (Elghaish et al., 2021). Processing payments is administratively time-consuming because it requires data entry tasks from multiple parties using siloed software (Swai & Arewa, 2018). Furthermore, communication between these parties typically occurs over fragmented communication channels such as phone and e-mail (Wu, Zhang, et al., 2022). Better integration between users and technology systems is required to improve cash flow management performance in construction (Kochovski & Stankovski, 2021). Current software systems struggle with data integration because of how centralised technology companies are built, whereby each provider privatises their codebase to maintain competitive advantage (Hargaden et al., 2019a). This makes systems interoperability between competing technology companies complex and resourcefully costly due to the extensive middleware and APIs (application programming interfaces) required to bridge centralised systems (Hargaden et al., 2019a). A more specific example from the construction industry includes how users of BIM software require IFC to convert 3-D models from one software to another (e.g., from Revit to ArchiCAD); however, substantial model intelligence is lost even when using IFC (Xue & Lu, 2020). A general-purpose data layer is one method to improve data interoperability between fragmented systems (Berglund et al., 2020). The open-source, permissionless/unrestricted, and decentralised properties of blockchain make it a suitable technology to explore as a general-purpose data layer (Berglund et al., 2020). The blockchain operates with a more economical model than centralised technologies companies because it does not incur typical business expenses, such as employee wages (technically, all of the blockchain's developers contribute voluntarily), building leases, and stakeholder dividends; instead, it uses a crypto-economic system (i.e., mining/staking) to incentivise external parties to maintain its ledger, and developers cooperatively maintain its protocol for individual and mutual benefit (Gurgun et al., 2022). Due to its open-source and decentralised nature, it cannot impose proprietary fees or restrict user access (Veuger, 2018). The only fees associated with the blockchain are those charged by the blockchain miners/stakers (computer nodes that process transactions) running the consensus algorithm that validates transactions (Coyne & Onabolu, 2017). However, these blockchain miners are self-governed entities whose fees are algorithmically calculated based on network demand; furthermore, they are not owned by the blockchain and do not pay commissions on their earnings (Coyne & Onabolu, 2017). Blockchain is a public asset that anyone can utilise to build and deploy apps without intellectual property or technology license restrictions; thus, it is a popular choice for software developers who want to exploit its free protocol infrastructure (Tezel et al., 2020).

Regarding the contribution of this research, blockchain for payments has been explored extensively; however, aside from the author's own publications on blockchain for PBAs (i.e., (Scott & Broyd, 2024; Scott et al., 2022b; Scott et al., 2024)) only one other research article by Tezel et al., (2021) proposed a conceptual framework of a PBA blockchain application; however, the work by Tezel lacked functionality in terms of how it would adapt to project change orders, and how various payment approvers, such as the client, main contractor, quantity surveyor, and PBA manager, can collectively interact with Tezel's PBA application to control the flow of cash from the PBA to the PBA payment recipients. The author's proposed PBA blockchain application carefully considered how crucial PBA processes, such as incorporating the PBA trust deed, are included in the proposed application to ensure it closely aligns with the UK Government's PBA strategy. Aside from the publication by Tezel et al. (2021), section *2.6: Related Works* of Chapter *2: Literature Review* presents 12 other publications that proposed a conceptual framework of a blockchain payment application; however, those 12 publications covered construction payment more generally instead of targeting a specific payment strategy used in the UK construction industry. The UK Government have mandated the use of PBAs on public sector projects, and public sector clients, such as National Highways, use PBAs on all their government contracts (Abrahams, 2019). This research provides evidence for how PBAs are not used effectively in UK construction and provides solutions for potentially mitigating its challenges through using a more automated approach. Therefore, this research has strong practical implications by directing its attention to a payment system enforced by the UK Government and adopted by UK public sector clients.

1.6 Structure

The structure of this research was organised into seven chapters. The Introduction chapter is omitted from this section because it has already been discussed above. Therefore, an outline of chapters two to seven is listed below.

Chapter Two: ***Literature Review***: This chapter is structured into five sections: (1) *Cash flow and payments*, highlighting the cash flow problems of construction; (2) *government payment legislations*, discussing payment legislations that exist alongside

PBAs; (3) *blockchain*, providing a summary of blockchain, smart contracts, escrows, and cryptography; (4) *systematic review of blockchain in construction*, analyses the expansion of the topical area using descriptive statistics and scientometrics, and qualitatively reviews application categories of blockchain in construction; (5) *related works*, examines several blockchain test apps from existing literature that overlap with the proposed application's framework, regarding using blockchain and smart contracts for cash flow management in construction.

Chapter Three: ***Methodology**:* This chapter was organised into five sections: (1) *philosophy*, comparing the key research philosophies, such as positivism, interpretivism, critical realism, and pragmatism, and identifying which of these best fits the research questions; (2) *approach*, classifying whether the research took an inductive, deductive, or abductive approach; (3) *methodological choice*, regarding whether the research is qualitative, quantitative, mixed methods, or multi-method; (4) *strategy*, discussing which theoretical framework, model, or guideline was used for collecting the data; and finally (5) *data collection*, highlighting which data collection type was used, sample sizes, and analysis method.

Chapter Four: ***Conceptual Framework**:* This chapter is structured into six sections: (1) *blockchain selection*, discussing the decision process for choosing which blockchain was most appropriate for the study; (2) *technology setup*, highlighting the platforms, tools, and Web services that combine to create the proposed application; (3) *process flow,* illustrating how project participants would interact with the technology components to perform project management tasks; (4) *user interface*, displaying screenshots of the proposed application's user interface; (5) *cost*, showcasing all cost associated with deploying and operating the proposed application for an estimated one-year project duration; and finally (6) *codebase*, displaying the open-source codebase of all deployed smart contracts, allowing for external replicability.

Chapter Five: ***Data and Analysis**:* This chapter is organised into two sections relating to the two types of data collected: (1) *focus group,* presenting the focus group interview data from construction practitioners experienced in PBAs, and (2) *questionnaire*, showcasing the questionnaire responses from the blockchain engineers regarding the technical aspect of decentralised application development for the enterprise environment.

Chapter Six: ***Discussion****:* This chapter is structured into four sections: (1) *the framework*, which evaluates the decision points that led to the development of the proposed application; (2) *the findings,* which amalgamates, analyses, and discusses the findings of the focus group interview and questionnaire; (3) *improvement proposals*, filtering the findings for suggestions on how to improve the proposed application; and finally, (4) *key findings*, summarising the primary points of discussion.

Chapter Seven: ***Conclusion****:* This section is organised into four sections: (1) *summary of the findings*, providing an overview of the findings discussed; (2) *contribution*, outlining how the research contributes to the topical area and addresses gaps in the existing literature; (3) *limitations*, highlighting the primary research limitations, such as how the research could not benefit from a longitudinal study despite it using a multi-stage validation process, and how quantitative data collection was not used to substantiate the findings due to the exploratory nature of the research; and finally (4) *further work*, outlining the next steps required for transitioning the PoC into an industry pilot with construction companies, and strategies for how this could be achieved.

2 Literature Review

The literature first examines the cash flow and payment culture of the construction industry and the reasons why late payments are frequently exercised in projects; furthermore, it reviews the state of construction contracts and how they affect the supply chain. Afterwards, government payment legislation associated with improving cash flow is presented to provide context to the legislative environment surrounding PBAs. After that, the blockchain is reviewed, investigating its primary components, such as its protocol, consensus algorithm, and smart contracts. Afterwards, a systematic review of blockchain in construction identified 121 academic documents related to the topical area and uncovered 33 application categories for construction. Of the 121 reviewed literature, 13 related works were selected that overlap with the research's vision of deploying a blockchain test application for managing payments.

2.1 Cash Flow and Payments

Bad payment practices in the construction industry are documented in literature as early as the 1964 Banwell report, formally titled "The Placing and Management of Contracts for Building and Civil Engineering Work" (Hardcastle et al., 2003, p. 55). The Banwell Report stated that the method by which cash cascades down each tier of the supply chain is a significant contributor to late payments and advocated for reform in how construction contracts are managed (Hardcastle et al., 2003, pp. 63-64). Banwell highlighted the importance of prompt payments and how they should not be affected by administrative procedures or workflow fragmentation; furthermore, he discouraged open tender approaches to procurement because it leads to underqualified contractors winning work, which inadvertently causes cost escalations and programme delays later in a project (Hardcastle et al., 2003, p. 64). Twenty-nine years after the Banwell report, and in response to its concerns regarding contract and cash flow management, the first edition of the UK New Engineering Contract (NEC) was published in 1993. NEC was also endorsed in the 1994 Latham report as the best way to increase contract standardisation to reduce project complexity and improve cash flow management (Latham, 1994, p. 42). The Latham report (1994, p. 37) discoursed several methods for improving cash flow in construction, such as (1) frequent interim payments for subcontractors, (2) chargeable interest for overdue payments, (3) payment provisions for main contractors and subcontractors to cover material costs, and (4) rules for fairly managing payments throughout disputes.

The construction industry’s supply chain is extensive, with each participant bound to various agreements, roles, and responsibilities (Luo et al., 2019). Management becomes unnecessarily challenging when contract conditions are ambiguously defined; furthermore, opportunistic behaviours are exercised in contract drafting to manipulate agreements to benefit tier-one contractors (Luo et al., 2019). A healthy supply chain depends on fair and timely payments for delivered works; however, due to the normalisation of unethical payment practices, fair payment terms and adherence to them remains an ongoing challenge and is one of the industry’s biggest problems (Vadgama, 2019, p. 47). The lack of prompt payments results in elevated project risk because payees are in a perpetuating state of financial uncertainty (Ahmadisheykhsarmast & Sonmez, 2020). Research on the construction industry of the UK, Malaysia, and Sri Lanka suggests that the primary party to blame for late payments is the main contractor because they use the project’s funds to artificially prop internal cash flow, invest in new work, and pay outstanding debts in other projects (Azman et al., 2014; Francis et al., 2022; Swai et al., 2020). In a study comprising 20 main contractors and subcontractors in the Sri Lanka construction industry, 90% stated that late payments most frequently occurred in public sector projects (Francis et al., 2016). A justification main contractors use for delaying payments is that they receive the same service from clients (Francis et al., 2016). Although government legislation stipulates maximum payment terms of 30 days (e.g., the UK Prompt Payment Code (Cowton & San-Jose, 2021)), they have done little to minimise the harmful effects of overdue payments (Abdul-Rahman et al., 2009). The industry’s culture has normalised late payments as an acceptable by-product of contract delivery (Francis et al., 2016). A survey was conducted with 100 participants in the Malaysian construction industry, which identified that companies expect and tolerate late payments as part of their standard working culture (Azman et al., 2014). *Normalisation deviance* is the term given when bad working practices are exercised regularly over many years and become normalised, causing people to overlook its damaging effects (Vaughan, 1996, p. 153). Another reason main contractors delay payments is that clients have a reputation for altering the project scope late in a project, sometimes even at the construction stage (Abdul-Rahman et al., 2009). This increases project costs because contractors are forced to procure new materials, equipment, and labour at short timescales (Abdul-Rahman et al., 2009). Thus, contractors delay cash outflows to their supply chain to cover unpredictable increases in capital expenditures brought by the client (Abdul-Rahman et al., 2009). Furthermore, it creates a working culture where main contractors internally standardise the withholding of supply chain payments because of tight margins and the fear of financial uncertainty, frequently leaving subcontractors with over-extended periods of partial payment and non-payment (Francis et al., 2016).

The construction industry is dominated by a small selection of large companies that enforce unfair contract conditions (e.g., overextended payment terms) to small and medium enterprises (SMEs), which creates over-competition among SMEs while granting main contractors the power to exercise opportunistic behaviours; furthermore, it forces subcontractors to accept high-risk work for less pay because of unsustainable levels of competition (Gruneberg & Ive, 2000, p. 132). Current contractual processes in construction are unsupportive for safeguarding project funds; furthermore, upper-tier contractors frequently abuse contract clauses, which leads to elevated project risk (Motawa & Kaka, 2009). SMEs are forced to accept unfair contractual conditions with overextended payment terms due to the hierarchical nature of the industry. This comprises contractors exercising cash farming techniques (Kenley, 2003, p. 234). Cash farming is a strategy implemented by contractors to improve internal cash flow at the cost of delayed payments to their supply chain (Gyles et al., 1992). However, cash farming starves the downstream supply chain of the cash they need for survival (Lowe & Moroke, 2010). In a cross-industry survey by the UK's Office for National Statistics (ONS) on company insolvency rates from 2016 to 2020, 20% (2411 number) are credited to the construction industry (Office For National Statistics, 2016, 2017, 2018, 2019a, 2020). This translates to an average of seven construction companies filing for bankruptcy daily in the UK (Office For National Statistics, 2016, 2017, 2018, 2019a, 2020). The data was further supported by academic research suggesting that since the 1970s, construction companies in the UK have occupied an average of 20% of the total insolvent population (Lowe & Moroke, 2010). The two suggested leading causes of insolvencies are (1) lack of project profitability and (2) poor cash flow management (Lowe & Moroke, 2010). Statistics on construction companies in the UK show that 99.84% (182,155 number) are SMEs, whereas only 0.16% (300 number) are large enterprises (Clark, 2021). Therefore, a high majority of insolvencies are suffered by SMEs. An SME (small and medium enterprise) is a company with between 1 and 249 employees, whereas 250 or more is considered a large enterprise (Clark, 2021).

The danger of bad cash flow management is exemplified by the demise of Carillion, the UK's second-largest construction company in 2017 (based on turnover) (Hajikazemi et al., 2020). Carillion went into liquidation in 2018 with a debt of £7.1 billion, which directly affected over 30,000 stakeholders and businesses, consisting of subcontractors, employees, pensioners, shareholders, joint venture partners, and worldwide customers (Hajikazemi et al., 2020). £1.3 billion of the £7.1 billion debt was owed to SMEs for unpaid work (Thurley et al., 2018). Carillion took advantage of their superior position as a main contractor and imposed payment terms of 120 days to SMEs, which is four times the duration of what is typically agreed upon in UK construction contracts (Hajikazemi et al., 2020). In 2016 (two years before Carillion's collapse), the unethical practices of Carillion were protested by the Federation of Small Businesses in the UK, which stated that subcontractors were waiting over 120 days to receive payments (Hajikazemi et al., 2020). Despite the warning signs and strong evidence of unethical business practices, Carillion's dominating presence in UK construction enabled them to persist in exercising opportunistic and unethical behaviours (Hajikazemi et al., 2020).

When construction companies operate on tight margins, they regularly have insufficient staff to cope with workloads, which leads to resources being unfairly concentrated on projects that contribute to higher profits (Haron & Arazmi, 2020). Tight margins result in main contractors increasing their use of cash farming strategies to improve cash flow (Kenley, 2003, p. 231). Despite the damaging effects of cash farming, books such as 'Financing Construction: Cash Flows and Cash Farming' by Kenley (2003), were written to inform contractors on how to implement cash farming effectively. Nevertheless, the growing disdain and harmful effects of cash farming led to the UK Government publishing the project bank account (PBA) payment strategy to prevent it (Biddell, 2015, p. 4). In addition to PBA, the government published the revised prompt payment code in 2021, which stipulates maximum payment terms of 30 days (UK Government, 2021b). Similarly, the construction supply chain payment charter was also published in 2014, which made it compulsory for companies to pay their supply chain within 30 days (Construction Leadership Council, 2016, pp. 1-2). However, despite these legislations, little is done to audit their adoption; thus, main contractors continue to exercise opportunistic behaviours in contract management (Hajikazemi et al., 2020).

Project delays and cost increases are inextricably connected (Adams, 2008). The entire supply chain is affected by late payments when project delays occur (Akintoye et al., 2011). This leads to disputes that cause further delays and unnecessary expense of time and money to manage the dispute resolution process (Akintoye et al., 2011). In a typical construction contract, main contractors customise contract clauses to protect themselves against legal disputes, giving them an unfair advantage when disputes arise (Theodore, 2009). Dispute resolution in the construction industry is typically managed through adjudication, a lightweight process that involves an impartial third party managing the disagreement between the parties (Goodman Derrick LLP, 2016). However, in the event of an unsatisfactory settlement, large companies can enforce litigations, a costlier method of dispute resolution, placing SMEs at a disadvantage because payments remain withheld until a court settlement is agreed upon, which can take over 12 months to process (Goodman Derrick LLP), 2016. The low working capital of subcontractors forces them to accept unfair dispute resolution settlements, which main contractors strategically exploit (Chan, 2015). Countries such as France and Australia include regulations allowing SMEs to request overdue payments directly from the client; furthermore, Japan includes severe governmentally enforced penalties for construction companies that impose unfair payment terms (Greenwood, 2020). Although the UK Government's Housing Grants Construction and Regeneration Act provides adjudication (an alternative dispute resolution system that reduces the dispute process to 28 days), the appointed adjudicator does not have the legal authority to enforce their final decision (Ndekugri & Russell, 2005). Nevertheless, adjudication does provides the subcontractor a legal right to suspend work.

2.2 UK Government Payment Legislations

Below is a list of the five most relevant payment legislations in the UK construction industry, organised according to their publication year.

1. **2021 - Revised prompt payment code (initially published in 2008):** The UK Government revised the prompt payment code to reduce payment terms from 60 to 30 days; however, according to them: “despite almost 3,000 companies signing the code, poor payment practices are still rife, with many payments delayed well beyond the current target” (UK Government, 2021b). Furthermore, the UK government commented, "Currently, £23.4 billion worth of late invoices are owed to firms across Britain, impacting businesses’ cash flow and ultimate survival” (UK Government, 2021b).

2. **2013 - Revised late payments of commercial debts regulation (initially published in 1998):** Published by the UK *Department for Business, Innovation and Skills*. This legislation allows subcontractors to charge statutory interest on invoices 30 days overdue (UK Government, 2013b, pp. 1-2). However, the legislation requires intermediaries in the form of judiciary authorities that authorise the validity of claims, which causes processing delays (Hetherton & Charlson, 2015). Although supply chain parties can charge interest, there is no guarantee of payments because tier-one employers can dispute the claim in court, and subcontractors do not have the capital to withstand outdrawn legal proceedings.

3. **2012 - Supply chain finance scheme:** This allows the subcontractors to more easily obtain bank loans if they can provide signed proof that their upper-tier contractor has approved their invoices (UK Government, 2012b). Subcontractors qualify for the loan when their main contractor cannot satisfy liabilities (Gelsomino et al., 2019). There are several variations to supply chain finance; however, the most common variant used in the construction industry is reverse factoring, which is a contract clause that allows the subcontractors to request liabilities earlier than the payment due date if their works are verified as complete (Wu et al., 2019). In reverse factoring, the bank provides payment to the subcontractors on behalf of their client, and the client repays the bank (effectively, reverse factoring is a loan between the client and the bank, but the subcontractors triggers it when they request early payment).

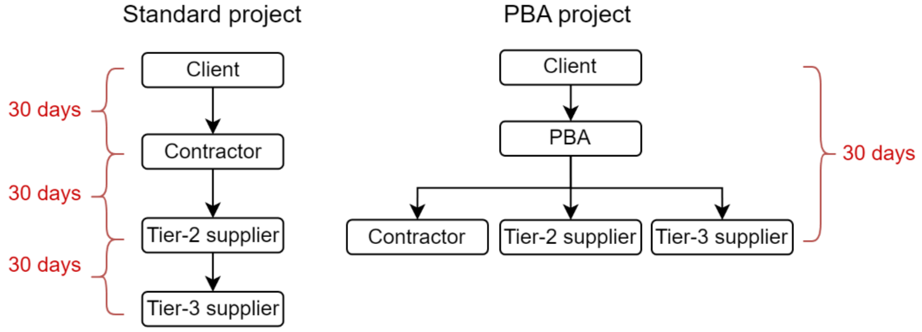
4. **2012 - A Guide to Implementing Project Bank Accounts (PBAs):** Published in 2012 by the UK Government’s *Cabinet Office* (UK Government, 2012a). PBAs use a ring-fenced bank account for managing project cash inflows from the client and

cash outflows to the supply chain (Abrahams, 2019). PBA differs from the traditional payment system because the client sends project payments to the PBA rather than the main contractor (Ahmadisheykhsarmast & Sonmez, 2020). This prevents the main contractor from exercising cash farming (i.e., withheld payments) (Lord et al., 2010). PBA stipulates maximum payment terms of 30 days from the client to the lowest tier supply chain (UK Government, 2012a)

5. **2011 - Part 2 of the Housing Grants Construction and Regeneration Act 1996:** This Act was originally published in 1996 (UK Parliament, 1996). A UK Government Act is a legislative bill approved by the UK House of Parliament (Carnell, 1996). The Housing Grants Construction and Regeneration Act (also called the Construction Act) provides an alternative dispute-resolution system, called adjudication, that bypasses traditional methods such as mediation, arbitration, and litigation (Ndekugri et al., 2022). Adjudication is managed by a governing body that appoints adjudicators to manage construction disputes (Ndekugri et al., 2022). Adjudication stipulates a resolution period of 28 days; however, in complicated cases, the duration is known to protract to several months (Redmon, 2009). In contrast, litigation and arbitration can take years to process because of their formality with judicial proceedings (Dancaster, 2008).

The first conceptualisation of a trust/escrow account similar to PBAs was in the 1994 Latham report (Latham, 1994, p. 94). The Latham report proposed using two trust accounts for each project: the first trust account would be used for payments between the client and main contractor, and the second trust account would be used for payments between the client and subcontractors; however, Latham admittedly expressed the complications of the client making direct payments to subcontractors because it overlaps with the main contractor’s responsibility (Latham, 1994, pp. 94-95). PBAs simplified Latham’s view on trust accounts by stipulating only one account (the PBA) for managing all supply chain payments (UK Cabinet Office, 2012a). According to the PBA strategy, all cash inflows from the client to the project are made to the PBA and all cash outflows authorised by the main contractor to the supply chain are made from the PBA (UK Cabinet Office, 2012a). PBA uses a trust deed to manage the permission controls between payers and payees, granting multiple parties debit rights to use the PBA to execute payments (UK Cabinet Office, 2012a).

Figure 1.
Payment structure of a traditional project vs a PBA project.



The first recorded evidence of an escrow/trust account (similar to PBA) used in a construction project was in 2005, comprising a joint venture between Defence Estates (a UK armed forces client) and a UK main contractor (National Audit Office, 2005, p. 73). A project escrow was used because of the construction industry's reputation for being adversarial and the client having a trusting relationship with the subcontractors (National Audit Office, 2005, p. 73). The result was successful, with all payments to subcontractors made on time and within the agreed project budget; furthermore, all expenditures were openly auditable throughout the project (National Audit Office, 2005, p. 73). According to a report published by the UK Office of Government Commerce, clients can save up to 2.5% on public sector projects (UK Office of Government Commerce, 2007). The UK trialled PBAs on public sector projects between 2012 and 2015 and it was used to manage over £4 billion worth of work (UK Cabinet Office, 2012b). In 2013, the government of Northern Ireland, in conjunction with the Central Procurement Directorate, mandated PBAs for construction projects worth over £1 million; similarly, in the same year, Wales mandated PBAs in projects valued at over £2 million (Hooks, 2019). In a questionnaire conducted of 58 supply chain participants at various tiers, "fear of reprisal" was suggested as the number one factor preventing subcontractors from requesting PBAs in projects, followed by "legal expenses" and "culture" of the industry (Griffiths et al., 2017, p. 331). The use of PBAs in existing contract standards such as NEC, JCT, and FIDIC has steadily increased since PBAs were introduced for managing public-sector projects (note, PBAs can be accommodated in these contract standards but their use is optional); however, PBAs are challenging to enforce across all built environment projects due to the uniqueness and complexity of construction contracts (Penzes, 2018, p. 20). Using PBAs reduces cash flow risk by preventing cash farming and cascading payments down each tier of the supply chain; furthermore, it provides SMEs protection against upstream insolvencies due to the partitioning of the project account away from the main contractor's private account (UK Cabinet Office, 2012b, p. 3). The problem with payment legislation (such as PBA) is that the government does not adequately enforce and audit its adoption, thus rendering it only partially effective (Maritz & Robertson, 2010).

A similar variant to PBAs emerged in Canada through the Ontario Construction Lien Act, which discussed using a multi-project banking model (Gowling WLG, 2017). However, the difference is that the Ontario Act uses a partitioned account for executing payments across multiple projects (Reynolds & Vogel, 2016). In the Ontario Act, payment terms are 28 days (similar to PBAs); however, it permits paid-when-paid clauses; therefore, it is prone to delays caused by cascading supply chain payments (Thomas et al., 2011). Furthermore, it suffers from privacy and trust issues because an account manager is appointed to oversee project-sensitive transactions across the entire supply chain of multiple projects (Thomas et al., 2011).

2.3 Blockchain

Distributed ledger technology (DLT) is the umbrella term given to the genre of technology that includes blockchain, which operates through a decentralised ledger and peer-to-peer network (Chen et al., 2020). Blockchain emerged in 2008 through a whitepaper titled "Bitcoin: A Peer-to-Peer Electronic Cash System", authored by a pseudonymous person/entity named Satoshi Nakamoto (Nakamoto, 2008, p. 1). With all the attention directed at Satoshi for the invention of Bitcoin, it would be unfair to forget the official curator of the accounting framework that enables blockchain to operate: triple-entry accounting. Yuri Ijir (1986), an accounting researcher, was the founder of triple-entry accounting, he conceptualised the system as a puzzle for researchers in the mathematics field to solve. However, triple-entry accounting was cryptographically challenging to design and did not have practical use until the emergence of blockchain (Jeffries, 2020; Nimfuehr, 2018). Triple-entry accounting is when a global ledger stores signatures/proofs of all transactions between all transacting parties to mitigate reconciliation conflicts (Ijir, 1986). As a point of reference, double-entry accounting is the most popular and standardised form of accounting system used globally, and its functionality has remained unchanged since its invention in the Middle East in the 11th century (Penzes, 2018, p. 12). The advent of technology has enabled double-entry accounting to be used optimally with scale (Penzes, 2018, p. 12). Double-entry accounting is simply the recording of credits and debits from a ledger (i.e., cash inflows and outflows), and each person/company is responsible for managing and updating their ledger (Penzes, 2018, p. 12). Organisations spend vast resources on the reconciliation and cybersecurity of double-entry ledgers (Hearn & Brown, 2019, p. 4). Blockchain makes reconciliation more efficient because it uses a global shared ledger to record transactions, making each transaction immutable and transparent (Nakamoto, 2008). Despite everyone on the blockchain sharing the same ledger, privacy tools are available that enable private transactions (Banerjee et al., 2020). Updating current systems to accommodate blockchain is challenging because existing financial infrastructure is heavily entrenched with double-entry accounting technologies (Ijir, 1986). Nevertheless, institutions such as J.P. Morgan and Bank of America have begun using an internal private blockchain to reduce costs associated with reconciliation and auditing (Ullah et al., 2022).

The terms ‘block’ and ‘chain’ derive from a sequence of miniature ledgers linked and secured by cryptography (Tezel et al., 2019, p. 2). In terms of their accessibility, there are two main types of blockchains: public and private (Das et al., 2020). Public blockchains allow anyone to join the network (Bhushan et al., 2020). In contrast, private blockchains are invite-only (Bai et al., 2019). Each blockchain has three key characteristics: (1) decentralisation, (2) consensus, and (3) cryptography.

1. Decentralisation refers to how the blockchain’s system (i.e., its codebase and ledger) is distributed across many computer nodes and how its governance system is managed without a central authority (Hunhevicz, Dounas, et al., 2022, p. 7). A blockchain is maintained and updated by its governing council members. Users on the blockchain vote on updates while the governance council append the changes to its protocol (Foti et al., 2020; Kochovski et al., 2019). Each node on the blockchain network holds a replicated and complete copy of its codebase and ledger (McNamara & Sepasgozar, 2020). Blockchain networks that have a higher number of nodes are more decentralised and secure (Tao et al., 2021). Anyone can run a node on a public blockchain;

however, only authorised members can run nodes on private blockchains (Fu & Zhu, 2020).

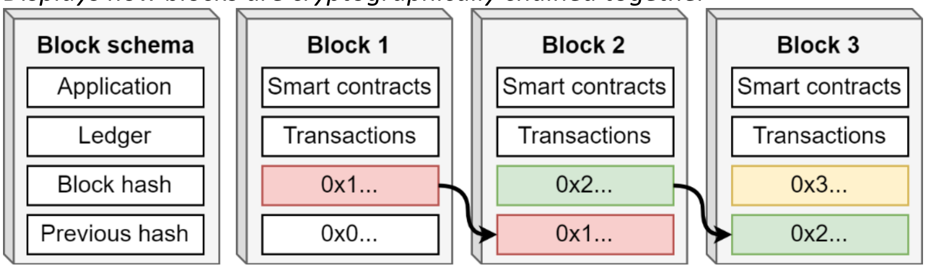
2. Consensus: Whether on a public or private blockchain, the blockchain protocol comprises hard-coded rules to protect how transactions are validated (Dutta et al., 2020). For example, when users send transactions on the blockchain, algorithmic functions are in place that govern which transactions get approved or declined (López & Farooq, 2020). This is the consensus mechanism, and it is expressed as a percentage (Xiong et al., 2019). For example, 51% consensus means that this percentage of the blockchain network's node validators must agree on the validity of a transaction before it can be permanently recorded on the blockchain (Mistry et al., 2020; Singh, Sharma, et al., 2020). A transaction is valid if 51% of the nodes agree on its correctness (Wang, Song, et al., 2020). The consensus mechanism is hard-coded into the blockchain's protocol when the platform is first launched (Sheng et al., 2020). Private blockchains are modular in that their consensus mechanism is configurable and can be altered based on the requirements of a specific application (Dutta et al., 2020). Since private blockchains are substantially smaller than public blockchains, latency is greatly reduced while transaction throughput significantly increases (Perera et al., 2020). For example, public blockchains such as Ethereum can scale up to 15 transactions per second (TPS), whereas private blockchains such as Hyperledger can scale up to several thousand TPS (López & Farooq, 2020). Another crucial differentiating feature is that all identities on a private blockchain are known and trusted, whereas users on a public blockchain are pseudonymous because they can only be known by a randomly generated wallet address (Teisserenc & Sepasgozar, 2022).

3. Cryptography: Cryptography is a primary component of the blockchain (Perera et al., 2020). Each block contains a unique identifier called a hash (Lu et al., 2021). Each block also includes the hash of the previous block in the chain (as per Figure 2), which makes it easy to identify where a block sits within a long chain (van Leeuwen et al., 2020). The hash of a block is algorithmically generated based on the data stored within it; therefore, altering data within a block will autonomously generate a new unique hash (Chen et al., 2020). If a

block hash changes due to data manipulation, the successive block in the chain will identify the change and break the chain (Tezel et al., 2021). Breaks in the chain do not damage the blockchain because a copy of the ledger is stored on all network nodes (Veuger, 2018). All nodes of a blockchain store the same version of the ledger, mitigating malicious actors from attempting to hack it (Nakamoto, 2008). If a malicious actor tries to hack the blockchain by editing transactions in a previous block; it will not be possible because all nodes on the network use the consensus mechanism to verify which version is correct (Li & Kassem, 2021). For example, Bitcoin has amassed a cumulative total of 15,785 nodes, and changing a previous record would require taking control of 51% of the network, which is 8,051 nodes (Bitnodes, 2022).

The below Figure 2 is read in conjunction with point 3 above, which discussed how blockchain blocks are cryptographically chained together.

Figure 2.
Displays how blocks are cryptographically chained together



A public blockchain is governed bottom-up and is permissionless, allowing anyone to participate in the network or contribute to developing its ecosystem (Lu et al., 2021). In contrast, a private blockchain is governed by a preselected group of participants. Since no party or organisation owns the blockchain, it relies on a crypto-economic model called mining/staking to incentivise users to maintain the network (Hunhevicz & Hall, 2020). Blockchain miners/stakers (computer nodes that process transactions) are financially rewarded for storing a full copy of the blockchain ledger and running the consensus algorithm that validates transactions (Dutta et al., 2020). When transactions are validated, they are packed into a container called a block, which is then uploaded to the blockchain for permanent storage (Dutta et al., 2020). Blockchain is a general-purpose technology that is malleable for various functions; hence, it can be configured to manage construction data (Kifokeris & Koch, 2020).

Despite advances in digitisation in the modern economy, managing financial data (e.g., reconciliation and auditing) is unnecessarily time-consuming and manual-driven due to outdated systems (Hamledari & Fischer, 2021d). Assets, such as bonds, securities, properties, and mortgages, are typically represented by electronic paper documents; however, no one system enables these asset classes to be exchanged under one platform (Gaur et al., 2019, p. 3). Blockchain is being investigated on whether it can provide a general-purpose medium that allows users to exchange assets frictionlessly with a trusted and auditable data trail (Gaur et al., 2019, p. 3). Since only one version of a blockchain ledger exists for each blockchain platform, querying and auditing data is straightforward (Smith, 2019, p. 20). Some of the benefits of blockchain include near-instant cross-border payment settling, automated accounting, and data trail permanence (Li et al., 2019). Blockchain offers conveniences that financial institutions cannot rival, such as low entry barriers for users (e.g., anyone can join), self-sovereign wallets, and immutable bookkeeping (Ward & Rochemont, 2019, p. 6). Blockchain could also reduce the onboarding cost for small businesses to obtain financial services (e.g., via decentralised finance (DeFi)) (Tezel et al., 2019, p. 7). However, blockchain suffers from a lack of standardisation in dealing with blockchain-related disputes (e.g., cryptocurrency theft); furthermore, blockchain is difficult to insure because no single entity owns the technology, which creates challenges for the existing legal system because of a lack of central accountability (Goodell & Aste, 2019, p. 4).

Blockchain is also used for non-financial transactions, such as timestamping data flows and storing file hashes (Penzes, 2018, p. 20). From a commercial perspective, blockchain can avoid bank merchant fees while providing automated accounting (Tezel et al., 2019, p. 7). Public blockchains (e.g., Ethereum) are frequently cited for having high transaction fees; however, layer-two scaling solutions exist to mitigate this (Hunhevicz, Dounas, et al., 2022, p. 22). Other public blockchains, such as IOTA and Hashgraph, have also solved the scalability problem by implementing a Direct Acyclic Graph (DAG) architecture, which can scale up to thousands of transactions per second (Sun et al., 2020).

The price volatility of cryptocurrencies is mitigated by stablecoins (Bullmann et al., 2019, p. 3). Stablecoins are pegged at a one-to-one ratio with a fiat currency, such as GBP. Each stablecoin is backed by cash or financial assets stored in an escrow

(Bullmann et al., 2019, p. 3). Tether is an example of a popular USD stablecoin with an average daily volume £12 billion (Bullmann et al., 2019, p. 15). In contrast, Pound Token is a UK-based stablecoin provider issuing GBP tokens that are fully regulated in the UK (Pound Token, 2023b). Due to the potential usefulness of stablecoins in global finance, the European Central Bank (ECB) set up the EUROchain stablecoin initiative with banks from 18 European countries, including Austria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Portugal, Slovenia, Spain and Sweden (European Central Bank, 2019, p. 3). An alternative to stablecoins is central bank digital currencies (CBDCs). The difference between CBDCs and stablecoins is that a central bank issues the former while the latter is issued by non-governmental organisations or companies. China conducted a large-scale testing of a CBDC in 2021 (Becky, 2021). Whereas, in the UK, the Bank of England and HM Treasury created the CBDC task force in 2021 to further explore its viability as a legal tender (Bank Of England, 2021, p. 6).

Many blockchain adoptions occur where systems are less digitally sophisticated. For example, the Marshall Islands passed a bill in 2018 to use the SOV stablecoin cryptocurrency as their country's national currency (Republic of the Marshall Islands, 2018, p. 5). The Marshall Islands achieved this because they are less entrenched with existing financial technology infrastructure; therefore, incorporating new technologies, such as blockchain, was more accessible.

The Ethereum blockchain previously had a reputation for being a big carbon emitter due to the electricity it consumed to run its consensus algorithm. However, In September 2022, the Ethereum blockchain updated its consensus mechanism from proof of work (PoW) to proof of stake (PoS), reducing its annual MtCO2e (million tonnes of carbon dioxide equivalent) emissions from 11 to 0.0009, a reduction of 99.992% (CCRI, 2022). Table 1 shows the carbon emissions of the new versus superseded Ethereum, and Bitcoin. Since Table 1 references carbon emissions of countries as a percentage, the exact carbon emissions of those countries are referenced in Table 2. The CO2 emission of the Ethereum 2 (i.e., PoS consensus) is equivalent to roughly 200 typical gasoline/petrol cars (Environmental Protection Agency, 2023). Ethereum 1 (i.e., PoW consensus) has been shut down and is no longer running. Table 1 shows the emissions of Bitcoin and Ethereum vs four countries, highlighting that while Ethereum 1 occupied as much as 42% of the emissions of Denmark, it now occupies the equivalent of 0.003%. Despite that, Bitcoin is still the highest CO2 contributor, equivalent to the total emissions of Cuba and 88% of Denmark.

Table 1.
Percentage MtCO2e emissions of Bitcoin and Ethereum vs. countries.

Blockchain	**MtCO2e**	**UK**	**Denmark**	**Cuba**	**Kenya**
Bitcoin	23 (Stoll et al., 2019)	7%	88%	100%	144%
Ethereum 1 (superseded)	11 (CCRI, 2022)	4%	42%	48%	69%
Ethereum 2	0.0009 (CCRI, 2022)	0.0003%	0.003%	0.004%	0.006%

Note. MtCO2e = Million tonnes of carbon dioxide equivalent.

Table 2.
Annual MtCO2e emissions per country.

UK	**Denmark**	**Cuba**	**Kenya**
314 (World Population Review, 2023)	26 (World Population Review, 2023)	23 (World Population Review, 2023)	16 (World Population Review, 2023)

Note. MtCO2e = Million tonnes of carbon dioxide equivalent.

According to a survey by Forrester, preservation of data, automated payments, and new business models were the top drivers for blockchain adoption (Forrester, 2019, p. 3). Blockchain is reminiscent of the ambitions of the early Internet (i.e., the 1990s), whereby data was democratised, and information exchange was less restricted; however, since blockchain is a decentralised technology, there is less risk that it will fall victim to centralised control of large technology companies (i.e., Google, Facebook, etc.) (Gaur et al., 2019, p. 7). Blockchain is unique in that it achieves trust amongst untrusting parties without requiring the services of trusted third parties, achieved through cryptography and algorithms (Li et al., 2018a). Research suggests that blockchain can potentially increase innovation in the construction industry to that of the manufacturing and automotive industries (Li et al., 2018a). However, this claim is highly speculative.

The Construction Industry Training Board (CITB) and Construction Skills Certification Scheme (CSCS) conducted a 12-month survey of 419 certificate verifiers in the construction industry (Construction Industry Training Board, 2015, p. 5). The results revealed that 18% encountered counterfeit qualification certificates used in construction projects within the past year (Construction Industry Training Board, 2015, p. 12). The British Standards Institution (BSI) partnered with the OriginTrail blockchain application to store qualification certificates on the Ethereum blockchain (Trace Labs, 2020). This allows subcontractors to append QR codes onto documents that link directly to the blockchain to provide proof of certificate award and compliance with standards (Trace Labs, 2020). An alternative solution to decentralised certificate verification is available through the Hyperledger private blockchain; However, it requires users to register and pay membership fees for using their services (Shojaei et al., 2019). Additionally, Hyperledger's certificate authority requires manual configuration before it can be used (Yang et al., 2020). Most blockchain innovations emerge from public blockchains due to their permission-less nature, providing developers with unrestricted codebase access and free protocol infrastructure (Yang et al., 2020).

2.3.1 Smart Contracts

In a survey conducted of 104 project participants in the UK construction industry, consisting of clients, consultants, main contractors, and subcontractors, on the topic of smart (automated) contracts, 60% agreed that it could potentially reduce disputes among contracting parties (Badi et al., 2021). Smart contracts are the most helpful tool invented for blockchains because it allows the programmability of business agreements on the blockchain (Badi et al., 2021). Ethereum is a second-generation blockchain that emerged in 2015 and introduced smart contracts (i.e., programmable money) (Xu et al., 2017). Smart contracts are small software programs users code and deploy on the blockchain to perform specific, preprogrammed tasks (Mason, 2019). They contain *if and then* statements and sit atop the blockchain, awaiting user commands (Scott et al., 2021). The concept of smart contracts was proposed in 1994 by Nick Szabo, a computer scientist who claimed that computer code preprogrammed into an automated/smart contract could replicate the functionalities of standard contracts and reduce processing fees (Szabo, 1994). The term 'smart contract' was coined because agreements between transacting parties can be hard-coded into a digital contract without needing a trusted third party to manage the agreement, enabling autonomous contract executions (Das et al., 2020; Perera et al., 2021). Because of this, transacting parties cannot unfairly withdraw or alter predefined agreements, and costly intermediaries are mitigated (Hamledari & Fischer, 2021b). However, one of the limitations of smart contracts is that they can be challenging to programme (Boucher et al., 2017, p. 14). This is because human-readable contracts are designed to be interpreted by other humans and not machines; thus, communication that comes naturally to humans is difficult to translate into computer code (Boucher et al., 2017, p. 15). Furthermore, minor grammatical errors in human-readable contracts can be read by people with minimal ambiguity (Boucher et al., 2017, p. 15). In contrast, smart contracts must be perfectly codified because slight errors can cause complete malfunction (Boucher et al., 2017, p. 14). One of the earliest examples of a smart contract is with a crowdfunding application, whereby a smart contract was used to manage the agreement rather than relying on an intermediary that may act maliciously with the funds or charge high fees (Hassija et al., 2020). In that application, if the desired funds are raised according to the predefined conditions of the agreement, then the beneficiary is sent the funds; however, if inadequate funds are raised by the predefined deadline, then a full automated refund would be given to each contributor (Hassija et al., 2020).

Each blockchain is codified in a programming language. For example, Ethereum is written in Solidity, the language used for writing Ethereum smart contracts (Hunhevicz, Motie, et al., 2022). Smart contracts are deployed on the application/execution layer of the blockchain (Perera et al., 2020). Table 3 displays an example of a smart contract's code that the author wrote in Solidity. The smart contract displayed in Table 3 has no real-world value and is used for illustration purposes only.

Table 3.
Example of a smart contract's codebase.

Code Syntax	Description
`pragma solidity ^0.8.7;`	Specifies the smart contract's version.
`contract TestContract {` `    string public myText = "abc";`	Creates a contract called "TestContract". Stores text data called "abc".

`    function newText() external {`
`        myText = "xyz";`
`    }`
`}`
	Creates a function called "newText" that changes the text data from "abc" to "xyz".

Figure 3 displays a screenshot of a smart contract's user interface deployed on the Remix integrated development environment.

Figure 3.
The user interface of the Table 3 smart contract.

The fragmentary nature of communications in construction projects, such as over-reliance on excessive use of e-mail and phone, results in inefficiencies that could be mitigated through a more integrated system (Li et al., 2019c). Smart contracts (SCs) contribute the most value in automating repetitive tasks that typically require manual entry (Mason, 2017). SCs can automate the processing of agreements and enable users to engage in contract activities peer-to-peer with fewer data administrators (Dutta et al., 2020). SCs are also usually integrated with a user interface to allow non-technical users to interact with them, reducing the onboarding barriers of users (Martinez et al., 2019). For example, when the main contractor and project manager approve a subcontractor's completion of works via a Web application connected to smart contracts, it can trigger a smart contract to execute liabilities autonomously. Transactions executed over smart contracts do not differ from standard blockchain transactions in terms of security; thus, all the usual benefits of the blockchain apply, such as data traceability and immutability (Cohn et al., 2017).

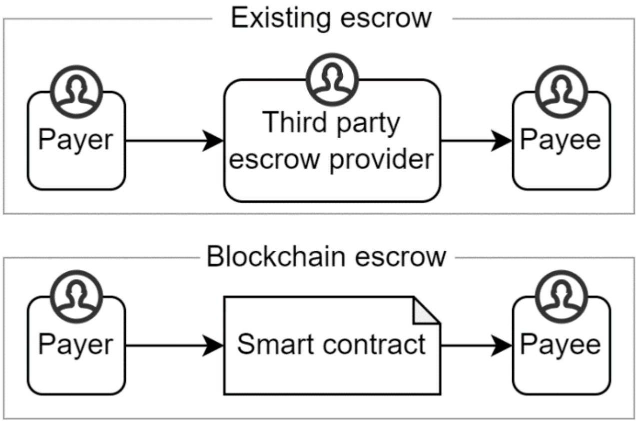
The primary cost to be concerned about with blockchain is outsourcing programmers/developers to code the smart contracts since the technology itself is costless due to it being open-source, decentralised, and permissionless; however, blockchain developers are in short supply which leads to over-inflated fees for outsourcing them, potentially making blockchain unfeasible in the current environment (Igbojekwe, 2019). The estimated cost for outsourcing a smart contract (i.e., paying someone else to build it) can range from £5,500 to £80,000 for each contract, depending on its complexity (iOlite, 2018). However, building and testing a smart contract is only part of the equation; specialist programmers must also audit it before commercialisation, which can range from £4,000 to £80,000 for each contract, depending on its technicality (Zapotochny, 2018). A smart contract audit is when its code is cybersecurity tested for faults to ensure it is safe for commercial use and cannot be hacked.

Programming reactive systems like smart contracts to execute pre-programmed functions and execute tasks is not unique to the blockchain. For example, Uber and Airbnb already use algorithmic systems that enable employees and drivers to self-manage without the necessity of a human manager (Waterhouse et al., 2018, p. 5). Technology increasingly turns consumers into prosumers, merging the boundary between users and service providers (Kelly, 2017, p. 21). A prosumer is a user who simultaneously consumes/buys and produces/sells a product or service from the same platform. Prosumer platforms do not create content themselves and instead provide a medium for users to consume and produce content simultaneously (Kelly, 2017, p. 21). For example, in their book, Kelly (2017, p. 109) mentions that “Facebook, the world’s most popular media owner, creates no content; Alibaba, the world's most valuable retailer, has no inventory; And Airbnb, the world's largest accommodation provider, owns no real estate”. Facebook is worlds most popular media owner without them creating any videos; Airbnb is the largest hotel provider without them owning any hotels; and Uber is the largest taxi provider without them owning any taxis. Smart contracts are projected as the next major component to reform the prosumer culture (Nanayakkara et al., 2019). Sectors where smart contracts have had the most influence include finance, banking, supply chain, and healthcare (Guo & Liang, 2016).

2.3.2 Escrows

An escrow is an intermediary account between two transacting parties (Saygili et al., 2022). It is used when transacting parties do not trust each other or if both parties want greater financial assurances (Saygili et al., 2022). PBAs are a form of escrow (Scott et al., 2022b, p. 141). Escrows are typically set up and managed by centralised companies and are used to safeguard contract funds until both transacting parties are satisfied with contract delivery (Witkowski et al., 2011). However, centralised escrows can charge up to 3% of the transaction value (Escrow, 2022). Smart contracts are used in the replacement of escrow providers in decentralised systems.

Figure 4.
Existing/traditional escrows vs. blockchain escrows.



An example of a smart contract escrow used in construction was demonstrated in a study by (Saygili et al., 2022), who used the Kleros escrow to automate the release of progress payments; furthermore, the Kleros escrow was configured to manage the withholding of liabilities during dispute resolutions. PBAs share several principal characteristics with blockchain, such as transparency, auditability, and disintermediation, through creating a partitioned bank account co-managed by trusted authorities (Scott et al., 2022b, p. 149).

2.3.3 Cryptography and Encryption

The terms asymmetric keys and encryption are mentioned several times in this section. The former relates to an address, while the latter relates to signatures conducted from that address. The cryptography used in the blockchain is asymmetric encryption (synonymously called public key cryptography), which comprises the use of a public-private key pair (Ray, 2017). These keys serve two primary functions: (1) wallet address and (2) signatures (Agrawal, 2018). The public key is the user’s wallet address used for receiving funds (similar to a user’s bank account number), whereas the private key is used for authorising/sending transactions from the user’s wallet (Pal et al., 2019). The public key can be openly displayed, whereas the private key must never be shown to anyone (like a password) (Zhang et al., 2020). Asymmetric keys are not a product of the blockchain despite their central role in its operations (Wirdum, 2019). Asymmetric encryption allows the private key to remain encrypted even if the public key is publicly displayed (Bhakhra, 2020). Asymmetric encryption was invented in 1976 and is the successor of symmetric encryption (Simmons, 1979). Asymmetric keys are the standard encryption used when computers exchange data over the

Internet and are fundamental to Internet security and privacy (Mousavi et al., 2021; Wong, 2019). Asymmetric keys are produced through the Elliptic Curve Digital Signature Algorithm; this algorithm is also accessible on most programming languages (ECDSA) (Marx, 2018a). Because of this, key pairs can be created whilst disconnected from the Internet to increase security (Asolo, 2019). Blockchain transactions can also be initiated off-chain (off the blockchain) by storing a signed private key signature that authorises a transaction, storing the signature in a database, and pushing it to the blockchain for execution at a future time (Eberhardt & Tai, 2017). The blockchain treats off-chain transactions no differently than standard transactions. A decentralised exchange (DEX) is an example of an application that integrates off-chain and blockchain functionalities (Boguslavsky, 2019).

2.4 Exploratory Review of Blockchain in Construction

The subject area of blockchain in construction includes many topics under its umbrella, such as blockchain for cash flow management, which is the focus of this research. However, blockchain for cash flow management is not a topic that exists in isolation. Instead, it co-occurs with other topics such as blockchain for BIM, supply chain management, and smart cities (Hargaden et al., 2019a; Lv et al., 2021; Teisserenc & Sepasgozar, 2022). Investigating these topical overlaps is crucial to understanding the context in which this research is positioned within the blockchain in construction subject area. Since blockchain is the technology researched, the exploratory review will undertake the narrative of exploring application categories for blockchain in construction, followed by a scientometric mapping of topical overlaps. A bottom-up approach was implemented to assess the existing environment through an exploratory lens. The document types used in the review include journal articles, conference papers, and book chapters. Non-academic sources, such as company reports, were not included in the study as they do not have the same level of scientific rigour and information openness as scholarly material; furthermore, the number of documents attained from academic sources was of sufficient quality and quantity for a comprehensive review.

The timescale of the exploratory review spanned from January 2017 to December 2020 and incorporated 121 academic documents. That timescale was delimited to December 2020 because the review took place in early 2021, and the author wanted to capture the bibliometric results for full complete years (i.e., from January to December of each year). However, after the exploratory review was completed, this thesis continually reviewed academic literature as the thesis progressed. For example, this thesis reviewed literature up until the year of its submission in 2024.

Altogether, 33 application categories were uncovered and organised into seven main subject areas, comprising (1) procurement and supply chain, (2) design and construction, (3) operations and life cycle, (4) smart cities, (5) intelligent systems, (6) energy and carbon footprint, and (7) decentralised organisations. The first academic literature on blockchain in construction emerged in 2017 in the categories of BIM (Turk & Klinc, 2017), smart cities (Coyne & Onabolu, 2017), and peer-to-peer energy markets (Sikorski et al., 2017). Scopus was selected as the scientific database for extracting documents because it contains the most extensive bibliographic archive of academic literature on construction research (Burnham, 2006). Only one scientific database was used for the review due to data format inconsistencies when conducting scientometric analysis on the merged bibliographic databases. The author compared the literature results from Scopus and Web of Science (WoS), the two most voluminous databases for construction research, and the results revealed that Scopus had 53% more publications. Furthermore, 85% of the literature indexed in WoS was already listed in Scopus; thus, Scopus was selected as the database for the exploratory review. Other scientific databases considered for the review included IEEE Xplore, Science Direct, Directory of Open Access Journals (DOAJ), and JSTOR (Paperpile, 2021). However, they had substantially less literature, and most of their content was also listed in Scopus. Scopus and WoS included a balanced range of top-tier journals (top 25% based on the Scientific Journal Ranking (SJR) indicator); however, Scopus had a higher number of mid to lower-tier journals.

Figure 5 displays the two search queries used to obtain the search results for the review, which initially returned 412 publications. However, upon removing duplicates and filtering content for topical suitability, the final result totalled 121 publications. The two search queries are as follows:

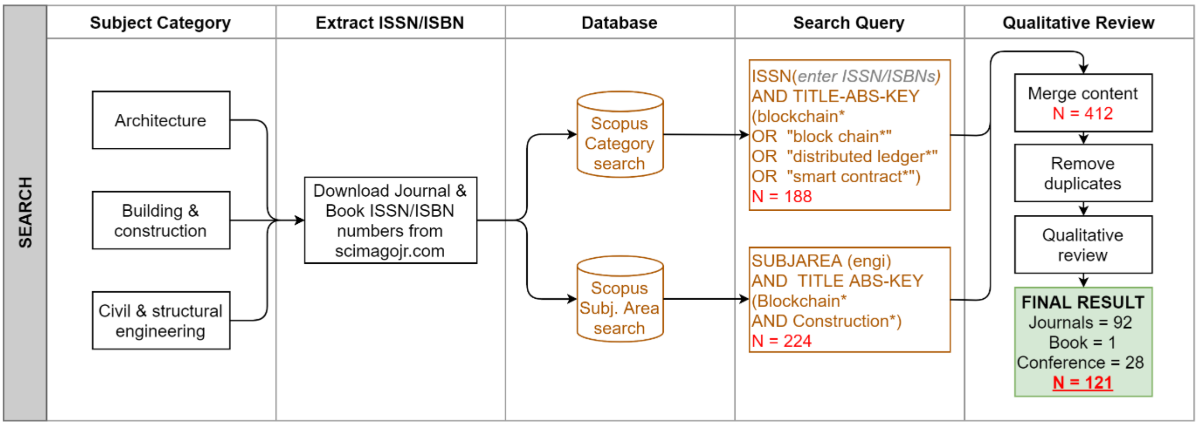
1. Search one: Incorporated accessing the Scopus database via their webpage (https://www.scopus.com) and inserting the ISSNs of journals and ISBNs books in the subject categories of architecture, building and construction, and civil and

structural engineering, followed by keywords such as “blockchain”, “distributed ledger”, and smart contract”. ISSNs and ISBNs are unique identifiers provided for each journal or book. They can also be downloaded from SCIMago (https://www.scimagojr.com). SCIMago is a webpage that indexes and scores the performance of academic journals and books across many subject areas (SCImago). Searching for publications via ISSNs and ISBNs allows researchers to target relevant sources more efficiently.

2. Search two: The Scopus webpage allows users to search for documents according to a predefined list of subject areas; in this case, “SUBJAREA(engi)” was inserted into Scopus’s search box with key terms such as “blockchain” and “construction”.

Figure 5.

Search query and process flow for obtaining literature for the review.



From the sample of 121 publications, six publications included literature/systematic reviews of a similar nature and are shown in Table 4. Of these, four delimited their results to academic sources, whereas two incorporated grey literature such as organisation reports.

Table 4.

Review papers on blockchain in construction by other researchers.

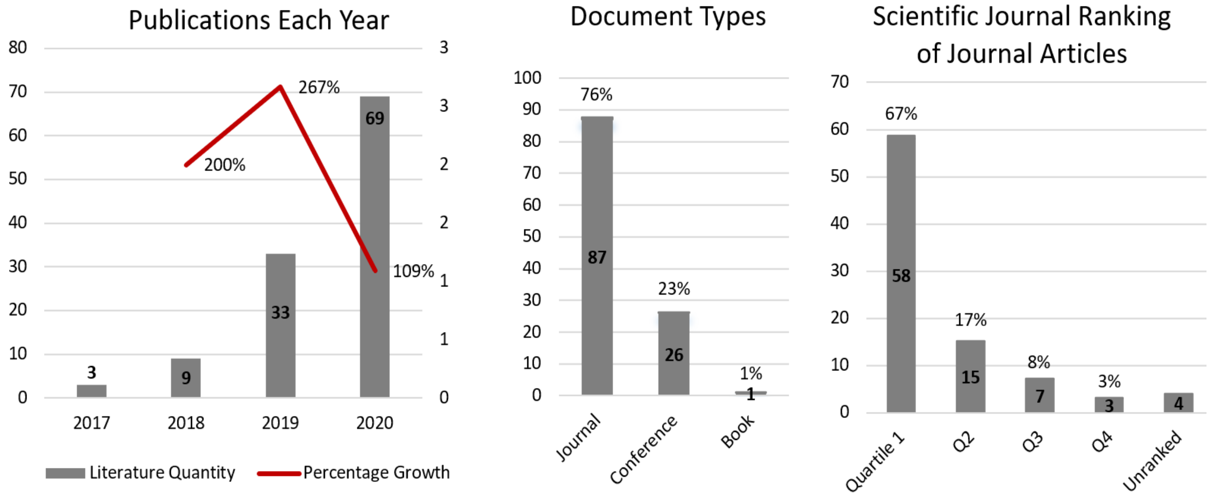
Reference	Categories	User-cases	Reference count
(Bhushan et al., 2020)	6	10	42
(Hunhevicz & Hall, 2020)	7	24	15*
(Kiu et al., 2020)	6		57*
(Li et al., 2019)	7	3	75
(Perera et al., 2020)		18	27*
(Yang et al., 2020)	4		83

Note. * Includes content from grey (non-academic) literature (e.g., reports).

Descriptions of the literature displayed in Table 4 data are as follows: Bhushan (2020) conducted a comparative literature review of blockchain in smart cities, published in Sustainable Cities and Society journal, which outlined six subject areas and eight application categories. Hunhevicz & Hall (2019) produced a literature review of blockchain in construction, published in Advanced Engineering Informatics journal, which included seven subject areas and 24 categories. Kiu et al., (2020) Composed a systematic review of blockchain in construction, published in the International Journal of Construction Management, and outlined six subject areas. Li et al., (2019) composed a systematic literature review published in Automation in Construction, which extrapolated seven built environment subject areas; furthermore, three application categories were substantiated through interviews with academics and industry practitioners, such as “automated project bank accounts”, “regulation and compliance”, and “single shared-access BIM model”. Perera et al., (2020) published a literature review article on blockchain in construction in the Journal of Industrial Information Integration and identified 18 application categories; however, their review included grey literature sources. Finally, Yang et al., (2020) conducted a literature review in their blockchain proof of concept article published in Automation in Construction, which included four subject areas for managing business processes.

From 2017 to 2021, the number of new publications on blockchain in construction increased at an annual growth rate of 184%, as shown in Figure 6. It also shows the number of documents published yearly from the search results, document types, and scientific journal rankings (SJR). SJR is the impact factor of each journal, which is calculated through a network analysis of citations. SJR is measured in quartiles, whereby Q1 represents the top 25% of journals, while Q4 is the lowest 25%. The results in Figure 6 are based on whole years (i.e., 1st of January to 31st of December) from 2017 to 2020. Since this review was conducted in 2021, results from that year were not included because statistics based on the whole of 2021 could not be collected.

Figure 6.
The expansion of blockchain in construction from 2017 to 2022.



The exploratory review identified seven subject areas and 33 application categories, as shown in Figure 7. The subject areas were used to group application categories of similar nature. Each application category was substantiated by a minimum of three publications to ensure a level of academic consensus was achieved. For example, application categories with less than three publications were excluded from the review.

Figure 7.

Subject areas and application categories of blockchain in construction.

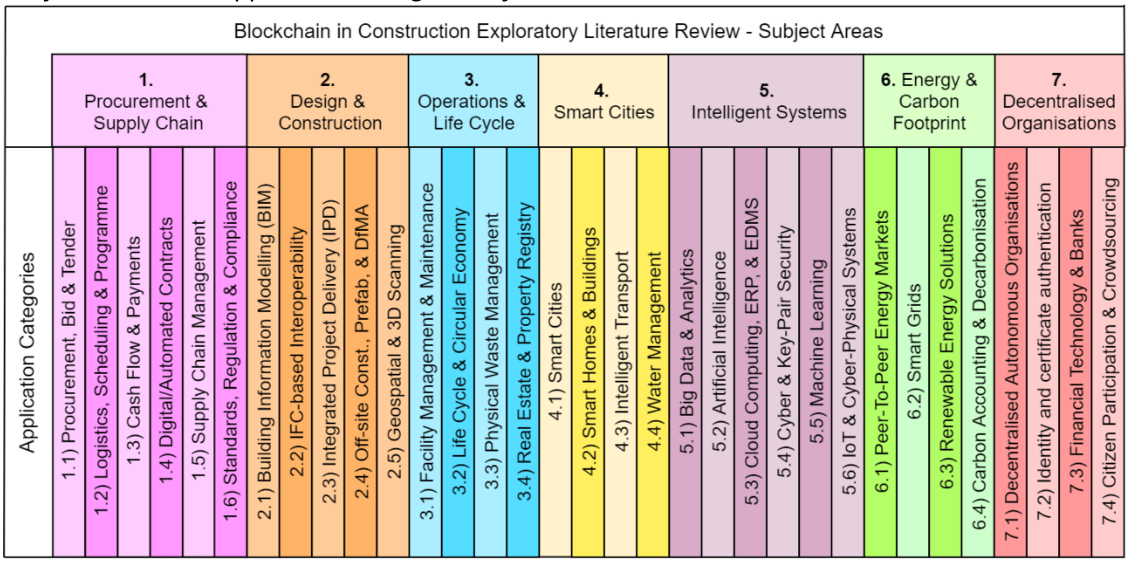


Figure 8 displays a timeline showing when each application category emerged in literature. The colours in Figure 8 are assigned in conjunction with Figure 7. The first publications on blockchain in construction appeared in 2017 with three publications and six categories; 2018 included nine new publications (a 200% increase from the previous year) with nine new categories, 2019 displayed 33 new publications (267% increase of the prior year) with 13 new categories, and 2020 included 69 new publications (109% increase from the previous year) with five new categories. The result is 33 application categories.

Figure 8.

Timeline showing when each category emerged in literature.

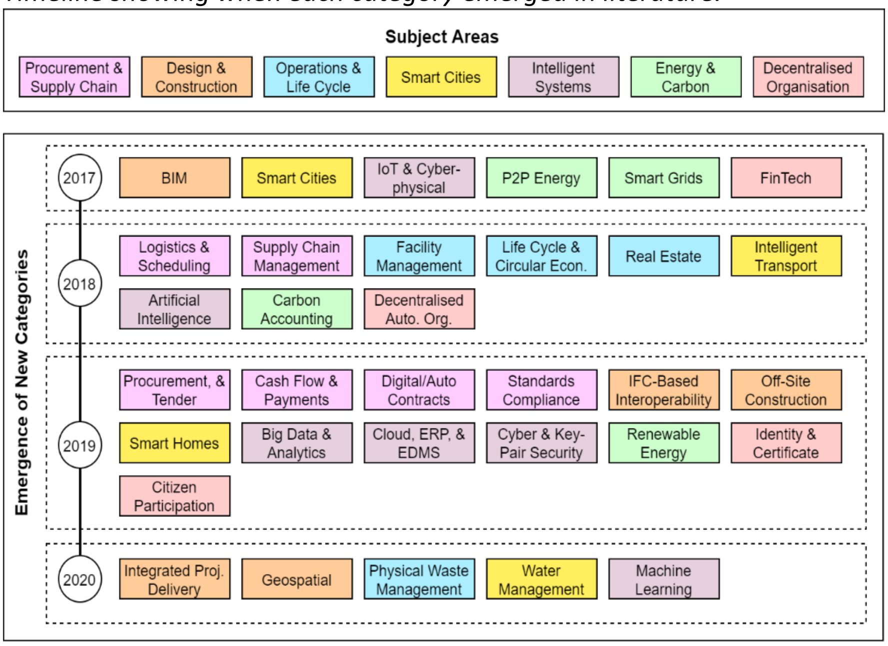
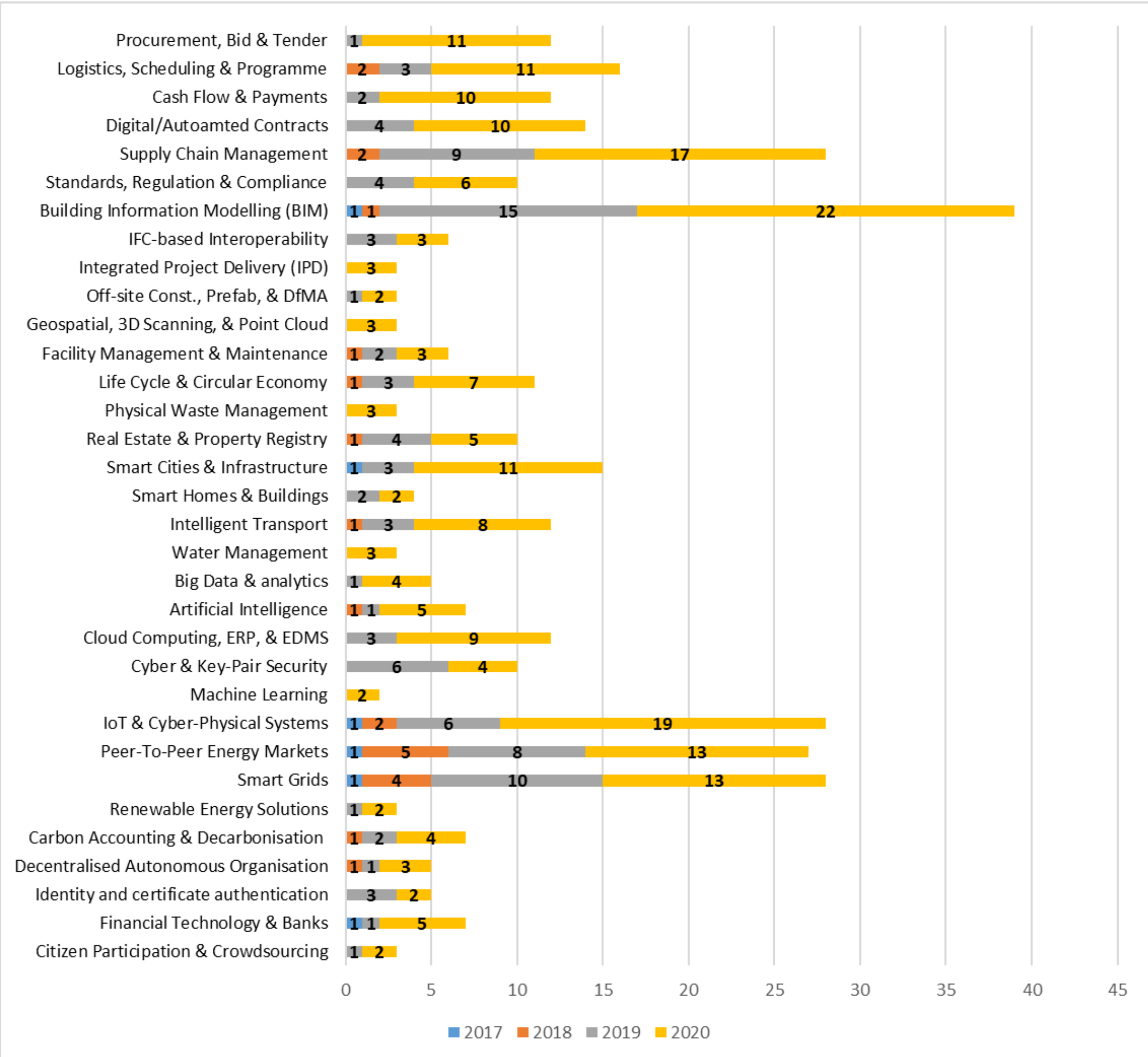


Figure 9 displays the number of academic documents published for each of the 33 application categories. The category with the highest number of publications, with 39 documents, was building information modelling (BIM). Joint second with 28 publications each was the Internet of Things (IoT), supply chain management, and smart grids. Finally, the peer-to-peer energy markets category ranked third with 27 documents. The newest categories that emerged in 2020 included machine learning, water management, construction waste management, geospatial, and integrated project delivery (IPD).

Figure 9.

Quantity of publications published for each category from 2017 to 2020.



A complete list of the 121 reviewed documents, along with all the metadata collected during the exploratory review, such as application category co-occurrences, document types, data collection types, and SJR rankings, can be found in the following link:

https://docs.google.com/spreadsheets/d/1V4UICRdoyWycaGENH9rnuxukRNQJFIArQ-feV7NM0a4/edit?usp=sharing. This link was last updated in 2021 and last checked on July 2024.

The data from the above link was transferred into visual mapping software, VOS-viewer, to produce the Figure 10 co-occurrence map, illustrating how each of the 33 application categories overlaps in research. VOS-viewer algorithmically maps data using natural language processing techniques (Ozturk, 2020). Figure 10 is broken down into three parts: (1) application categories, shown as the coloured nodes with annotations; (2) colour clusters, shown as the groups of nodes that share the same colour; and (3) links, shown as the lines/links that connect the nodes together. Colour clusters are assigned when a group of application categories frequently co-occur in literature. Categories with a high number of shared links naturally gravitate to the centre, as a central position has greater equidistance with its shared links. However, categories also gravitate to each other based on their link strength. For example, if two categories frequently appear together in literature, they will be positioned close to each other on the Figure 10 map. *Blockchain* was positioned most centrally because it shares links with all 33 application categories, whereas BIM was also positioned centrally because it shares links with 32 of the 33 categories. *IPD*, *carbon accounting*, *fintech* and *off-site construction* were all placed in the outskirts due to their low number of shared links with the overall categories.

Figure 10.
Scientometric visual mapping of the reviewed categories.

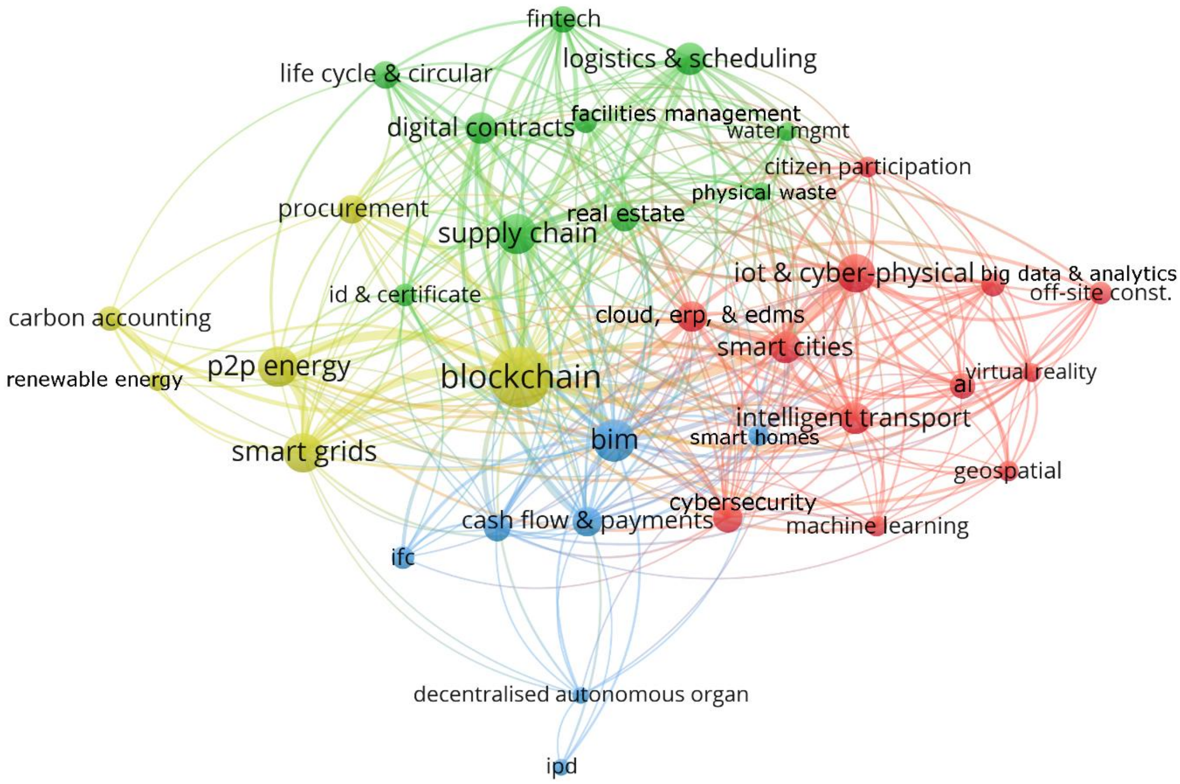


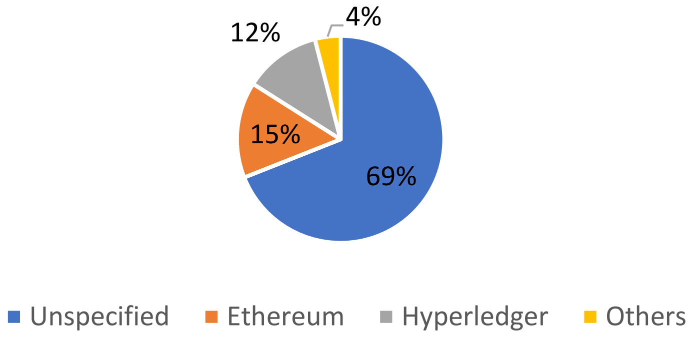
Table 5 displays the results from the Figure 10 map. The table is sorted from largest to smallest according to *link count*. *Links* records whether one application category co-occurred with another. For example, BIM co-occurred with all other categories; therefore, it has a *link* count of 32. The *total link strength* factors in the weight of each link. For example, BIM co-occurred 146 times with all other categories; thus, it has a *total link strength* of 146. In contrast, *occurrence* is calculated by the number of times each category appears in literature regardless of its *total link strength*. For example, BIM appeared in 37 of the 121 documents; thus, its *occurrence* is 37. The results show that 89% (108 number) of the reviewed documents discussed multiple application categories in their paper, whereas 11% (13 number) focused solely on one category.

Table 5.
The values from the Figure 10 visual map.

Application categories	Links	Total link strength	Occurrence
BIM (building information modelling)	32	146	37
Supply chain	29	132	31
IoT and cyber-physical	27	131	27
Intelligent transport	27	79	15
Smart cities	25	73	15
Cybersecurity	25	54	12
Logistics and Scheduling	24	81	16
Cash flow and payments	24	56	12
Smart grids	23	84	29
Cloud, ERP & EDMS (electronic doc. Management)	22	61	13
Digital contracts	22	70	14
Fintech	21	57	9
Standards	21	40	9
AI (artificial intelligence)	20	47	8
Physical waste	20	28	3
Real estate	20	48	10
Water management	20	28	3
Citizen participation	19	26	4
P2P energy	19	95	31
ID and certificate verification	18	29	5
Big data and analytics	17	39	6
Smart homes	17	26	4
Facility management	16	25	5
Virtual reality	15	25	3
Geospatial	14	25	4
Life cycle and circular economy	14	44	10
Machine learning	14	21	4
Procurement	14	36	11
Off-site const.	11	27	5
Decentralised autonomous organisation (DAO)	10	12	2
Carbon accounting	8	19	7
IFC (industry foundation class)	8	16	5
Renewable energy	6	8	3
IPD (integrated project delivery)	4	6	3

Figure 11 displays that Ethereum was the preferred blockchain platform in 15% of the reviewed publications, followed by Hyperledger in 12%; however, 69% of publications did not state a preference. Ethereum emerged in 2015 as a public blockchain platform; furthermore, it is currently the leading blockchain for decentralised applications and includes the largest population of programmers (Zhang et al., 2019). Hyperledger (by the Linux Foundation) also emerged in the same year (recently after Ethereum) and introduced the first private blockchain protocol (Suliyanti & Sari, 2019). The *others* section in Figure 11, occupying 4% of the publications, includes Multiledger (Khaqqi et al., 2018), Bitcoin (Xiong et al., 2019), Corda (Singh, Jeong, et al., 2020), and IOTA (Sun et al., 2020).

Figure 11.
The popularity of blockchain platforms in the review.



Note. The 'others' section includes Multiledger, Bitcoin, Corda, and IOTA.

Figure 12 displays the various data collection types implemented by the reviewed publications. A conceptual framework was incorporated in 46% of documents, which was often used as a foundation to formulate high-level ideas (Talat et al., 2020). Case studies were also a popular method used in 27% of publications, which included joint ventures between academia and industry (Hu et al., 2019). Literature reviews were used in 26% of the documents, which were typically implemented as a prerequisite to support the development of conceptual frameworks (Shojaei et al., 2020), such as with the Brooklyn micro-grid project, which used a literature review to assess the existing environment before the implementation of a case study (Mengelkamp et al., 2018). Statistics were incorporated in 23% of publications, such as measuring the performance of blockchain vs centralised systems (Wang, Liu, et al., 2020). The other types of data collection types that appeared less frequently included systematic reviews (12%), proof of concepts (12%), interviews (7%), surveys (7%), and questionnaires (1%).

Figure 12.
Most common data collection types used by the reviewed publications.

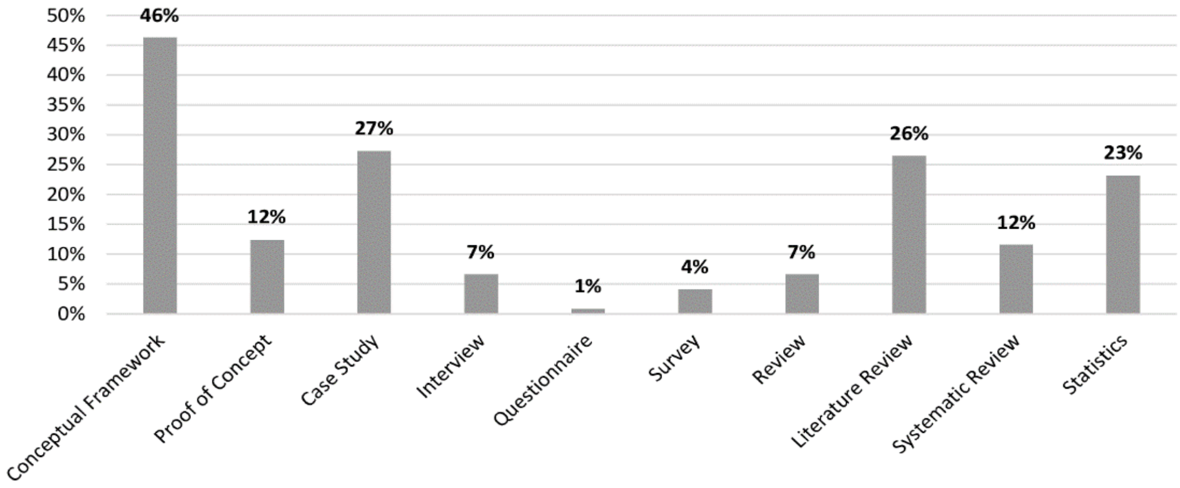


Figure 13 displays a visual map showing the co-occurrences of the data collection types in Figure 12. The *links* are displayed in red numerals, whereas the *total link strength* is displayed in blue numerals. The *total link strength* is calculated by summing all the *links* that intersect with a node (e.g., *systematic review* has a *total link strength* of three because it has three *links* that intersect it). From analysing Figure 12, the top three data collection types that co-occurred most frequently included conceptual frameworks (with a link strength of 48), case studies (with a link strength of 43), and statistics (with a link strength of 39). The outer position of systematic reviews revealed that it co-occurred less frequently than literature reviews. Some data collection types were merged for simplicity. For example, proof of concepts (PoCs) included pilot studies and prototypes. Similarly, conceptual frameworks included conceptual models and theoretical frameworks. Only 10% of publications presented PoCs. The data collection types with the least co-occurrences included questionnaires, systematic reviews, and surveys. Altogether, 55% of the reviewed publications incorporated multiple data collection types in their research, while 45% included only one. The publications that included a higher number of data collection types were typically less technical overall, such as literature/systematic reviews. In contrast, publications that included only one data collection type were more in-depth, such as with PoCs.

Figure 13.
Co-occurrences map of the data collection types shown in Figure 12.

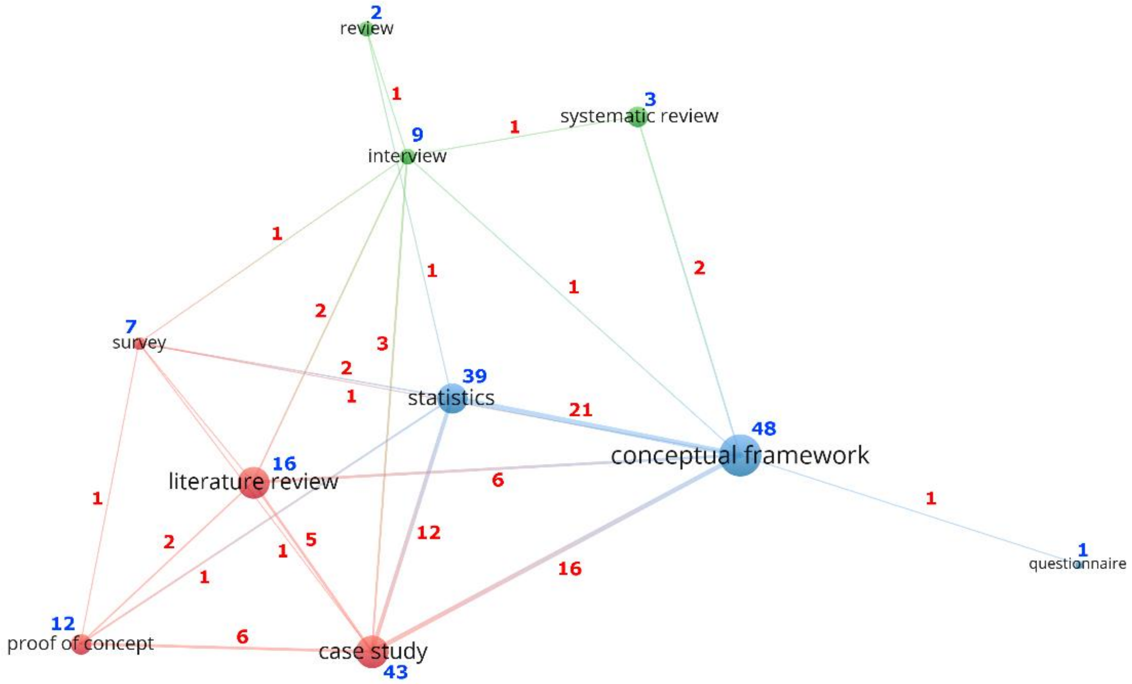


Table 6 is to be read in conjunction with Figure 13 and is organised according to *link* count. Table 6 shows that the conceptual framework data collection type occurred 52 times in the reviewed publications; thus, its *occurrence* is 52. However, in 48 instances, it co-occurred with another data collection type; therefore, its *total link strength* is 48. This means four publications (52 minus 48) used a conceptual framework as their paper's only data collection type.

Table 6.
The values from the Figure 13 visual map.

Data collection type	Links	Total link strength	Occurrence
Conceptual framework	7	48	52
Case study	6	43	32
Interview	6	9	8
Survey	6	7	5
Statistics	5	39	27
Literature review	5	16	31
Proof of concept	4	12	13
Systematic review	3	3	12
Review	3	2	7
Questionnaire	1	1	1

2.4.1 Key Application Categories

Of the 33 application categories identified in the exploratory review, ten overlap with this research’s topic (blockchain for cash flow management in construction). Descriptions of them are recorded below.

1. **Digital and automated contracts:** McNamara and Sepasgozar (2020) interviewed construction industry practitioners and revealed that trust, risk, and dispute management are ubiquitous concerns in almost all projects, with main contractors exerting dominance through unfair contract conditions. In a survey with 104 respondents in the UK construction industry regarding smart contracts, the main factors determining their adoption with enterprises are competitive advantage and commercial value (Badi et al., 2021). Hunhevicz et al. (2020) proposed a digital contracting framework that simulated the decision points of a typical design-bid-build project in Switzerland, which included the client, owner, planner, contractor, and subcontractor, all interacting with smart contracts to manage the approvals and validations process of contract activities, such as project definition, design coordination, tendering, subcontractor selection, and contract signing; furthermore, it was prototyped through a Web application connected to Ethereum smart contracts.

2. **Supply chain management:** Qian and Papadonikolaki (2020) interviewed practitioners in the construction industry knowledgeable in supply chain management and blockchain. They identified that blockchain could potentially mitigate the trust problem in construction through data traceability, non-repudiation, and disintermediation; furthermore, it was projected that blockchain could save up to 70% on project costs associated with data processing and management through automated compliance, payments, and analytics (Qian & Papadonikolaki, 2020). Sheng et al. also proposed a framework for automated compliance checking whereby project participants upload contract documents, project schedules, and cost information into an application that verifies compliance accuracy (Sheng et al., 2020). Furthermore, the application notifies users if more information is needed (Sheng et al., 2020). Dutta et al. (2020) conducted a systematic review of blockchain for supply chain management and identified several key attributes where blockchain can

improve performance, such as traceable records, immutable bookkeeping, resilience from network disruption (e.g., systems downtime), enhanced data synchronicity, improved data trust in cyber-physical systems, business process automation through smart contracts, and improved tracking of document revisions.

3. **Integrated project delivery:** Integrated project delivery (IPD) uses a shared risk and reward contract to improve collaboration in construction projects (Elghaish et al., 2020). Hunhevicz et al. (2020) discussed how the characteristics of IPD overlap with the ideologies of Elinor Ostrom's common pool resource principles, which discourses how mutual and economic benefit can be achieved for participants who work together to achieve a common goal. Research suggests that IPD can leverage the crypto-economic model of the blockchain by designing smart contracts to execute automated rewards to participants that engage with collaborative project delivery (Hunhevicz, Pierre-Antoine, et al., 2020). Elghaish et al. (2020) conducted a proof of concept (PoC) of a simulated IPD blockchain project that demonstrated how smart contracts can manage project funds and automate the execution of payments, retentions, and bonuses.

4. **Big data:** The quantity of new data produced yearly is increasing exponentially (Woodhead et al., 2018). The construction industry is under pressure to exploit the benefits of data-driven solutions while suffering from low profitability and a lack of investment in innovation (Woodhead et al., 2018). Blockchain could reduce the resource requirements for data security by leveraging its data immutability properties (Ahad et al., 2020). Integrating blockchain with big data in the construction industry could improve data traceability, project reporting, and the capacity to use analytics more effectively (Wang, Wang, et al., 2020).

5. **Cloud computing and electronic document management systems:** An electronic document management system (EDMS) enables users to manage, store, and process enterprise data electronically (Sun et al., 2020). The centralised model of EDMS software makes it challenging to interoperate with EDMS applications by other technology providers (Kiu et al., 2020). To combat

this, blockchain-based EDMSs are being investigated as a potential solution to the interoperability problem of digital document management (Kiu et al., 2020).

6. **Cybersecurity:** One of the problems with blockchain is that it places the responsibility of wallet management on its users by mandating them to safely store their wallet keys (Wang, Song, et al., 2020). Xiong et al. (2019) proposed a “secret-sharing-based key protection” protocol that allows users with compromised or lost private keys to retrieve access to their wallet. It involves multiple users generating the private key in fractions; furthermore, when the preselected users combine their keys, it generates the entire private key of the lost wallet (Xiong et al., 2019). Blockchain cannot store large amounts of data because it is designed as an accounting ledger that replicates and synchronises its state with many computer nodes, creating computational challenges, such as slow transaction speeds and high network fees (Parn & Edwards, 2019). To mitigate this, Bai et al. (2019) proposed an application that consists of blockchain and off-the-blockchain functionalities, whereby the hashes (unique identifiers) of files are stored on the blockchain, while an off-the-blockchain system handled data storage and computational processing. When the term off-the-blockchain is used, it refers to a system that integrates the computation capabilities of computer servers with blockchain applications.

7. **Decentralised autonomous organisation:** A decentralised autonomous organisation (DAO) is a decentralised entity that relies on smart contracts to manage the system; for example, using smart contracts to vote on decision points and enforce codebase updates (Hunhevicz & Hall, 2020). The construction industry is known for incurring frequent change orders and programme alterations, which is problematic for smart contracts due to their unalterable properties once deployed (Li et al., 2020). Translating written agreements into coding syntax creates linguistic challenges for construction managers and programmers because they are accustomed to different bodies of knowledge that shape their communications (Li et al., 2020). For example, the word ‘contract’ in construction translates differently than in computer science. Hence, the term *smart contract* is ambiguous from the construction perspective. From the computer science perspective, a smart contract is a miniature software with *If and Then* statements embedded. Nevertheless,

Dounas et al. (2021) proposed an application that uses a DAO and smart contracts to automate the tender process in construction projects, whereby smart contracts algorithmically score submitted bids and autonomously select the winner. DAO includes the potential to integrate with the operations and maintenance phase of built assets (Ye et al., 2018). For example, the solution proposed by Ye et al. (2018) uses a DAO for the automated servicing of building components by connecting prospective subcontractors to new work, managing payments, cross-checking compliance certificates, and quantitatively assessing each subcontractor's risk through their track record of delivered works (Ye et al., 2018).

8. **Identity and certificate authentication:** The fundamental properties of blockchains (traceability, transparency, and immutability) make them a suitable technology for incorporating identity authentication services, as centralised systems are prone to hacks and data manipulation (Wang, Song, et al., 2020). Nawari and Ravindran (2019a) discussed how Hyperledger, a popular private blockchain, can be used for identity management services in construction due to its modular architecture that enables better customizability of user access controls. This was further supported by (Shojaei et al., 2019), who discussed how Hyperledger includes a certificate authority built into its core codebase, designed for clients and contractors to manage their supply chain with privacy. Non-fungible tokens (NFTs), a type of cryptocurrency, are investigated in research on whether they can improve how building certificates are managed by storing title deeds and regulatory certificates in one place (i.e., within the NFT) (Hargaden et al., 2019a). This would reduce the volume of data exchanges between issuers, estate agents, and facility managers during certificate retrievals and verifications (Dakhli et al., 2019).

9. **Financial technology:** The emergence of blockchain-based decentralised finance (DeFi) in 2020 created opportunities for financial institutions to extend their product range for customers (Coyne & Onabolu, 2017). However, the pseudonymous nature of wallet addresses on the blockchain makes it challenging to trace hacked/stolen funds, and tens of millions of dollars are lost annually to DeFi hacks (Chong, 2020). Yao et al. (2020) proposed a conceptual framework integrating banks with DeFi to reduce the entry barriers and

processing delays of supply chain finance. One of the ways banks can provide new financial products is through smart contract escrow services, allowing transacting parties to formalise agreements amongst themselves while under oversight from regulatory controls (Bhushan et al., 2020). Smart contracts also include the potential to automate tax duties; for example, when goods are imported into a country, compliance certificates can be awarded autonomously upon payment of import taxes (Lu, 2018).

10. **Crowdsourcing:** Blockchain-based crowdsourcing is a decentralised alternative to procuring products and acquiring skilled talent from economically disadvantaged countries (Hassija et al., 2020). Public blockchains allow users to raise capital more easily through initial coin offerings (ICOs), which include launching a new blockchain platform or token and minting a new cryptocurrency that can be sold at pre-sales and on exchanges (San et al., 2019). ICOs are like the IPOs (initial public offerings) of stock markets (San et al., 2019). However, ICOs are a target for criminal activity due to their ability to raise funds from anonymous users and lack of regulation (Scott et al., 2021). Hassija et al. (2020) discussed how decentralised crowdfunding platforms, such as BitFund, enable clients to propose blockchain solutions while allowing programmers to submit bids; afterwards, the winner is selected, and smart contracts manage the agreement.

2.4.2 Evaluation of the Review

An exploratory approach was used to review application categories of blockchain in construction. Each category was documented by a minimum of three academic publications to ensure a level of consensus for each category. Categories discussed in less than three publications were omitted from the review to filter out highly experimental content. The categories were organised into seven subject areas: (1) procurement and supply chain, (2) design construction, (3) operations and life cycle, (4) smart cities, (5) intelligent systems, (6) energy and carbon footprint, and (7) decentralised organisations. Subject area one, *procurement and supply chain,* examined how blockchain is implemented in the tendering, pre-construction planning, and contract setup processes (Ahmadisheykhsarmast & Sonmez, 2020; Li et al., 2020; Pattini et al., 2020). Subject area two, *design and construction,* investigated how blockchain can improve construction activities such as automating project management tasks, supply chain management, and BIM-blockchain integration (Aleksandrova et al., 2019; Li et al., 2021). Subject area three, *operations and lifecycle,* reviewed how blockchain can improve facility management and asset maintenance (Gotz et al., 2020). Subject area four, *smart cities*, and subject area five, *intelligent systems*, assessed how the built environment could integrate blockchain, smart devices, and the internet of Things (IoT) for smart city and infrastructure services (Ghosh et al., 2020; Shinde et al., 2020). For example, smart transport and sensor-fitted utilities (Aljabri et al., 2019; Wong et al., 2020). Subject area six, *energy and carbon,* examined peer-to-peer energy trading solutions, sustainable technologies for the built environment, and carbon accounting strategies (Lüth et al., 2018; Wainstein, 2019; Woo et al., 2020). Finally, subject area seven, *decentralised organisations*, examined decentralised autonomous organisations (DAOs) and decentralised applications (Dounas et al., 2021). DAO is challenging to define in the current environment because its definition is still evolving (Scott et al., 2021). However, DAO is relatable to an entity that automates the main contractors' activities, such as automated payments (Scott et al., 2021). Research suggests that DAO can also be used to manage an ecosystem of decentralised services/applications for construction (Dounas et al., 2021).

The seven subject areas and 33 application categories were not distinctly siloed and included many overlaps. For example, the *supply chain management* category overlapped with most of the other categories. However, based on the scientometrics analysis conducted (as per figure 10), *supply chain management* was positioned most quantitatively relative in the *procurement and supply chain* subject area due to its high number of shared links with the other categories in that area (Hamledari & Fischer, 2021d; Kifokeris & Koch, 2020). *IoT* also overlapped with several subject areas, which include smart cities (Perera et al., 2020), energy and carbon (Kobashi et al., 2020), design and construction (Li et al., 2021), procurement (Kodym et al., 2020), and decentralised organisations (Berglund et al., 2020); however, *IoT* was placed in the *intelligent systems* subject area due to its strong correlation with the other categories in that area. The *electronic document management systems (EDMS)* and *digital/automated contracts* categories were placed in separate subject areas despite their similarities, as the former is characterised by the digital management of documents on a centralised system, whereas the latter uses smart contracts on a decentralised protocol; thus they use entirely different systems architecture (Luo et al., 2019). Two publications discussed health and safety monitoring and historical records of on-site accidents (Berglund et al., 2020; Hunhevicz & Hall, 2020). However, they lacked content for substantiation despite their practical applications. Another category excluded, despite being discussed in two publications, is smart governance, whereby governmental organisations implement blockchain for managing built environment assets (Li et al., 2019; Wong et al., 2020).

Businesses operate by balancing risks, such as economic risks through investments in new business models, social risks through job losses, legal risks through dispute resolution and corporate liability, environmental risks through sustainability and ecological sensitivity, and technical risks through increased pressure to integrate systems and provide data-driven solutions (Kodym et al., 2020). Blockchain mitigates against centralised hacks, data manipulation and accounting errors and provides a foundation for data trust (Zhao et al., 2019). Research suggests that enterprise adoption of blockchain relies on decentralised applications integrating with existing centralised systems; however, as blockchain matures, the transition to complete decentralisation is likely to increase (Scott et al., 2021). In a report regarding the impact of blockchain, it was identified as potentially transforming 58 industries globally, which includes the construction industry (CB Insights, 2021). An area that lacked discussion from the reviewed literature was the integration capabilities of blockchain with existing enterprise systems, as blockchain is considered a high-risk technology due to its decentralised design and lack of standardisation (Scott et al., 2021). *Trust* is a term that appeared most frequently in the reviewed publications, such as when describing the characteristics of blockchain. For example, “stakeholder trust” (Kifokeris & Koch, 2020), “peer-to-peer trust” (Lin et al., 2019), “trust in collaboration” (Liu et al., 2019), “information trust” (Suliyanti & Sari, 2019), “removal of trusted authority” (Turk & Klinc, 2017), and “trusted distributed ledger” (Yang et al., 2019). Other commonly used terms include transparency, traceability, immutability, security, automation, auditability, decentralisation, and disintermediation (Kobashi et al., 2020; Lüth et al., 2018; van Leeuwen et al., 2020; Wainstein, 2019; Woo et al., 2020; Ye & König, 2021; Zeng et al., 2020).

Limitations of the exploratory review included using only one scientific database, Scopus, due to the inconsistencies and errors that emerged when amalgamating information from various scientific databases. In comparing the search results from seven scientific databases, Scopus overshadowed its competition by a large margin; furthermore, around 85% of the documents indexed in other scientific databases were also indexed in Scopus. The exploratory review provided a solid foundation for aggregating the most common application categories for blockchain in construction, providing context to the existing environment in which this research's topic is positioned.

2.5 Related Works

Below are 13 publications that overlap with the topic and aim of this research. They include blockchain test applications for managing cash flow in construction projects; furthermore, they are tested through proof of concepts (PoCs) or case studies, which are methodologies used in this thesis.

Elghaish et al. (2022) published a PoC of a blockchain cash flow management application titled "Financial management of construction projects: Hyperledger Fabric and chaincode solutions". That application proposed a payment system using existing cost management practices such as lump-sum, target-cost, and cost-plus (Elghaish et al., 2022). The simulated participants in that PoC entered cost and schedule data into smart contracts that control the execution of payments to the supply chain (Elghaish et al., 2022). The PoC used smart contracts to automate the release of retentions to address the problem that contractors face when clients abuse the defects liability period (DLP) (Elghaish et al., 2022). There is a standard procedure in construction contracts that allows the client to retain a percentage of interim payments to insure against the defects at the project closeout stage. The DLP provision includes a procedure for the release of this retention. Hyperledger Fabric was used for the blockchain; furthermore, IBM's Blockchain Beta 2.0 Cloud Platform was used for the user interface and smart contract templates (Elghaish et al., 2022).

Hamledari and Fischer (2021c) conducted a simulated study of 14 participants (two groups of seven) to compare the data accuracy and efficiency of proprietary software versus a blockchain application. Their publication is titled "Measuring the impact of blockchain and smart contracts on construction supply chain visibility" and focuses on integrating product flows with cash flows (Hamledari & Fischer, 2021c). Product flows are the transportation and installation of materials and components, whereas cash flows are payments for delivered works. The results showed that blockchain provided higher quality information whenever project data was queried; furthermore, the data was more accurate and traceable (Hamledari & Fischer, 2021c). For example, tracing payments to invoices, cost codes, valuations, and scheduled works was more efficient. The application was deployed on Ethereum; it used JSON (JavaScript Object Notation) for the RPC (remote procedure calls) and IPFS (Interplanetary File System) for decentralised storage.

Ahmadisheykhsarmast and Sonmez (2020) published an article titled "A Smart contract system for security of payment of construction contracts" and conducted interviews with industry practitioners to investigate the viability of their proposal. Their application involved developing a software plugin that exports text data (e.g., '.txt' format) from MS Projects; furthermore, a user interface is used to import the text file into Ethereum smart contracts (Ahmadisheykhsarmast & Sonmez, 2020). One limitation is that the client must send milestone/progress payments one month in advance to a smart contract, which ensures project funds are secured; afterwards, subcontractors are paid directly from the smart contract. However, this is not how construction payments normally operate because the main contractor is the one that covers subcontractor liabilities and not the client; afterwards, the main contractor later claims the expense from the client at agreed milestones. Some forms of contract do contain provisions for direct payment to subcontractors in given circumstances, but these types of contracts are not typical.

Research shows that late payments typically start with the client (Abdul-Rahman et al., 2009). Thus, if the client is typically late when payments are due, they will not have the liabilities ready one month in advance. Nevertheless, the work was presented to construction practitioners, whose primary critique was the lack of privacy between the client's and the main contractor's liability payments because all data was publicly viewable (Ahmadisheykhsarmast & Sonmez, 2020). The comments also included "improves financial planning and management", "has a potential to eliminate the majority of the current payment issues of the construction industry", and "when all the payments are made on time, the project performance could improve substantially" (Ahmadisheykhsarmast & Sonmez, 2020). Wu et al. also published a similar article that proposes a blockchain payment application that includes payment-freezing (Wu, Lu, et al., 2022).

Yang et al. (2020) conducted a case study of a blockchain application for the construction industry titled “Public and private blockchain in construction business process and information integration”; it focuses on the procurement and transportation stages of building components. The process they documented is as follows: A contract manager and subcontractor both sign an agreement to supply a building component on-site; the procurement team pay the subcontractor a 30% deposit for the goods (via smart contract); and the remaining 70% is paid (via smart contract) when the item arrives on-site and passes a quality inspection (Yang et al., 2020). The entire process is conducted through the Ethereum blockchain, and smart contracts are used to automate all payments at delivery checkpoints (Yang et al., 2020).

Chong and Diamantopoulos (2020) conducted a case study of a Web application that integrates Internet of Things (IoT) sensors, BIM, and blockchain to trace façade panels from the manufacturer’s warehouse in China to its final installation on-site in Australia. Each panel was live-tracked via GPS (geographic positioning system), and the data was synchronised with a BIM model (Chong & Diamantopoulos, 2020). Smart contracts were used to record the data flows at key delivery checkpoints; however, automated payments via smart contracts were not utilised (Chong & Diamantopoulos, 2020). It is the only case study this dissertation’s author came across that used blockchain in a real-life construction project; however, its technical composition was not presented, such as which blockchain platform, Web services, or digital tools were used in the application’s development. Thus, the application could not be externally verified.

Sigalov et al. (2021) Created a Web application that uses APIs (application programming interfaces) to integrate a BIM model with a construction bill of quantities (BoQ); afterwards, data is pushed into a back-end system that calculates liabilities owed; finally, APIs are used to transfer data from the back-end to the smart contracts. However, payments were settled via standard bank transfers because of blockchain’s regulatory challenges when conducting the study (Sigalov et al., 2021). All technical components in that application were built and comprehensively presented, such as the user interface , back-end, data layer, and APIs; furthermore, it is suitable for industry piloting because it mimics a real-life application (Sigalov et al., 2021).

Sonmez et al. (2022) Created a Web application integrating a BIM model with smart contracts to execute payments. BIM objects were exported manually from Revit via a plugin that converts model data to a '.txt' file; afterwards, the text file was imported into a user interface that calculates liabilities owed (Sonmez et al., 2022). The study revealed that the cost of deploying the smart contract was ETH 0.3 (roughly £400 in early 2023) per 500 BIM objects (Sonmez et al., 2022). A limitation of that proposal is that the user interface is substantially underdeveloped and does not adequately mimic a real-life application.

Another study that integrated BIM with blockchain is an IPD (integrated project delivery) payment application by Elghaish et al., who presented how smart contracts can manage cash flow activities such as profit, cost saving, and reimbursed cost (Elghaish et al., 2020). Equations were shown in calculating cost data; however, no evidence was displayed on how the equations would be codified into smart contracts. Additionally, the user interface was minimally configured and did not display any project-relevant data (i.e., amount paid, payment status, payer and payee details, project references, etc.); therefore, users would have to manually call the smart contract every time cost data needed querying (Elghaish et al., 2020).

Hamledari and Fischer (2021b) prototyped a test application that uses an unmanned autonomous vehicle fitted with reality capture technologies (i.e., sensors) to scan the completeness of on-site construction (Hamledari & Fischer, 2021b). Afterwards, the data was uploaded into a 3-D BIM model that integrates with scheduling and pricing data (Hamledari & Fischer, 2021b). The project data is stored in an IPFS repository (a decentralised cloud), and an API (application programming interface) autonomously pushes the payment data into smart contracts for processing (Hamledari & Fischer, 2021b). However, no screenshots of the user interface or code were presented (Hamledari & Fischer, 2021b). Thus, the work could not be externally verified from an application development perspective. External verification via open-source code is crucial in research because it allows other researchers to replicate the work.

Ibrahim et al. (2022) developed and tested a Web application for managing project schedules, retentions, and liability payments; however, there was no evidence of how the Web application integrates with smart contracts. The main goal of the study was to record the status data of milestone payments (e.g., “submitted”, “approved”, or “paid”) (Ibrahim et al., 2022). However, that study insufficiently demonstrated whether the user interface is integrated with the smart contracts or if manual data entry is required to transfer data between the systems.

Perera et al. (2021) created a blockchain-based Web application for buying and selling land and real estate, using smart contracts to settle transactions. The user interface reflects a real-life application and displays evidence of transactions in Hyperledger Explorer (Perera et al., 2021). Hyperledger Fabric was used as the blockchain platform, and Hyperledger’s software development kit ‘was used to bridge the user interface to the smart contracts (Perera et al., 2021).

Tezel et al. (2021) presented a PBA (project bank account) blockchain payment application that uses smart contracts to represent the PBA. The user interface mimics a real-life Web application, and users interact with the user interface to approve scheduled works that trigger payment executions via smart contracts (Tezel et al., 2021). However, the study lacked sophistication in terms of adapting to project variations and change orders, and the system did not consider how various project participants, such as the client, main contractor, subcontractors, consultants, and PBA manager, would interact with the application to perform user-specific tasks (Tezel et al., 2021).

Das et al. (2020) Published an article titled “Securing interim payments in construction projects through a blockchain-based framework”, which proposed a conceptual framework for cash flow management and privacy-preserving data exchanges using a public blockchain. The article showcased how multiple users can combine the addresses of their public keys to generate a new shared project wallet for encrypting and decrypting data stored on the blockchain (Das et al., 2020). The interim payment data would be encrypted in smart contracts; then, authorised parties would decrypt the data with the shared project wallet, enabling privacy on a public blockchain (Das et al., 2020). However, payments are settled via standard bank transfers (Das et al., 2020). Smart contracts were only used to automate the process of authenticating payment information, validating payment certificates, and providing proof of executed liabilities (Das et al., 2020).

Of the 13 above-mentioned related works of blockchain payment applications for construction, five provided open-source code (Elghaish et al., 2020; Elghaish et al., 2022; Sigalov et al., 2021; Sonmez et al., 2022; Yang et al., 2020); and two provided pseudocode (Ahmadisheykhsarmast & Sonmez, 2020; Das et al., 2020). Pseudocode is when code syntax is written in a natural language rather than a programming language, which is done for human readability; however, pseudocode cannot be computed. Six of the above-mentioned related works did not display any code despite proposing blockchain applications (Chong & Diamantopoulos, 2020; Hamledari & Fischer, 2021b, 2021c; Ibrahim et al., 2022; Perera et al., 2021; Tezel et al., 2021). Not providing open-source code limits the ability of external researchers to audit and replicate the solutions. All blockchain platforms are open-source; therefore, building closed-source applications above an open-source technology is counterintuitive because external users cannot transparently verify it. External validation is vital in blockchain because of decentralisation, whereby no central authority can be held accountable if the technology malfunctions; thus, trust is achieved through codebase transparency. However, there are several reasons why researchers may not publicly display their code open-source, such as intellectual property restrictions, fear of others stealing their idea or non-disclosure agreements imposed by academia-industry joint ventures. However, due to the ubiquitousness of open-source code in the blockchain ecosystem, a solution built with closed-source code is uncompetitive.

Of the 13 abovementioned related works, only one article reviewed the cost implications of implementing blockchain in a practical context (Ahmadisheykhsarmast & Sonmez, 2020). However, none of the applications presented in those 13 articles provided a publicly accessible user interface, which is crucial because external users testing it is a significant aspect of application development. In contrast, the user interface of this dissertation's proposed application is publicly accessible via a standard weblink, and the smart contracts are presented open-source on GitHub (GitHub is an open-source code hosting platform). The proposed application's cost analysis and links to the open-source codebase are presented in Chapter Four (Conceptual Framework).

Change orders occur regularly in construction projects (Tezel et al., 2021). A change order is when a construction contract is updated to accommodate a project variation, such as alterations to deliverables, costs, or schedules. The data immutability of blockchain smart contracts is simultaneously a benefit and limitation. It is a benefit because contract conditions are hard-coded and immutable, which means contract conditions written within the SC cannot be breached; however, it is also a limitation because the hard-coded conditions within a SC cannot be changed to accommodate change orders. The problem with redeploying a SC is that it creates data and transaction fragmentation. An example of a crucial transaction stored within an SC would be when the main contractor approves a payment to the subcontractor via the SC. If the SC requires superseding and redeploying because of a change order, then the new redeployed SC would not carry the transaction records of the superseded SC. Transactions within SCs are stored on the blockchain and are thus immutable; however, if an SC is superseded, the transactions within the superseded SC remain with it and are not carried through to the new redeployed SC. This creates unnecessary business logic complexities when the data and transactions of multiple superseded SCs must be reconciled in the project. In the context of using SCs for PBAs, each redeployment of the SC would require PBA funds to be transferred from the superseded SC to the redeployed SC. Redeploying a SC numerously poses a cybersecurity risk because it opens more opportunities for a malicious actor to interfere with the SC code and steal project funds. A solution is needed where SCs do not require redeployment when change orders occur that change the logic of how the SC operates. In any of the literature referenced in this thesis, the author did not encounter discussions regarding how to accommodate change orders in a SC without having to redeploy the SC. This thesis provided a solution to the SC redeployment problem and confirmed its viability in its proof of concept. The solution is to deploy a network of SCs (instead of one SC) and connect them like relational databases. Therefore, when the data or logic of one SC is updated, it updates the data or logic of the other SCs in the network without needing to redeploy any of them. This is a technical solution that is discoursed in greater detail in Chapter 6: Discussion, section 6.2: Discussing the Framework.

Another gap in the literature reviewed of this research is the ability to configure smart contracts (SC) to encapsulate three processes in one system: (1) payment schedule, (2) payment approval form, and (3) payment execution. Traditionally, the data of the three abovementioned processes do not integrate even though they are related. The 13 related works reviewed in this section integrated two of these processes, but none integrated all under one system. For example, Hamledari and Fischer (2021c) integrated the payment approval form and payment execution system but not the payment schedule; Elghaish et al. (2022) integrated the payment schedule with the payment approval form, but no payment execution system; similarly, Sonmez et al. (2022) integrated payment approval form and payment execution system, but payment schedule data was managed with traditional schedule software, and data had to be manually exported from the schedule sotware and manually imported into SCs. The proposed PBA blockchain application integrated the three abovementioned systems (i.e., payment schedule, approval, and executions) while also integrating with a digital PBA trust deed in the form of a SC. The PBA trust deed provides a list of project participants with permission to approve or receive payment from the PBA; therefore, integrating the PBA trust deed as part of the proposed application was crucial. The technicality of how this was achieved is discoursed in Chapter 4: Conceptual Framework, section 4.3: Proposed Application Process Flow.

3 Methodology

This dissertation's methodological choice was multi-method, with qualitative data being collected from two groups of study participants: (1) construction consultants and (2) blockchain engineers. Multi-method differs from mixed methods because the former uses two types of qualitative data while the latter uses qualitative and quantitative data in research. Two groups of study participants were selected for the data collection to gain insight from the organisational and technical perspectives. The construction consultants are highly skilled in construction cash flow but lack general blockchain knowledge. In contrast, blockchain engineers are highly experienced in blockchain but lack general construction cash flow knowledge; therefore, a multi-method methodological choice was selected.

3.1 Strategy

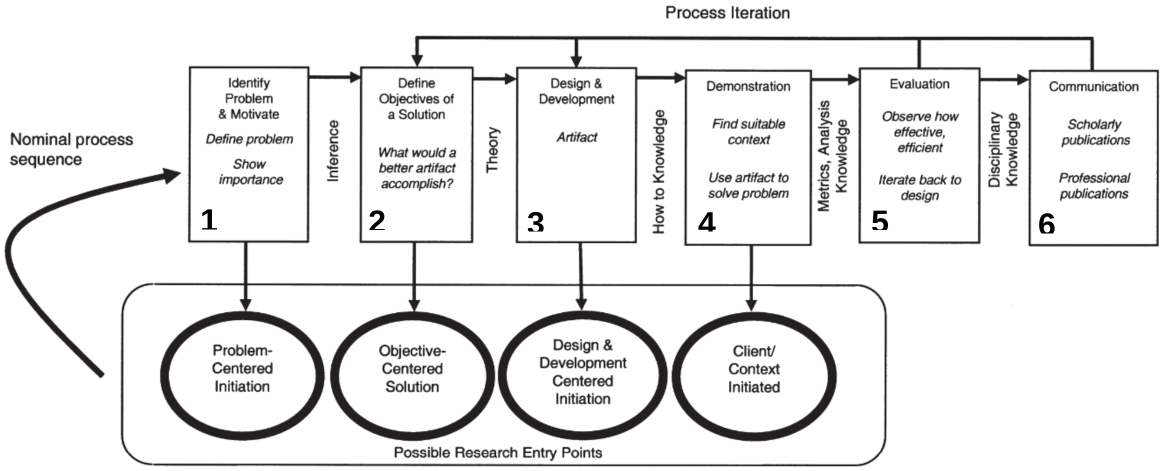
Simulations are discussed in research as an effective strategy for iteratively developing and testing applications (Eldabi et al., 2002). Simulations enable study participants to engage with research more effectively because they can visualise the solution in a more practical context (Akin et al., 2020). A simulation of the proposed PBA blockchain application was used as the strategy for presenting the work to the study participants, which was done to encourage better research engagement. According to (Udwadia, 1986), study participants are more responsive to research when given less abstract information. The simulation included a live demonstration of how various supply chain members engage with the application's user interface to perform cash flow management tasks. The author presented a simulation of the proposed application to the study participants at the start of each data collection.

A design science research (DSR) approach was used to structure this research into six phases, as shown in Figure 14, comprising: (1) identifying problem and motivation, (2) define objectives and solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. These phases are explained in greater detail later in this section. However, a summary of their activities encapsulates developing the proposed application, presenting the work to candidates knowledgeable in PBAs, presenting the work to blockchain engineers for technical feedback, and evaluating the findings to identify how the application can be improved from an organisational and technical perspective.

A DSR approach systematically collects and analyses data across many data collection stages (Collatto et al., 2018). However, this research delimited its data collection to two stages due to the time restrictions of this research. Accommodating two data collection stages, analysing it, discussing it, and concluding the research took up the entirety of the 4-year research duration. The development of the PBA blockchain application in this research consumed a significant portion of the research timescale; therefore, this was balanced with the data collection and other research chapters to ensure maximum efficacy was achieved from the findings. Following a DSR approach typically comprises numerous data collection stages because it relies on a feedback loop process for designing and developing a solution. A limitation of this research is that the full benefit of utilising the feedback loop process of the DSR was restricted to two data collection stages only. However, at the time of planning the deliverables of this research, the author made an educated judgement on the realistic output of this research and projected that achieving more research depth and clarity with less data collection stages was a more rational approach. Applying DSR to this research was a risk because of the complexity of designing, building, and testing the proposed application through a proof of concept is technically challenging and time-consuming, and the author also accepted that a minimum of two data collection stages was necessary for the DSR strategy to be feasible.

DSR shares similarities with action research in that they both attempt to solve a real-life problem (Collatto et al., 2018). The main difference between DSR and action research is that DSR "does not require a collaboration between researchers and participants in the environment in which the research is conducted" (Collatto et al., 2018). A solid theoretical foundation is crucial in DSR, such as having a clear, predefined structure for managing, analysing, and concluding data during the DSR study (Lee et al., 2011). DSR has an established body of knowledge instructing its implementation and strategies for accommodating deductive, inductive, and abductive approaches (Lee et al., 2011). However, there is a lack of academic consensus on which DSR strategy is best because it includes many adaptations (Peffers et al., 2007). Nevertheless, DSR is used in research that investigates systems integration and software development (Peffers et al., 2007). These are areas that overlap with the research strategy of this thesis. Figure 14 was the DSR model used to guide this dissertation's methodological strategy. According to Peffers, (Peffers et al., 2007), DSR includes six key steps: (1) *"Identify problem and motivation (define the problem and show importance)";* (2) *"define objectives of a solution (i.e., what would a better artefact accomplish?)";* (3) *"design and development"*; (4) *"demonstration (i.e., find suitable context and use the artefact to solve the problem)";* (5) *"evaluation (i.e., observe how effective and efficient, and iterate back to design)";* and (6) *"communication (i.e., scholarly publications)".*

Figure 14. The design science research (DSR) model used in this research.



Note. This Figure was taken from a scientific journal article titled "A Design Science Research Methodology for Information Systems Research" (Peffers et al., 2007).

Methodological steps of this dissertation's DSR project, as per the above Figure 15 guideline:

1) *Identify problem and motivation:* The problem of data processing delays, systems fragmentation, and lack of automation in construction cash flow management was identified in the literature review. This research uses the DSR strategy to structure the multi-method data collection to identify the organisational and technical potential for using blockchain to mitigate these problems. Across ten years spanning 2011 to 2021, the UK Government published six payment legislations ((Construction Leadership Council, 2016; GovUK, 2011) (UK Cabinet Office, 2012a) (UK Government, 2012b) (UK Government, 2013b) (UK Government, 2021b)) for improving cash flow management. Research suggests that governments struggle to enforce payment legislation because compliance auditing is administratively intensive and resourcefully costly (Maritz & Robertson, 2010).

This is because performance data in construction progress reports lack traceability due to the fragmentary nature of information in construction (Adel et al., 2022). The research hypothesises that transaction traceability should be straightforward to achieve in the proposed application due to blockchain being a transparent system. Blockchain has several attributes that make it an accessible technology to explore for testing applications, such as (1) how it uses cryptography and consensus to achieve high data trust and permanent transaction storage without intermediary systems (Agrawal, 2018); (2) it has an open-source codebase that is free to leverage and build applications without intellectual property restrictions (Igbojekwe, 2019); and (3) it mitigates the risks associated with centralised technology providers, such as vendor-lock, high proprietary fees, and technology monopolisation (Gaur et al., 2019). Blockchain is developed by a multitude of sectors, piloted by governments, and organisations are channelling substantial resources on its development; furthermore, critical insights from other sectors can be leveraged into construction due to it being a general-purpose technology, potentially reducing the cost of innovation (Al-Jaroodi & Mohamed, 2019). Hence, the motivation of this research is to test blockchain as a solution for construction.

2) *Define objectives and solution:* The objective of this research included proposing a conceptual framework, developing a test application, simulating how project participants interact with the application to manage cash flow, and collecting data on its practicality as a solution. PBA is selected as the test case because it aims to achieve increased transaction auditability, which is an inbuilt property of the blockchain; thus, both systems are harmonious to integrate. Despite the UK Government mandating PBAs in public-sector projects, they suffer from poor adoption because they are administratively time-consuming and costly to set up and manage. This adds to the workload of the main contractor, who already suffers from lack of profitability. Furthermore, clients do not pay additional fees for using PBAs, resulting in the main contractor absorbing the additional costs they impose on construction projects. The proposed application incentivises better adoption of PBAs through programming PBA and cash flow management functions into smart contracts to automate process flows.

3) *Design and development:* The *design and development* aspect of the DSR process is presented in Chapter Four (Conceptual Framework), where it is organised into

six developmental stages: (1) *blockchain selection*, discussing the decision process for choosing which blockchain was most appropriate for the study; (2) *technology setup*, highlighting the platforms, tools, and Web services that combine to create the proposed application; (3) *process flow,* illustrating how project participants would interact with the technology components to perform project management tasks; (4) *user interface*, displaying screenshots of the proposed application's user interface; (5) *cost*, showcasing all cost associated with deploying and operating the proposed application for an estimated one-year project duration; and finally (6) *codebase*, displaying the open-source codebase of all deployed smart contracts, allowing for external replicability.

4) *Demonstration:* The proposed application is presented to two groups of study participants: (1) construction consultants and (2) blockchain developers to test the application's framework from an organisational and technical perspective. In the first group, data was collected from a small number of construction practitioners with experience in managing PBAs in construction projects. In group two, data was collected from blockchain engineers via a questionnaire because a higher response rate was deemed more suitable, and a higher number of respondents could be reached more easily via an online questionnaire instead of interviews or video calls. The questionnaire's purpose was to extract technical comments regarding decentralised application development.

5) *Evaluation:* The evaluation uses thematic analysis to structure the responses into themes and subthemes; afterwards, the findings are fed back to DSR stage three: *Design and development* to improve the proposed application iteratively. The evaluation is presented in Chapter Six (Discussion).

6) *Communication:* The communication stage included writing this thesis, publishing the findings in construction journals, and publicly deploying the final version of the proposed application's user interface and smart contracts to allow anyone to test the application.

3.2 Data Collection

This dissertation's data collection adopted a multi-method, qualitative approach: (1) a questionnaire and (2) a focus group interview. Despite data being collected at two stages, the research was not longitudinal because a different sample of participants was used for each data collection and because the research is limited in time duration. Longitudinal research is when data is collected from the same sample of participants over many occasions (Kothari, 2004). Instead, the research was cross-sectional because data for the two data collection types was collected at relatively the same point in time.

There are multiple ways to collect primary and secondary data when conducting qualitative research. Examples of primary data include interviews (one-to-one and focus groups), questionnaires, and observations (Kothari, 2004). In comparison, secondary data includes archival research, which is data that has been previously recorded (Cassell et al., 2018). Archival research was used in Chapter Two (Literature Review) to identify existing conceptual frameworks of blockchain applications. Initially, the researcher aimed to build upon existing applications; however, due to the nascency of the topical area, no current frameworks could be used as a solid theoretical underpinning for the proposed application. Therefore, a new conceptual framework was proposed, and primary data was collected to verify the proposal's feasibility in the current environment.

Primary data is the main contribution of this dissertation's methodology. The Saunders research onion, shown in Figure 15, was used to organise the methodology into logical layers, such as the research philosophy (pragmatism), research approach (abductive), methodological choice (qualitative), research strategy (DSR), and data collection. Pragmatism was selected as the research philosophy because this research focuses on practical solutions to organisational problems. Blockchain's nascency, lack of governmental regulation, and lack of formal adoption in enterprises may appear counterintuitive for pragmatism; however, blockchain has many benefits that centralised technologies cannot rival, such as having a fully open-source codebase, programmable agreements, no proprietary/licence fees, and no intellectual property restrictions; furthermore, blockchain provides free protocol infrastructure for users to exploit at no cost. This is elaborated further in Chapter Six (Discussion).

The research philosophy (i.e., pragmatism) affects the strategy for the data collection; therefore, despite it being the outermost layer of the methodology and the data collection being the innermost layer, the research philosophy directly influences the data collection method and analysis. For example, while interpretivism focuses on personal narratives, pragmatism focuses on practical solutions. How interpretivism and pragmatism view truth is also dissimilar. For example, interpretivism places each participant's subjective experiences as valid perspectives of a multidimensional truth (Saunders et al., 2019, p. 148). Pragmatism, conversely, views truth as whatever solution/system best serves society and the organisations within it, emphasising practical utility as the ultimate purpose (Van Zyl, 2015).

The methodological approach affects the selection of the data collection type and the sampling of participants for the study. This thesis used an abductive approach because Chapter Two (Literature Review) identified thirteen related works by other researchers that overlap with the topical area of this dissertation; therefore, the topic already has some ideas on how to utilise blockchain for managing cash flow, found in the Related Works section of Chapter Two (Literature Review). However, these examples are early-stage and lack technical and practical focus. Nevertheless, the proposed application was influenced by the best ideas from the related works and used them to guide its development.

Multi-methods such as a questionnaire and focus group were used for the data collection because feedback from specialists from two subject areas (construction and software engineering) was necessary for developing the proposed application. Design science research (DSR) was the strategy used because it provides a theoretical model for managing multi-methods data collection and analysis. DSR is also an applied research strategy; thus, it is naturally incorporated with pragmatism research. DSR also operates effectively with abductive research because it does not rely on complete and large data sets to formulate a solution. For example, an organisation might use DSR to solve an internal problem with limited data and resource constraints. DSR is governed by an iterative feedback loop process (Collatto et al., 2018). This thesis adopted the DSR process by collecting data in two stages and feeding the findings back to this dissertation's proposed framework for improvements.

3.2.1 Sample Size and Selection Criteria

This section discourses the sample size and selection criteria for recruiting candidates for the focus group interview. The author's research studentship is sponsored by a UK main contractor that uses PBAs in construction projects. The contractor had previously informed the researcher of their willingness to assist with research; thus, a list of PBA managers was requested from them, to which they responded with a list of personnel with working experience of PBAs and consent for contacting them, of which 20 potential candidates were contacted. The introductory e-mail highlighted that the topic of discussion was *blockchain and PBAs* and that it was searching for interview candidates with general knowledge of the topic. Of them, three were knowledgeable and were enlisted for the study. The researcher managed to recruit another candidate via other means. In this case, the candidate made first contact with the researcher via e-mail, expressing an interest in a PBA blockchain conference paper (i.e., (Scott et al., 2022a)) published by the researcher. This participant was highly knowledgeable in blockchain and was in the process of conceptualising a PBA decentralised finance solution for construction and was working directly with a blockchain platform. The researcher sent an invitation e-mail to the candidate to participate in the research, and they accepted. This made the total number of confirmed focus group participants four. The only demographic data collected from the participants was regarding job occupation, country of employment, years in the role, and years working with PBAs. The focus group was conducted via video call vs. in-person based on the participants' preferences. The level of data saturation from the four participants was of satisfactory quality and quantity for thorough data analysis; therefore, a second focus group interview with other participants was considered unnecessary. The employment background of the participants included a treasurer, contract manager, legal consultant, and technology consultant, all within the UK construction industry. The participants agreed to a two-hour focus group interview. The researcher live-presented the proposed application during the interview, and the participants were encouraged to ask questions throughout the demonstration to promote discussions.

Table 7.
Demographics of the focus group participants.

Job occupation	Years in occupation	Country of employment	Years working with PBAs	Knowledge level of blockchain
Treasurer	20+	UK	10+	Beginner*
Contract manager	15-19	UK	6-9	Beginner*
Legal Consultant	15-19	UK	6-9	Intermediate*
Innovation consultant	15-19	UK	3-5	Advanced*

Note. * This is based on the researcher’s personal judgement post-interview.

The second part of the data collection includes a questionnaire with blockchain developers to investigate approaches for building the proposed application. A questionnaire was selected for the method because a variety of responses from a large sample is more valuable for this aspect of the data collection than in-depth interviews. This is because blockchain applications are built from numerous software components, and developers tend to favour specific tools; therefore, having several perspectives on decentralised application development is beneficial for this research. Roughly 800 candidates, from researchers to industry practitioners, were invited to participate in the questionnaire. Of this, roughly 50% were from the discipline of computer science, 40% from software engineering, and 10% from the construction industry. Computer science and software engineering were predominantly targeted because they are the subject areas with the highest technical competence in blockchain. Additionally, there is a lack of knowledge transfer from these domains to the construction industry. Amassing a list of questionnaire candidates followed two approaches: Firstly, a search query titled “TITLE-ABS-KEY (blockchain AND payment AND application)” was entered into the search box on the Scopus webpage (Scopus is a voluminous scientific publication database). The results were then filtered further (via Scopus’s filter function on their webpage) to display publications related to the abovementioned subject areas. Afterwards, each paper was assessed for suitability (i.e., checking whether the paper proposed, developed, or piloted a blockchain payment application). The authors of the relevant papers were then sent an e-mail invitation to participate in the questionnaire. The second approach for amassing a list of candidates was achieved by searching LinkedIn for blockchain engineers, followed by assessing whether they have technical experience developing blockchain applications, and finally, sending them an invitation to participate in research via a private LinkedIn message. Of the 800 prospective candidates contacted through Scopus and LinkedIn, 38 participants responded to the questionnaire (a response rate of 5%). Participation in the questionnaire was anonymous because the researcher did not want identifiable data to lower the probability percentage of responses. Furthermore, comparing subgroups of demographic data was not the focal point of the research since a purely qualitative analysis approach was planned (i.e., thematic analysis). The researcher also projected that the target sample size for the questionnaire responses would not be numerous enough to warrant quantitative generalisations; thus, the questionnaire opted for anonymous responses.

The researcher designed the questionnaire to be 15 minutes duration. In a study conducted on questionnaire durations, the results displayed that the drop-off rate (the rate at which invitees reject taking part in a questionnaire) was 52% at 25 minutes but only 21% at 10 minutes (Yan et al., 2010). A decision was made to design the questionnaire duration to 15 minutes because 10 minutes was overly limiting, while a more protracted duration was at risk of a higher drop-off rate. Invitations to the questionnaire were sent out in April 2022, and candidates were given a two-month timescale to complete it.

3.2.2 Ethical Considerations

Before any data was collected for this thesis, the author had to submit an ethics form to the University College London (UCL) Bartlett School of Sustainable Construction (BSSC) Ethics Committee. Furthermore, since the author of this thesis was sponsored by a UK construction company and employees from that company were interviewed for research, a separate ethics form from the company had to be completed. No data was collected until the ethics forms from UCL BSSC and the construction company were approved. The information within these ethics forms comprised:

- Overview of the topical area and aim of the research.
- Proposed methodology for the data collection, which was a focus group interview and a questionnaire. In the UCL BSSC ethics form, the two data collection types were disclosed. However, regarding the construction company's ethics form, only the focus interview data collection type had to be disclosed because the candidates for the interview were employees of the company. The questionnaire data collection type was not relevant to disclose to the construction company.
- The sampling strategy has to be discussed, justification for the approach taken, and the duration of the data collection. Specifically, the author expressed that a focus group interview was selected because the author wanted in-depth discussions, and a questionnaire was selected because a higher quantity of responses was required for the questionnaire data.
- Formal documentation had to be completed in preparation for inviting candidates to participate in research, such as the interview consent form,

questionnaire consent form, participant information sheet (which includes a section that informs candidates that their participation is voluntary), list of questions that will be asked to the candidates (for review by the ethics team only), and the method for how candidates would be invited to participate in research. All participants were invited to participate in research via an invitation e-mail). This e-mail included an introduction to the research and why data collection was being conducted, it also included attachments such as the interview consent form, questionnaire consent form, and participant information sheet.

- Because the author's PhD was funded by a construction company and data would be collected from them, he had to make a statement to the UCL Ethics Committee and to the construction company's ethics team on how the company's data would maintain privacy across two areas (1) corporate privacy, and (2) user privacy. Regarding corporate privacy, the author signed a non-disclosure agreement with the construction company stating that their corporate identity would remain private throughout the entirety of the research and that any data collected from them must remain confidential. Regarding user privacy, the author confirmed that only non-identifiable demographic data would be collected from the interview candidates, such as job title, years in occupation, country of employment, years of experience working with project bank accounts, and whether they have prior knowledge of blockchain. The interview candidates were informed that their names would not be recorded in transcripts, and the video recording of the interview would be deleted after the research was complete.
- Regarding the questionnaire data collection, candidates were informed that their responses would be entirely anonymous and that the online questionnaire would not record any data on who completed it. The author also informed the questionnaire candidates that their responses would be deleted after the research is complete.

When the abovementioned information was provided to both the BSSC UCL Ethics Committee and the construction company's ethics team, The UCL BSSC Ethic Committee scheduled an online call to confirm the details, whereas the construction company was satisfied with the completion of their ethics form. When approval was received for both ethics forms, granting permission to the author to collect data, the author initiated data collection.

3.3 Data Analysis

The data analysis was organised into two subsections: Thematic analysis, and Application readiness level. Both analysis methods were used to analyse the data.

3.3.1 Thematic Analysis

A thematic analysis was used to analyse the focus group and questionnaire data. Thematic analysis is one of the most common methods for reviewing and organising qualitative data and is used to identify patterns in data sets such as transcripts, observations, or documents (Saunders et al., 2019, p. 651). Thematic analysis “requires the researcher to engage in an iterative process of critical thinking, questioning, and categorising” (Lapan et al., 2012, p. 129). Thematic analysis uses axial coding to structure research data into themes and subthemes for better structure and evaluation (Cassell et al., 2018). An example of conducting thematic analysis for a focus group is as follows: Transcribe and thoroughly read through the responses, code the results into groups/themes, and document the findings (Lapan et al., 2012, p. 129). A similar thematic analysis was used on the questionnaire and focus group data. The questionnaire’s thematic analysis assessed the technical concerns of using decentralised technologies in the enterprise landscape. In contrast, the focus group’s thematic analysis investigated the proposed application's strengths, weaknesses, opportunities, and threats from the perspective of construction practitioners experienced in managing PBAs.

3.3.2 Application Readiness Level Analysis

A method is required to assess the maturity of the proposed application in this research. He et al., (2023) highlights that “technology readiness refers to the development level and maturity of a particular technology or system” and that “it includes the assessment of a technology's functionality, reliability, performance, and safety”. The first technology readiness level (TRL) scale was created by a NASA (National Aeronautics and Space Administration) researcher named Stan Sadin in 1974, which comprised a 7-point scale (Banke, 2010). This was later revised by John Mankins (1995, p. 1) of NASA to include a nine-point TRL scale. This nine-point scale has been widely adopted across many disciplines in research and industry for assessing technology maturity (Mankins, 2009, p. 1217).

The Mankins nine-point TRL scale is as follows:

> “TRL 1: Basic principles observed and reported;
> TRL 2: Technology concept and/or application formulated;
> TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept;
> TRL 4: Component and/or breadboard validation in laboratory environment;
> TRL 5: Component and/or breadboard validation in relevant environment;
> TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space);
> TRL 7: System prototype demonstration in a space environment;
> TRL 8: Actual system completed and “flight qualified” through test and demonstration (ground or space);
> TRL 9: Actual system flight proven through successful mission operations” (Mankins, 1995, p. 1).

An adaptation to the Mankins nine-point TRL scale was used to assess the proposed application’s maturity. The author named this adaptation the *application readiness level* (ARL). While the Mankins TRL focused on a successful spaceflight as its utmost level on its scale, the proposed ARL focuses on an application’s commercial adoption as its utmost level. The definition of each level on the proposed nine-point ARL scale is documented in Table 8 in this section.

The subthemes created in the thematic analysis of the data collection of the focus group and questionnaire participants were used as the factors for measuring the application’s ARL. The names of these factors are the same as the names of the subthemes. The terminology *subtheme* is qualitative in nature and is not typically used as a parameter in quantitative analysis, and thus, these *subthemes* were synonymously labelled as *factors* when calculating the application’s ARL. Furthermore, the term *factor* helps differentiate when discussing the ARL factors versus the thematic subthemes. The ARL scale was used to score each ARL factor individually, and then the average score across all the ARL factors equated to the total ARL score of the proposed application. Of the 27 subthemes created in the thematic analysis, 23 were used as factors for measuring the proposed application's ARL. The four subthemes that did not transpire into ARL factors include decentralised finance, relationship with banks, privacy solutions, and Web 3. The exclusion of these four subthemes is discussed in greater detail in Chapter 5: Data and Analysis, Section 5.3: Application Readiness Level. The 23 ARL factors were scored from 1 to 9 (like the Mankins nine-point scale), and the average score across the 23 ARL factors equated to the total ARL score of the proposed application. Each level on the proposed ARL scale is documented in Table 8.

Table 8.
Application Readiness Level scale

ARL	Description
ARL 1	ARL 1 is the exploratory research stage. It is the lowest measurement of the ARL scale because its purpose is not to develop a solution at this stage. ARL 1 is entirely research-focused and comprises providing evidence for the benefits and challenges of blockchain in general. It can include broad ideas (supported by research) on which blockchain is most suitable for construction, however, its primary aim is investigating its potential value contribution to the construction industry. At this stage, the research can include investigations on the socioeconomic, political, and organisational factors of blockchain in construction.
ARL 2	ARL 2 is the conceptual framework stage. The research aim is narrowed to one application, and creating a framework illustrating its functionality is crucial. The development of an application is not yet required at this stage; however, illustrations of the business process it aims to improve and an overview of the technology components it will comprise are vital. For example, a discourse of the formal processes and technology systems will be required, a discussion of how construction users would interact with the solution (i.e., would a Web application be built, will users manually send blockchain transactions, or will an application programming interface (API) be used to relay data from existing construction software). ARL 2 is when ideas and practicality merge to investigate the feasibility of an application.
ARL 3	ARL 3 is an application's first stage of development, demonstrating how its business processes are automated at the front-end and explaining how its application logic is performed at the back-end. ARL 3 is the stage that transitions this project from research-focused to development-focused; however, research continues to play a primary role throughout all ARL stages. At this stage, the researcher will simulate the application internally (i.e., self-testing the solution) and evaluate its functionality over many stages of trial and error. For example, when the author was developing the proposed application, he encountered many application logic issues while coding its smart contracts, which involved many iterations of application testing and redeployment until it functioned as intended.
ARL 4	ARL 4 is the proof of concept (PoC) stage. This stage requires primary data collection to validate the PoC's success or improve the application's functionality. This research adopted a design science research (DSR) methodology to provide structure to the PoC. An application can circulate frequently between ARL 2 to ARL 4 across many data collection stages because each feedback loop can cause a reconfiguration of the application's conceptual framework. The application's conceptual framework should be in a complete and final state before progressing to ARL 5.

ARL 5	ARL 5 comprises pilot testing the application to end-users to simulate a realistic industry environment and exemplify how it integrates with enterprise systems (i.e., business processes and software). No new business processes or technology components should be added to the application at ARL 5. However, minor alterations to the application's logic and user interface are typical. The primary goal for ARL 5 is proving that the application can operate effectively in conjunction with the other systems users by construction companies.
ARL 6	ARL 6 comprises prototyping the solution in an environment that simulates commercial adoption. Therefore, this stage not only exemplifies how it integrates with the systems of specific construction companies but also demonstrates its integration potential with the systems used in the wider commercial market. ARL 6 also requires proof that the application adheres to any business regulations and cybersecurity requirements, with proof of compliance. ARL 6 should present how a typical end-user can adopt the application without direct supervision from the application's development team. This can include the production of supporting documentation and tutorial videos for how to use and navigate the application. If an amendment of the application is required, it will need to revert to an earlier ARL.
ARL 7	ARL 7 is the minimum viable product (MVP) stage. Whether to scale the application back to a simpler solution or include all the desired functionality detailed in ARL 6 should be discussed, and a pathway for both scenarios should be planned. Factors that might cause the scaling back of the application include cost (i.e., who is funding its long-term development), time (i.e., maximum feasible duration of the project and future roadmap), and team (i.e., whether an appropriate team is in place to manage the workload demands of commercial adoption, market competition, and end-user support).
ARL 8	ARL 8 is the formal publication of end-of-project reports and documentation before commercial adoption (including standardising contracts for terms of use, intellectual property, and any other agreements). The application with all its functionality is complete, and all major and minor issues, along with stress tests, are formally documented and published.
ARL 9	The proposed application is formally deployed to the public and is closely monitored by the development team. It will likely require bug fixes (i.e., real-world errors that were impossible to predict during testing) to improve its operational performance. Maintenance and end-user support are the primary goals of this stage.

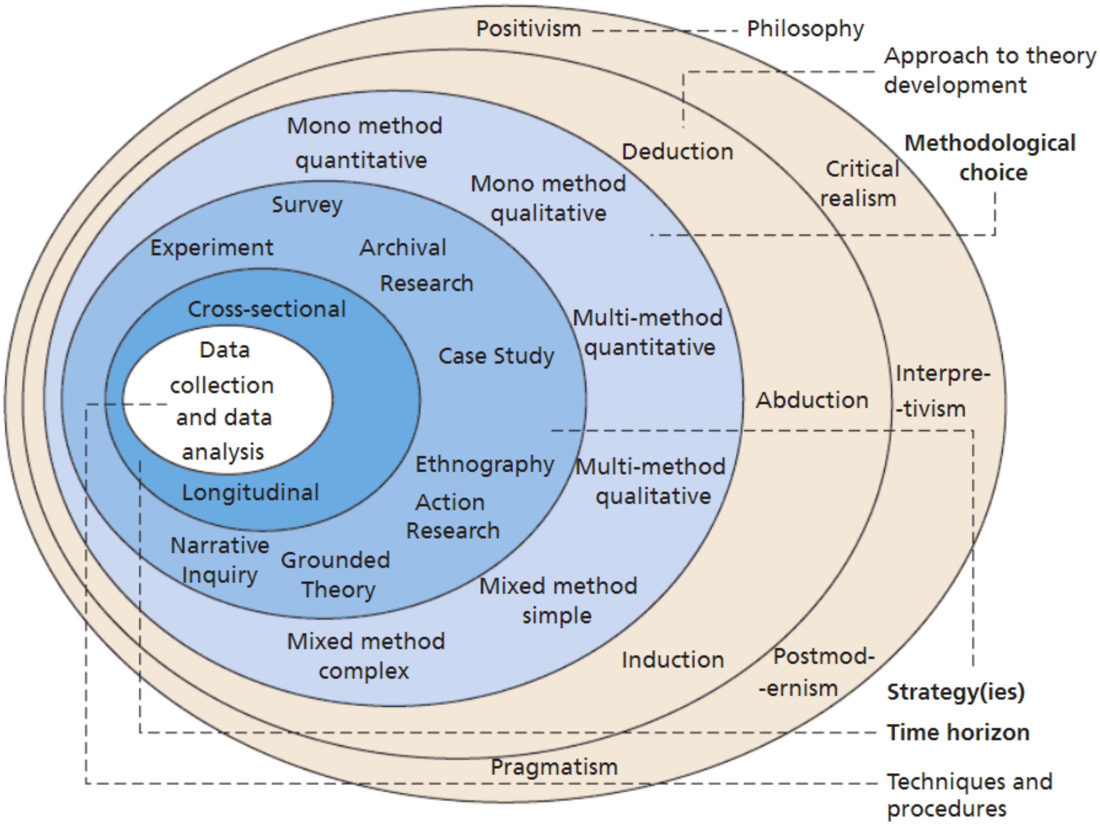
Note. The nine-point ARL scale discussed in this table is an adaptation of the nine-point TRL scale of John Mankins published in a NASA (National Aeronautics and Space Administration) report titled *Technology Readiness Levels* (1995, p. 1)

3.4 Philosophy

Writing about a philosophy of science would be incomplete without first touching upon its two fundamental components: ontology and epistemology (Hubert & Peter, 2020). Ontology is the study of being and the science of existence (Brinkmann, 2017). Ontology is also considered the foundation layer to understanding the nature of reality (Hubert & Peter, 2020). In particular, the relationship between the physical and metaphysical (thoughts, perceptions, consciousness, etc.) (Hubert & Peter, 2020). Ontology includes critical questions concerning whether an objective reality exists beyond human consciousness or whether all human knowledge is subjective (Cassell et al., 2018). Furthermore, ontology is the taxonomy (classification) of knowledge and its growing body (Hubert & Peter, 2020). A researcher's ontological starting point (their research philosophy) provides a framework for obtaining and creating knowledge from an epistemological perspective (Saunders et al., 2019). Epistemology answers the question: What is knowledge, and how can it be created? (Saunders et al., 2019). Each research philosophy has a different view of reality and may use different methods for creating, classifying, analysing, and validating knowledge (Silverman, 2021). Epistemology is "what we know and how we know it" (Brinkmann, 2017). There has been a longstanding battle of philosophies between the quantitative and qualitative spectrums, and each has its view on what constitutes epistemology (Cho, 2017). Epistemology also investigates the meaning of truth. For example, does an independent objective reality exist, or are individuals limited by their subjective experiences of perceiving the world through a human-centric lens (Hammersley, 2013). Furthermore, what is the relationship between the physical and metaphysical (non-material) world? (Hammersley, 2013) Moreover, should the meaning of truth be consistent for the natural and social sciences, or can different realities of truth co-exist under one philosophy? (Hammersley, 2013) This chapter tells the story of what research philosophy was adopted in this thesis, how it achieves epistemology, and its methodological underpinnings.

The Saunders "research onion" (as per Figure 15) was used as the skeleton for organising the methodology design into five key layers/sections, comprising (1) philosophy, (2) approach, (3) method, (4) strategy, (5) and data collection (Saunders et al., 2019, p. 130). The research design starts with the decision points governing the selection of the research philosophy and ends with the chosen methods for data collection.

Figure 15.
Research onion showing the various layers of a research methodology.



Note. This figure was copied from *Research Methods for Business Students* (Eighth edition. ed.), Pearson Education Limited (Saunders et al., 2019).

There are many different research philosophies; however, the four most conventional ones are positivism, interpretivism, critical realism, and pragmatism. A summary of these will be discussed before proceeding with this dissertation’s chosen philosophy.

Positivism uses quantitative methods to measure the physical and objective world (Saunders et al., 2019). It is deep-rooted in mathematics and the natural sciences (Saunders et al., 2019). Positivism is grounded on empirical research, hard facts, and equations/models (Lapan et al., 2012). It upholds clarity, measurability, and replicability as fundamental to its practice (Saunders et al., 2019). Furthermore, positivism states that data should be mathematically valid and not based on human beliefs or values (Hubert & Peter, 2020). However, this is one of the main critiques of positivism because social phenomena, such as sociology, economics, and psychology, encompass a large portion of reality; therefore, some researchers claim that positivism is biased in its quest to uncover the truths of existence (Brinkmann, 2017).

Interpretivism and positivism, which emerged in the early 19^{th} century, are the oldest but most polar opposite research philosophies (Hammersley, 2013). While positivism is macro-orientated, general, objective, and quantitative, interpretivism is micro-orientated, subjective, and qualitative (Hammersley, 2013). Interpretivism argues that people cannot be studied entirely from an objective lens because they create subjective meaning in their existence and cannot be generalised (Saunders et al., 2019). Interpretivism challenges the positivist's view on universality and advocates that the richness and depth of humanity will be lost if social science is reduced to generalisations and quantitative data (Saunders et al., 2019). An example of where an interpretivism philosophy excels is with biographical research on the complex lives of specific individuals, such as CEOs, to capture the narrative of their experience, life, and mindset (Saunders et al., 2019).

Critical realism (CR) investigates the nature of reality beyond the natural sciences (Hubert & Peter, 2020). It stipulates that more can be understood about reality if approached from a mixed-methods viewpoint (Hubert & Peter, 2020). CR accepts the positivist view that an observable world exists; however, the CR also accepts that people with their subjective realities and social structures exist and make up a large portion of reality; thus, simply viewing the world from a positivist lens would be inaccurate since society is built from people with subjective experiences (Hubert & Peter, 2020). However, viewing reality purely from an interpretivist perspective would also be unsatisfactory because reality exists in a duality of objectivity (external, physical, material) and subjectivity (internal, personal, and psychological) (Hubert & Peter, 2020).

Pragmatism, as practised by the classical pragmatists John Dewey (1859–1952), Charles Sanders Peirce (1839–1914), William James (1842–1910), and George Herbert Mead (1863–1931), is built on "knowledge, meaning, truth, and value" (Dixon, 2019). Pragmatism does not have a clear definition and is based on several epistemological viewpoints (Khin & Fui, 2012). However, according to John Dewey's view of pragmatism: "Truth is defined as the process of change that helps humans to solve practical problems or deal with the world" (Khin & Fui, 2012). Pragmatism sees value in practical solutions to real-life problems over theory and generalisations; hence, it is used as a problem-solving philosophy (Melles, 2008). Historically, research was divided into two spectrums, qualitative and quantitative; however, over time, it evolved to include mixed methods and paved the way for alternative philosophies such as pragmatism (Feilzer, 2010). Pragmatism focuses on “socially useful knowledge” and accepts qualitative, quantitative, and mixed-method research without biases (Feilzer, 2010). Pragmatism differs from CR in that it views practicality as inseparable from truth, whereas CR views practicality and truth as separate things. Truth for pragmatism is finding the most practical solution to solving society’s problems (Van Zyl, 2015).

Of the four research philosophies suggested, positivism is the least viable because this research is not seeking an objective, universal law governing how all construction companies should manage payments, nor is it using a quantitative method to collect hard, generalisable facts. Interpretivism is not a suitable philosophy either because, although this research included elements of subjectivity, it is not entirely concerned with personal narratives. Critical realism (CR) is more accepting as a research philosophy because it allows for a mixed methods approach and accepts social science as a regular part of understanding reality. However, pragmatism was chosen for this dissertation’s philosophy because it aims to solve a societal/organisational problem. While CR can be used to analyse the relationship between societal factors, it is less concerned with the operational efficiencies of companies, which this research aims to achieve. Where pragmatism differentiates from CR is that it accounts for the subjective realities of organisations. For example, construction companies all share some objective truths, such as how they suffer from a lack of digitisation and are mandated to abide by government legislation; however, they individually have internal subjective realities, such as how they are all affected by various problems at various intensities. Therefore, the practical solution for one company is different from another. For example, a more financially stable company will have a greater capacity to invest in innovation than a less financially stable company; thus, they have different realities for improvement. Pragmatism is not as concerned as CR with defining an objective/general and subjective/personal reality; instead, pragmatism looks at problems at an organisational level, which is a more practical approach to problem-solving because organisational constraints, such as time and money, directly affect the pragmatist view on truth. Since this thesis is focused on investigating organisational solutions to existing problems in construction, pragmatism is the philosophy most applicable to the research. For example, part of this dissertation’s data collection included collecting data from industry practitioners; thus, the reality of how organisations can leverage new technologies is the focal point.

To summarise what truth means for each of the four discussed research philosophies:

- For positivism, truth is understanding reality from a quantitative and objective lens (Saunders et al., 2019). Positivists use empirical research to collect hard (fact-driven) data that is highly replicable and generalisable (e.g., scientific laws that govern reality) (Lapan et al., 2012). Positivists believe humans and the observable world exist in one reality (Brinkmann, 2017).

- For interpretivism, truth is realised by investigating people and their subjective experiences of reality (Hammersley, 2013). Data collection is qualitative, personal, and challenging to replicate, and each person has a different truth because reality is subjectively experienced regardless of science's attempt to objectify it (Saunders et al., 2019, p. 148).

- For critical realism (CR), truth is achieved by merging positivism and interpretivism perspectives to create a holistic view of reality, reducing biases by integrating insights from quantitative and qualitative methods (Hubert & Peter, 2020). CR postulates that a large part of human existence is deep-rooted in social structures; thus, a philosophy incorporating subjective experiences is more likely to have a clearer view of reality than one that excludes it (Hubert & Peter, 2020). CR believes the physical and metaphysical worlds should be investigated under the same research philosophy (Hubert & Peter, 2020). Mixed methods research is commonplace in CR (Hubert & Peter, 2020).

- For pragmatism, truth is loosely defined as the most practical and verifiable solution to a problem and accounts for socio-economic, political, and organisational factors (Khin & Fui, 2012). Pragmatism is not as concerned as positivism and CR with objectifying reality (Van Zyl, 2015). Instead, pragmatism is deeply rooted in practical solutions for society (Van Zyl, 2015). This makes pragmatism suitable for applied research (Feilzer, 2010).

3.5 Approach

This research included assessing whether to undertake a deductive, inductive, or abductive approach. A deductive approach is when the research starts from an established theoretical framework and uses a top-down method to identify whether the framework applies to a specific use case (Saldaña, 2011). For example, conducting an experiment on whether a scientific law/fact holds true under different conditions/environments. Deductive reasoning is commonplace in quantitative research since it is used for testing the hypothesis of scientific models (Chandra & Harindran, 2017). However, this dissertation's approach is not deductive because although the research starts with a conceptual framework, the framework is used to initiate data collection rather than testing a scientific model.

Unlike a deductive approach, which starts with a theoretical framework. An inductive approach is bottom-up and starts with collecting data and then developing a theory based on the findings (Saldaña, 2011). An inductive approach is typically associated with qualitative research and is commonly used in the social sciences (Chandra & Harindran, 2017). Induction starts with a specific case and concludes with a generalisable theory, whereas deduction starts with a generalised theory and concludes with a specific case.

Finally, an abductive approach is used when a topical area lacks theoretical frameworks and uses research to produce the most probabilistically correct conclusion based on limited data (Silverman, 2021). Abduction is also best used when developing a framework/solution that is iteratively improved over several data collection stages (Saunders et al., 2019). Where abduction differentiates from induction is the starting point of the research. Abduction is not entirely bottom-up like induction because it starts from some conceptual underpinnings that guide the research. Abductive research typically takes on a qualitative form because it is more exploratory than deductive research and is not reliant on hard/quantitative data to create theories (Saunders et al., 2019). Essentially, abductive research is the middle ground between inductive and deductive research.

This research uses an abductive methodological approach because a conceptual framework is created from reviewing existing academic literature on the topical area. Afterwards, the framework is showcased to two groups of participants at various stages, and then qualitative data is collected to improve the framework. Throughout the entirety of this thesis, its framework is a work in progress; thus, an abductive approach is the most suitable for the research because the theoretical underpinning of the topical area is predominantly conceptual and immature for deductive studies.

4 Conceptual Framework

This chapter evaluated, in detail, the decision points that led to the proposed application's technology selection, architecture, and development. It was structured into six sections: (1) Blockchain Selection, (2) Technology Setup, (3) proposed Application Process Flow, (4) User Interface , (5) Cost, and (6) Codebase. This chapter showcases the integration of construction management and cash flow processes by integrating payment schedules, approvals, certificates, and executions in one application to increase system integration.

Blockchain was selected as the foundation infrastructure because it enables the deployment of applications on its protocol without needing to set up any platform infrastructure, databases, or cybersecurity systems (Tezel et al., 2020). Blockchain was explored because it allows users to deploy smart contracts that enable programmable money without building complex and costly APIs (application programming interfaces) that pull and push data between management and payment software. Escrows were one of the first use cases for smart contracts and are one of the least technical applications to test on the blockchain (Hassija et al., 2020). This makes it a good starting point for testing a blockchain project bank account (PBA) proof of concept (PoC) for the construction industry, as PBAs are simply a more sophisticated form of escrow. The core functionality of a PBA is to create a shared/collaborative account while having high transaction auditability (UK Government, 2012a, p. 4). These are inherent properties of the blockchain due to its transaction transparency and ability to manage multi-party agreements with smart contracts Scott et al. (2022b).

The UK Government commissioned the PBA payment strategy in 2012 and provided a schema for implementing it in construction projects (UK Government, 2012a). This schema was utilised in the proposed application. Due to the payment problems of construction, public sector clients, such as National Highways (formerly known as Highways England), mandated using PBAs to ensure that the cash flow of government-funded construction projects were correctly managed (Abrahams, 2019). Aside from the primary contribution of the PoC (i.e., systems integration and process automation), this research was a preliminary step toward exploring whether the terms of government payment legislation can be hard-coded into smart contracts to improve the ability of PBAs to comply to government standards.

4.1 Blockchain Selection

Assessing which blockchain platform was most suitable for the proposed application was a two-stage process. Stage one included amassing a list of public/permissionless and private/permissioned blockchain platforms and reviewing which are satisfactory for managing construction cash flow. A list of the 50 most successful blockchains (according to market capitalisation) was obtained from the CoinMarketCap website (Coin Market Cap, 2022). Furthermore, a list of prominent permissioned blockchains was obtained from research (Chai et al., 2020). Afterwards, the whitepapers of the blockchain platforms were reviewed for suitability to the study. Most blockchains from the above sources were based on cryptocurrency trading solutions and were easily filtered out. The final result was the seven blockchain platforms shown in Table 7.

The next stage for assessing blockchain suitability included evaluating seven key areas: (1) extensive ecosystem of decentralised applications; (2) supports stablecoins; (3) includes high security and data trust; (4) supports smart contracts; (5) supports privacy; and (6) consensus is low in CO2 emissions. Having high security and private transactions in the same criteria is a dilemma because both cannot be simultaneously satisfied. For example, public/permissionless blockchains (e.g., Ethereum) are more secure but have less transaction privacy, whereas permissioned blockchains (e.g., Hyperledger) are less secure but offer greater transaction privacy (Chain Stack, 2020).

Table 9.

Blockchain selection scoring matrix.

Blockchain	Parameters for selecting the blockchain platform						
	1. Extensive ecosystem of decentralised applications	2. Supports stablecoins	3. Provides high security & data trust	4. Supports smart contracts	5. Supports private transactions	6. consensus is low in CO2 emissions	Yes (Y) score
Ethereum	Y (Atra, 2019)	Y (Buterin, 2022)	Y (Buterin, 2022)	Y (Buterin, 2022)	N (Banerjee et al., 2020)	Y (CCRI, 2022)	5

Hyperledger Fabric	Y (Handy, 2020)	N (Hyperledger, 2017)	N (Hyperledger, 2017)	Y (Hyperledger, 2017)	Y (Hyperledger, 2017)	Y (Hyperledger, 2017)	4
Cardano	N (Joget, 2022a)	Y (Cardano Cube, 2021)	Y (Kiayias et al., 2017)	Y (Kiayias et al., 2017)	N (Cardano, 2022)	Y (Kiayias et al., 2017)	4
Polkadot	N (Nova Bloq, 2022)	Y (Chen, 2020)	Y (Wood, 2020)	Y (Polkadot, 2022)	N (Zk Mega, 2020)	Y (Wood, 2020)	4
Hedera Hashgraph	N (Joget, 2022b)	Y (Hedera, 2022)	Y (Baird et al., 2020)	Y (Baird et al., 2020)	N (Baird et al., 2020)	Y (Baird et al., 2020)	4
Internet Computer	N (Blocks, 2022)	Y (Blocks, 2022)	Y (Hanke et al., 2018)	Y (Hanke et al., 2018)	N (Hanke et al., 2018)	Y (Carbon Crowd, 2022)	4
Quorum	N (Quorum, 2022a)	Y (Quorum, 2022a)	N (Quorum, 2022b)	Y (Quorum, 2022b)	Y (Quorum, 2022b)	Y (Quorum, 2022b)	4

“Extensive ecosystem of decentralised applications” was a parameter in Table 7 because blockchain applications can be built from templates and third-party services, enabling users to deploy lightweight applications that leverage the blockchain’s ecosystem of decentralised applications. This is a practical approach for industries, such as construction, that suffer from low-profit margins that lead to a lack of investment in innovation.

Despite Hyperledger Fabric’s popularity as a permissioned blockchain, it scored low in Table 7 because it lacks security and stablecoin services; furthermore, it relies on users manually setting up the network (e.g., configuring the architecture, appointing nodes, and managing user permissions) (Hyperledger, 2017). For example, a permissioned blockchain may occupy 20 nodes set up with trusted parties, whereas a public blockchain would have several thousands of nodes because it accommodates anonymous users transacting on its network. Furthermore, the vast decentralisation of nodes makes public blockchains more secure in terms of data persistency (Bitnodes, 2022). Cryptocurrencies minted on Hyperledger do not have value outside its network, unlike the cryptocurrencies of public blockchains that can be exchanged for fiat currency (Hyperledger, 2017). Cryptocurrencies such as stablecoins cannot be used on Hyperledger (Hyperledger, 2017). This was problematic because the proposed application used cryptocurrency payments as a core feature of its functionality. However, a key selling point for Hyperledger is that it includes private transactions as part of its standard architecture (Hyperledger, 2017).

One of the benefits of using Ethereum is its large ecosystem of services that enable users to deploy test applications with minimal coding experience. For example, the proposed application was built through the Atra Cloud Platform, a no-code platform that allows users to customise and deploy decentralised applications with all technology components preconfigured, such as the Web application, wallet and node services, and smart contract templates (Atra, 2019). Another reason a private permissioned blockchain was not selected for the proposed application is that setting up the network and incentivising participants to run nodes on a private blockchain is a technical and costly responsibility (Quasim et al., 2020). Although privacy is not built into Ethereum's protocol, it can achieve private transactions through layer two privacy solutions (Banerjee et al., 2020). Chapter Five (Data and Analysis) reveals several methods for achieving privacy on a public blockchain.

Analysing the number of active developers on a blockchain is also a good indicator of its progression. In a study of monthly active blockchain developers, Ethereum scored the highest with 3900, followed by 1400 for Polkadot, 435 for Hyperledger Fabric, 350 for Cardano, 190 for Internet Computer, 132 for Quorum, and 40 for Hedera (Chain Stack, 2020; Shen et al., 2021). This indicates that Ethereum has the largest ecosystem of active developers improving its protocol and services. The other blockchains in Table 7 are strong contenders; however, they offer fewer services than Ethereum and are more challenging for developing and testing blockchain applications. From the carbon emissions perspective, a benefit of private blockchains, such as Hyperledger Fabric, is that they emit relatively no carbon emissions (the exact CO_2 emissions depends on the quantity of nodes on the network, which might be around 100 nodes; therefore, the CO_2 emission is negligible). Nevertheless, public blockchain Ethereum recently updated its consensus algorithm from proof-of-work to proof-of-stake, reducing its annual tCO_2e (tonnes of CO_2 equivalent) emissions from 11 million to 870, a reduction of 99.992% (CCRI, 2022). This led to it becoming the winning contender vs. the other blockchains listed in Table 7.

One of the key reasons blockchain was investigated for this research is because of its process automation capabilities. This research identified that PBAs are administratively laborious to set up and operate; therefore, the objective for developing the proposed application was to test and validate, through a proof of concept (PoC), whether the automation capabilities of blockchain can be used to increase cash flow automation in PBAs by integrating management processes, such as payment approvals, with cash flow process, such as payment executions. Some of the barriers to creating an automated system is the cost implications of setting up and managing it, and the lack of availability of open-licence and open-source technologies that enables third-party users, such as the author, to build and test new payment applications. Initially, the author wanted to create two applications: (1) a financial technology application built from centralised systems, and (2) a blockchain application built from decentralised systems. However, the author could not find a single centralised application provider that provided templates and open-source code for deploying and testing centralised payment applications. In contrast, from the decentralised application landscape, several options were available and the author settled on the Atra Cloud Platform because they provided the necessary open-source templates.

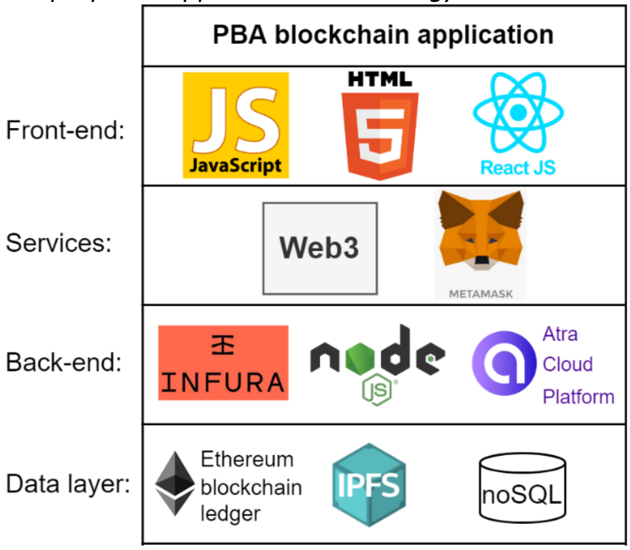
Private blockchains, such as Hyperledger by the Linux Foundation, are a midway point between centralised and decentralised systems because they are technologically decentralised but politically centralised. Politically centralised means that they are governed and funded by centralised entities that can determine their future roadmap. For example, Hyperledger is funded by the Linux Foundation, and the largest financial contributors to the Linux Foundation are Microsoft, Google, Oracle, and several other large technology companies (Linux Foundation, 2025). Therefore, big technology companies have an influence over the Linux Foundation which in return have an influence over Hyperledger. In contrast, public blockchains are politically and technologically decentralised because they are internally funded by the selling of cryptocurrencies to the public and a decentralised community vote on its future roadmap. Nevertheless, casting aside the financial influence large technology companies can have on private blockchains, the researcher attempted to build a PBA payment application on Hyperledger to test its viability; however, the author soon realised that cryptocurrencies on Hyperledger have no value outside its network and thus it cannot be used for payments. A cryptocurrency only has value if it can be publicly traded for another currency of value. For example, Bitcoins can be traded for fiat (e.g., GBP, USD) at currency exchanges. In contrast, cryptocurrencies minted on Hyperledger cannot be traded for fiat at currency exchanges. If a currency, whether it be cryptocurrency or fiat currency, cannot carry value, then it cannot be used as a medium of exchange (i.e., payments). Public blockchains have stablecoins, which are cryptocurrencies pegged at one-to-one ratio with fiat currencies. More importantly, these stablecoins can be traded for fiat currencies at currency exchanges. Therefore, based on the ability to use stablecoins as medium of exchange, a public blockchain was selected as the best option for testing a payment application.

When designing the conceptual framework of the proposed application, the author contemplated the idea of digital public goods (DPGs) for the construction industry. The Digital Public Goods Alliance (2025), cite that "According to the UN Secretary General's Roadmap for Digital Cooperation, digital public goods are open-source software, open standards, open data, open AI systems, and open content collections that adhere to privacy and other applicable best practices, do no harm, and are of high relevance for attainment of the United Nations 2030 Sustainable Development Goals (SDGs)." If the proposed application were to be developed in the future, the most valuable impact it could have on a profit-starved industry such as construction is to release it as a DPG. Admittedly, a DPG for construction would benefit more by being more general-purpose than targeting PBA specifically. Nevertheless, using the open-source codebase of the proposed application, a variant of it could be redeployed to accommodate various types of payment systems, with PBAs being one of its solutions. When contemplating the idea of using a blockchain platform to provide the technology infrastructure for a DPG for the construction industry, both private and public blockchains could encapsulate the space. However, one consideration that must be noted is the potential corporate influence large technology companies can have on the future roadmap of private blockchains. DPGs under corporate influence may include a profit motive behind its development compared to a DPG that is not funded by large technology companies. Public blockchains are not influenced by large technology companies and are self-sustaining in the context that they raise all their funds when they launch their blockchain, mint cryptocurrency tokens, and sell these tokens to the public. Therefore, hypothetically, public blockchains are more autonomous and would potentially be better suited as a DPG compared to a private blockchain.

4.2 Technology Setup

The proposed application's technology stack was displayed in Figure 16 (shown in the following page). The application's user interface was a website coded in JavaScript, the most popular programming language for front-end webpage applications (Vailshery, 2022a). Furthermore, React.JS is the most popular code library used alongside JavaScript (Vailshery, 2022b). The application ran an instance of Web 3 to allow third-party blockchain services, such as MetaMask, to connect to the blockchain. The Ethereum blockchain and its smart contracts are the back-end system of the application. Rather than setting up a blockchain node, which was unnecessarily complicated, Infura was used as the third-party node provider that enables the application to send transactions to the blockchain. In the blockchain application template the author used to build the proposed application, its default node provider was Infura, and the author saw no reason to alter it. Since a standard Web 2 webpage was used as the proposed application's user interface, the runtime environment of Node.JS was needed to process the user interface of the proposed application's JavaScript code. Therefore, the proposed application was a Web2-Web3-blockchain hybrid system. The data layer consists of Ethereum's ledger for logging transactions and IPFS for decentralised cloud storage. Technically, any cloud storage provider can be used instead of IPFS, as all that is needed is a link that directs users to the data repository. The document link would be stored in a smart contract's data field; thus, only the link is stored on the blockchain, not the entire document.

Figure 16.
The proposed application's technology stack.



A description of each layer of the proposed application's technology stack (as shown in Figure 16) was as follows:

- The data layer included the Ethereum ledger, where all transactions and smart contracts on the blockchain are stored (Han et al., 2020). IPFS for the decentralised storage of contract documents (Hamledari & Fischer, 2021a), and cloud-based NoSQL for any general data storage that does not require decentralisation.

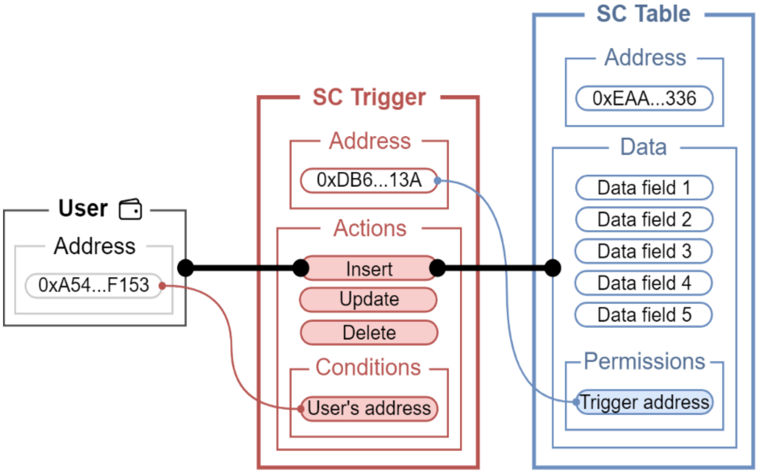
- The back-end of the technology stack included Infura, which provided the node services that connect the proposed application to the blockchain (Hamledari & Fischer, 2021b). Furthermore, Infura provides inbuilt services for interoperating with IPFS. An alternative to Infura is Alchemy, and an alternative to IPFS includes Storj. However, itemising the most efficient technology setup for the proposed application was beyond the scope of this research. Node.JS was the runtime server that processed the proposed application's code (e.g., requests made through the user interface). The Atra Cloud Platform hosted the proposed application's user interface and provided its smart contract templates.

- The services layer of the technology stack consists of Web 3, a mandatory component for Web applications to connect to the blockchain. MetaMask is a Web 3 wallet application that enables users to connect their digital wallets to the blockchain through a standard Web 2 browser (Saygili et al., 2022). For context, Web 1 is the Internet in read-only format. Web 2 is the Internet with an application layer built atop, allowing users to read and write on the Internet; however, it is dominated by large, centralised technology companies. In contrast, Web 3 is a fully democratised Internet, where user data is not monetised, and applications are permissionless and open-source (Rudman & Bruwer, 2016). Due to the nascency of Web 3, it currently does not have the same level of sophistication as Web 2 (Liu et al., 2021). Thus, the proposed application used a hybrid system where its user interface was hosted in Web 2 while the node and wallet services were hosted in Web 3.

- For the front-end (webpage user interface): JavaScript provided all the proposed application's business logic (e.g., connecting the user interface to the smart contracts), and React.JS was the code library that provided all the necessary tools and templates for running the proposed application's user interface.
- The proposed application's smart contracts were coded in Solidity, the native programming language of Ethereum. Solidity is also similar in coding syntax to JavaScript, making JavaScript a suitable programming language for the proposed application due to its syntax similarities with JavaScript.

The proposed application's smart contract functions are shown in Figure 17. Two types of smart contracts are used: Smart contract (SC) triggers and SC tables. An SC trigger provides an endpoint (i.e., a way for one piece of technology to connect to another) for users to interact with to send data to an SC table. Users would use a third-party blockchain wallet, such as MetaMask, to send transactions to an SC trigger; afterwards, the SC trigger would update the SC table.

Figure 17.
Smart contract (SC) trigger and SC table schema.

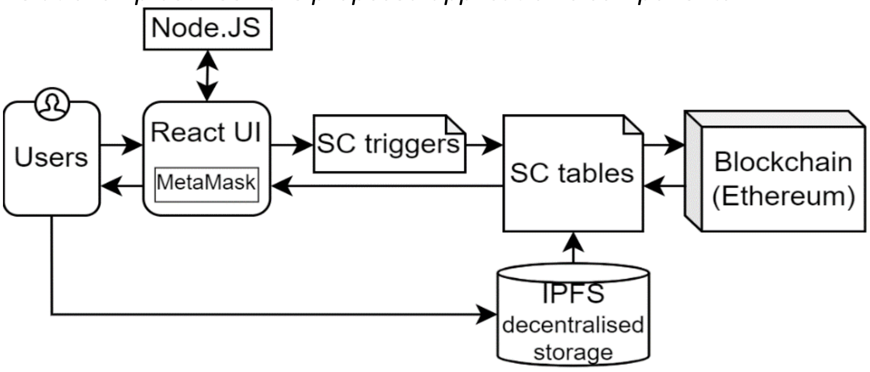


SC triggers (as per Figure 17) have three action types: *Insert, update, and delete*. Action types are how users interact with the SC trigger to send requests to the SC table. *Insert* adds new data, *update* revises it, and *delete* removes it from the SC table. Even though data may appear deleted from the SC table, the blockchain keeps a permanent and traceable record of all events. Thus, any deleted data can be recovered or audited at any time. Users can initiate payments through the SC trigger by calling the *update* function and requesting it to execute payments listed in the SC table.

Smart contract (SC) triggers store codified *conditions* that cannot be altered once a smart contract is deployed, whereas SC tables store codified *permissions* in them that can be changed even after the SC table's deployment. However, SC table permissions can only be granted to SC triggers and not to the wallet addresses of users. Thus SC triggers were incorporated as user endpoints in the proposed application. SC tables are spreadsheet-style databases that store project management data. Therefore, ensuring SC tables are not redeployed midway through a project was vital; otherwise, project-critical data and timestamps would be lost when the data is rewritten.

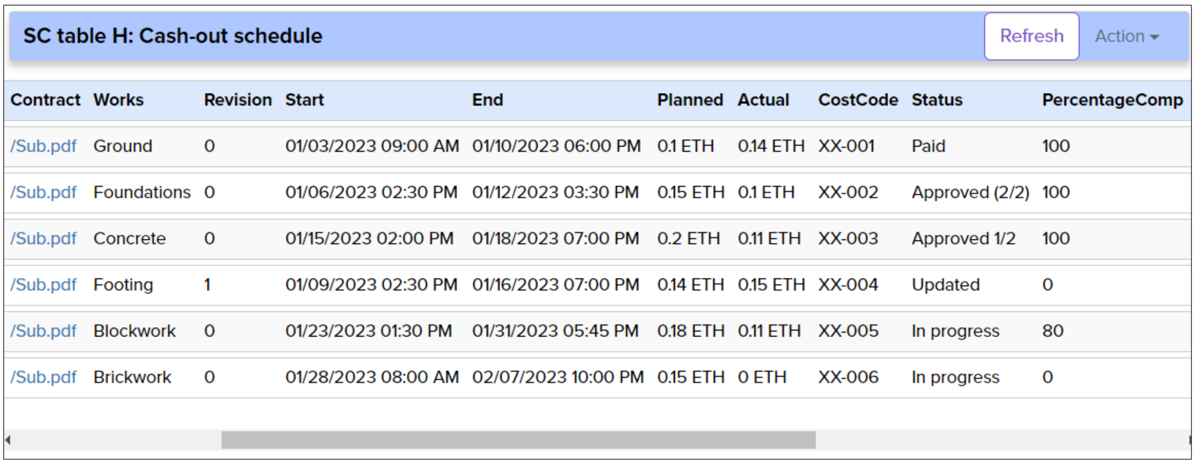
Figure 18 illustrates how the technology components from Figure 17 interoperate with the smart contracts. The process flow was as follows: Users interact with the Web user interface and log in with their MetaMask wallet. Afterwards, the user interface enables them to send transactions via a smart contract (SC) trigger to insert, update, or delete data in an SC table. When an SC table receives a transaction request, the transaction is autonomously sent to the blockchain for validation. Once validated, the SC table updates its state with the new data.

Figure 18.
Relationship between the proposed application's components.



The proposed application has an API (application programming interface) that autonomously pulls data from the smart contract tables and displays it on the user interface, as shown in Figure 19.

Figure 19.
Screenshot of a smart contract t on the application's user interface.

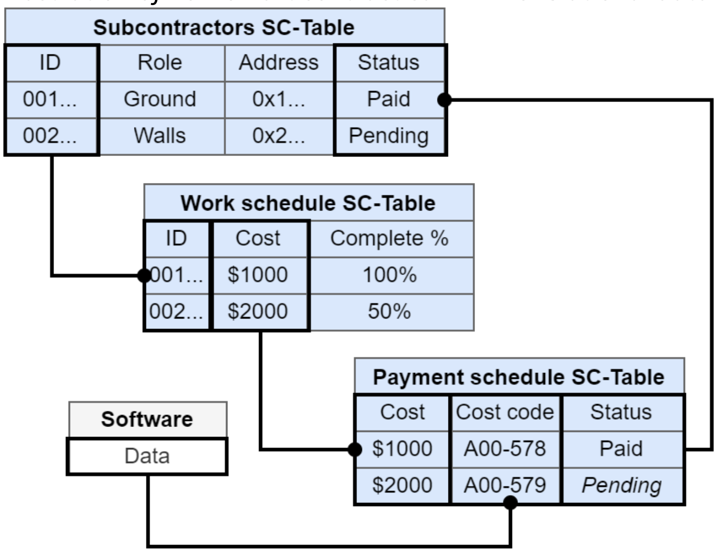


SC table H: Cash-out schedule Refresh Action

Contract	Works	Revision	Start	End	Planned	Actual	CostCode	Status	PercentageComp
/Sub.pdf	Ground	0	01/03/2023 09:00 AM	01/10/2023 06:00 PM	0.1 ETH	0.14 ETH	XX-001	Paid	100
/Sub.pdf	Foundations	0	01/06/2023 02:30 PM	01/12/2023 03:30 PM	0.15 ETH	0.1 ETH	XX-002	Approved (2/2)	100
/Sub.pdf	Concrete	0	01/15/2023 02:00 PM	01/18/2023 07:00 PM	0.2 ETH	0.11 ETH	XX-003	Approved 1/2	100
/Sub.pdf	Footing	1	01/09/2023 02:30 PM	01/16/2023 07:00 PM	0.14 ETH	0.15 ETH	XX-004	Updated	0
/Sub.pdf	Blockwork	0	01/23/2023 01:30 PM	01/31/2023 05:45 PM	0.18 ETH	0.11 ETH	XX-005	In progress	80
/Sub.pdf	Brickwork	0	01/28/2023 08:00 AM	02/07/2023 10:00 PM	0.15 ETH	0 ETH	XX-006	In progress	0

Figure 20 displays how the proposed application's the smart contract (SC) tables operate like relational databases, whereby when one table was updated, the other tables autonomously update. Figure 20 is a simplified illustration that shows only three SC tables; however, the proposed application deployed 12 SC tables with more complex relational functions. The proposed application's SC tables also operate like escrows because they control the release of project payments to the supply chain during the application's testing phase. For example, when payment authorisers (e.g., the contractor, project manager, etc.) approved a subcontractor's works, payments were executed from an SC table to the subcontractor without using a bank's services to process the payment, thereby integrating management flows with cash flows.

Figure 20.
Illustration of how smart contract can mimic relational databases.



4.3 Proposed Application Process Flow

The proposed application's user interface and smart contract codebase are available in the following GitHub link: https://github.com/D-UCL/PBA-dApp (last visited on July, 2024) and a video demonstration of the proposed application is available in the following YouTube link: https://www.youtube.com/watch?v=mwAAAhnowxQ (last visited on July, 2024).

Figure 21 (shown on the following page) illustrates the high-level processes of the proposed PBA blockchain application, and the twelve stages at which users interact with the system to perform tasks. During the proposed application's development, the author went through countless iterations of trial and error while he was figuring out how the PBA processes shown in Figure 21 could be designed into smart contracts. It took substantially longer in duration to solve, and the author was close to abandoning the application's development altogether because it was consuming too much research time. Nevertheless, with perseverance, the author managed to build a working model of the application and all 12 processes shown in Figure 21 were validated as fully operational by the author. The author also published the codebase of all the deployed smart contracts open source to allow for external validation. The smart contract code is displayed in Appendix 3.

Figure 21.

This figure illustrates the primary activities of the proposed application.

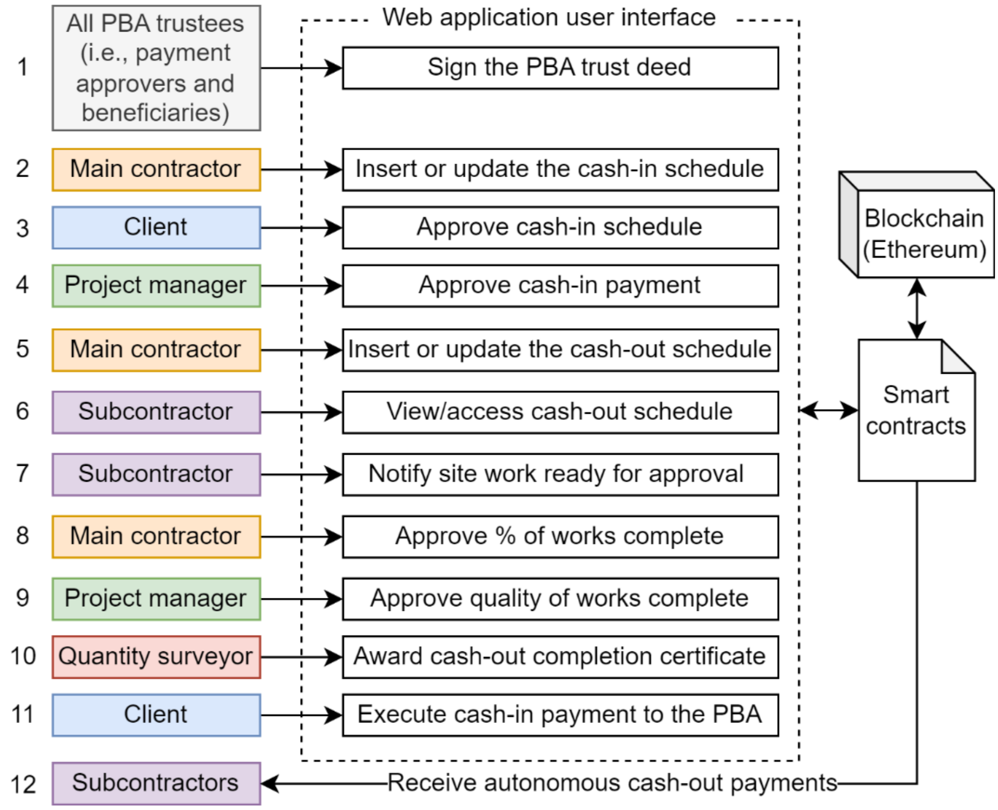


Figure 22 (shown on the following page) displays a swim lane diagram showcasing the actions of each participant in the PBA system. The purpose of this diagram was to illustrate the process flows that were automated through the proposed application.

Figure 22.

Comparison of the existing vs. proposed PBA system.

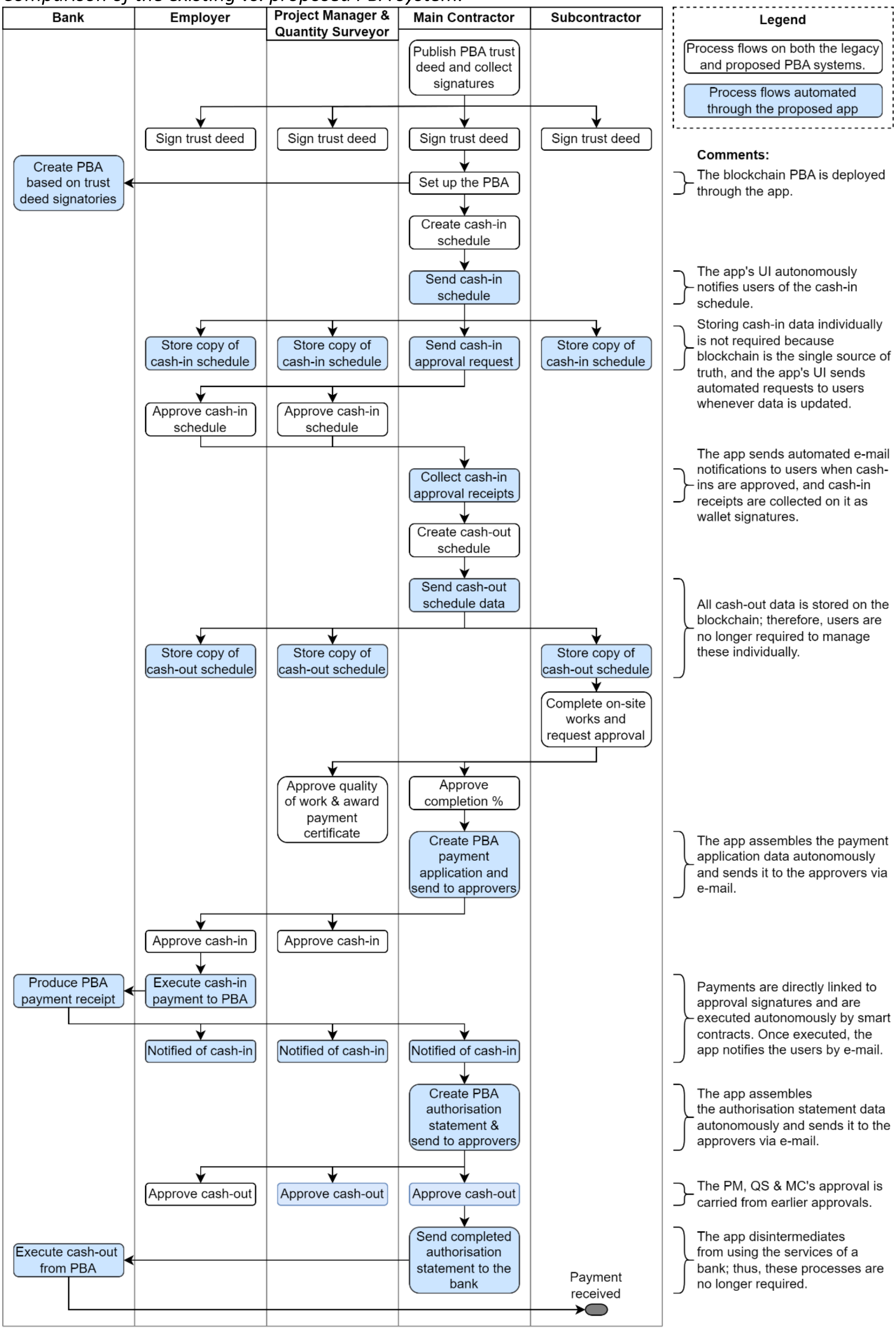
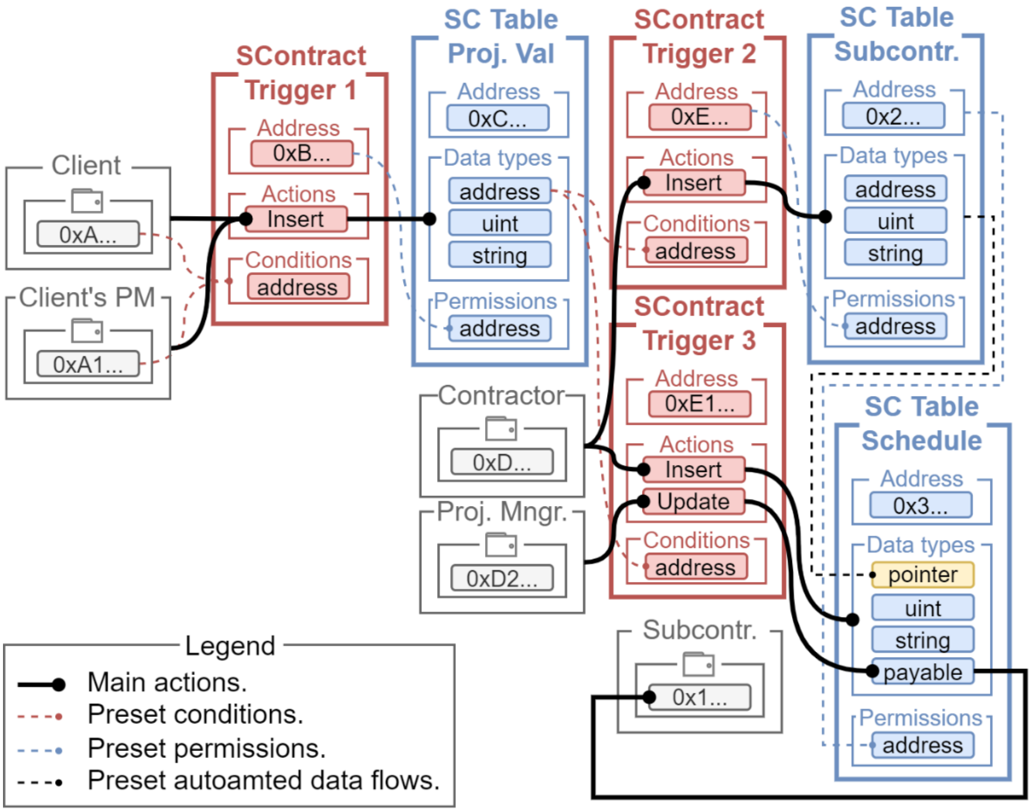


Figure 23, shown below, is a simplified abstraction of how the proposed application's numerous smart contract (SC) triggers and SC tables interoperate. It displays three SC triggers and three SC tables; however, the entire smart contract map in the proposed application could not be displayed because it contains 57 smart contracts (45 SC triggers and 12 SC tables), thus too extensive to illustrate entirely.

Figure 23.
Architecture of the smart contracts deployed



The *smart contract (SC) trigger 1*, shown in Figure 23, has a codified condition pointing to the wallet addresses of the client and the client's PM; thus, only these participants can interact with *SC trigger 1. SC trigger 2* and *SC trigger 3* operate differently because their conditions point to the address field in *SC table Proj. Val* (project validator); thus, any participants entered in *SC table Project Validator* are granted access to interact with *SC trigger 2* and *SC trigger 3.* The contractor interacts with *SC trigger 2* to store a list of the subcontractors in *SC table Subcontr.* The contractor also interacts with *SC trigger 3* to insert the scheduled works of the subcontractors into the *SC table Schedule.* The project manager interacts with *SC trigger 3* to verify the completion of works in the *SC table Schedule*, which triggers a payment to the subcontractors. *SC table Schedule* has a pointer data function that automatically pulls any relevant data from *SC table Subcontractor* (e.g., start/end date, ID numbers, job role, contract documents, etc.). This imitates the functionalities of a relational database because if *SC table Subcontr.* is updated, it autonomously updates the state of *SC table Schedule*.

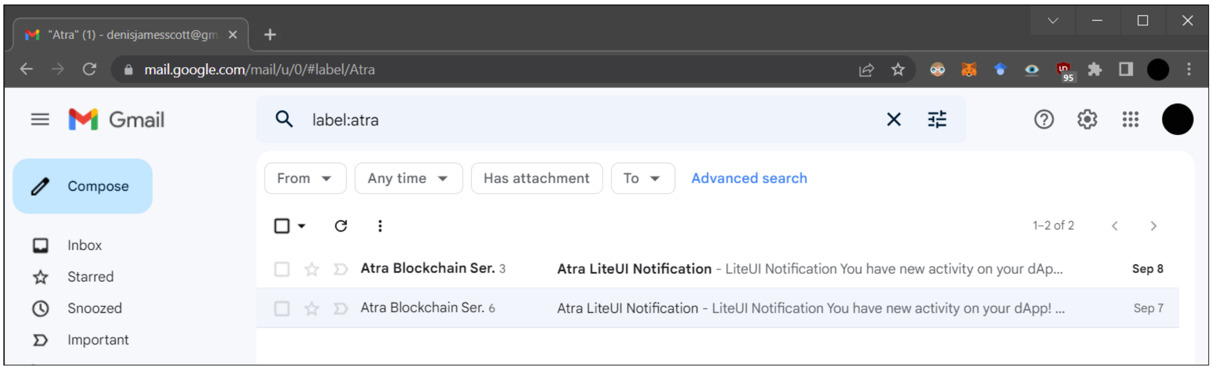
4.4 User Interface

The blockchain application proposed in this research was built with five main user interfaces: (1) Trust Deed, (2) Cash-in, (3) Cash-out, (4) Subcontractors, and (5) Retentions, as per Figure 24. Screenshots and flowchart diagrams of each interface is displayed in this section. The proposed application was lightweight and ran on a standard webpage, and users were not required to download any software to use it.

Figure 24.
Screenshot of the proposed application's webpage.

The proposed application also sent e-mail notifications to users whenever they have been appointed or when actions from them are required (as per Figure 25). For example, when the subcontractor verified (through the proposed application) that on-site works are ready for approval, the application sent an automated e-mail to the main contractor notifying them of their responsibility to approve the works within a timescale.

Figure 25.
E-mail notifications users receive from the proposed application.



4.4.1 Trust Deed User Interface

A PBA trust deed is a legal document that states who the PBA payment authorisers and beneficiaries are. The PBA trust deed in the proposed application was a smart contract, and project participants would sign it by clicking “submit” in Figure 26; afterwards, their signature would be uploaded to the smart contract. The trust deed smart contract also acted as a permission control system, granting participants access to perform actions on the other five abovementioned user interface pages shown on Figure 24. For example, only the user wallet that signed the trust deed smart contract as the main contractor would have permission to insert payment schedule data into the Cash-in and Cash-out user interfaces.

Figure 26.
The Trust Deed interface of the proposed application.

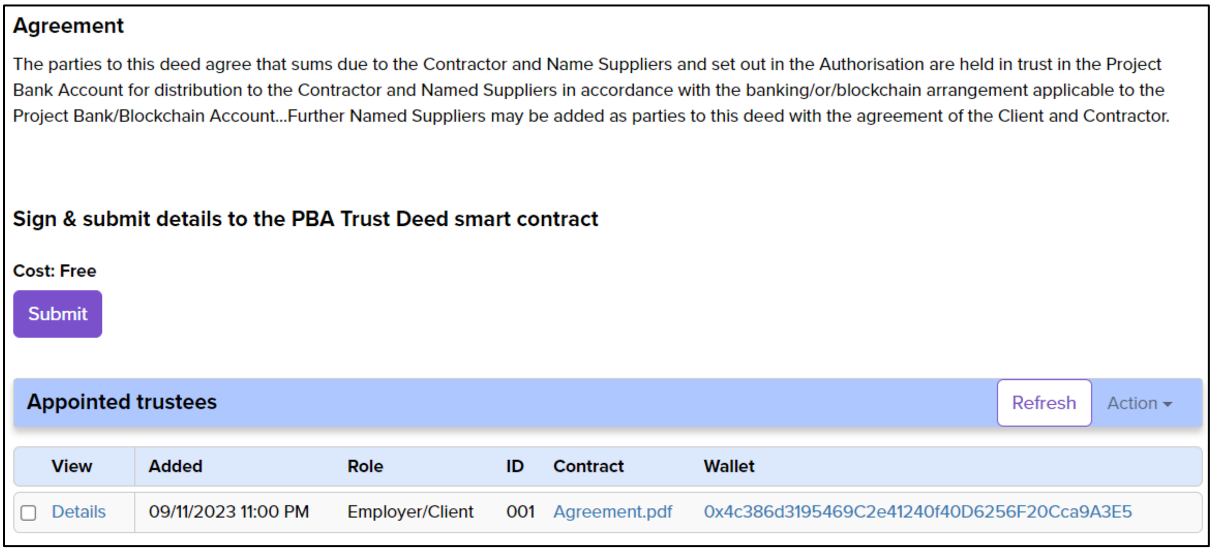
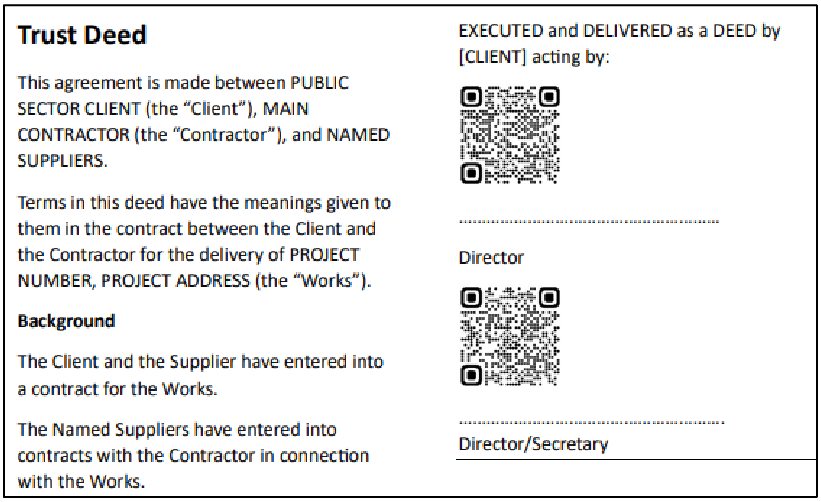


Figure 27 is a screenshot of the paper-based version of the smart contract trust deed shown above. When participants signed the trust deed, their digital signature was recorded onto the below document and linked to the blockchain.

Figure 27.
Paper-based view of the trust deed.



Trust Deed

This agreement is made between PUBLIC SECTOR CLIENT (the "Client"), MAIN CONTRACTOR (the "Contractor"), and NAMED SUPPLIERS.

Terms in this deed have the meanings given to them in the contract between the Client and the Contractor for the delivery of PROJECT NUMBER, PROJECT ADDRESS (the "Works").

Background

The Client and the Supplier have entered into a contract for the Works.

The Named Suppliers have entered into contracts with the Contractor in connection with the Works.

EXECUTED and DELIVERED as a DEED by [CLIENT] acting by:

....

Director

....

Director/Secretary

4.4.2 Cash-In User Interface

Cash inflows (cash-ins) are the flow of cash from the client's account to the PBA. Figure 28 illustrates its process flow, whereas Figure 29 was the application's user interface where the actions were performed.

Figure 28.
Process flow for inserting, managing, and executing cash-ins.

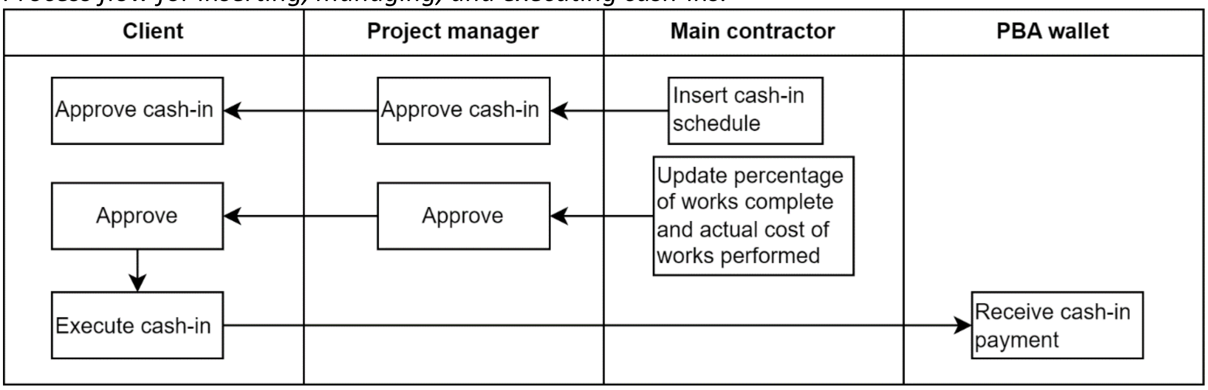
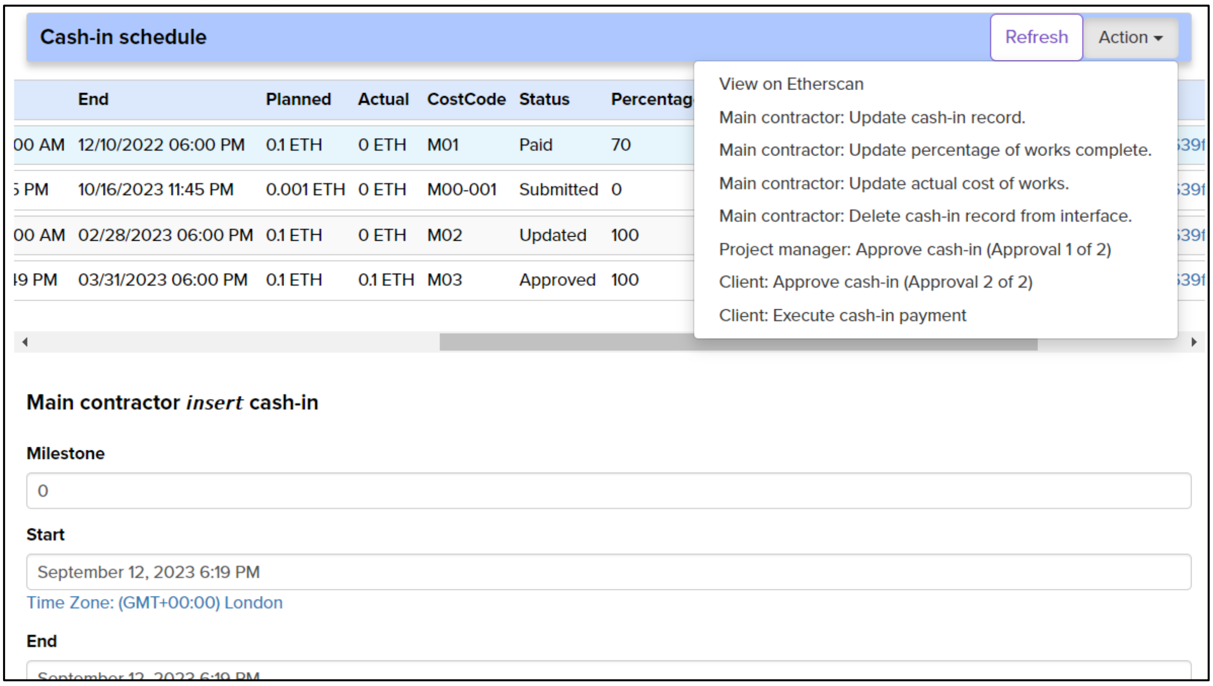


Figure 29.
The Cash-in interface of the proposed application.



4.4.3 Cash-Out User Interface

Cash outflows (cash-outs) are the flow of cash from the PBA to the subcontractors. Figure 30 illustrates the proposed application's cash-out process, while Figure 31 was the user interface where the actions were performed.

Figure 30.
Process flow for inserting, managing, and executing cash-outs.

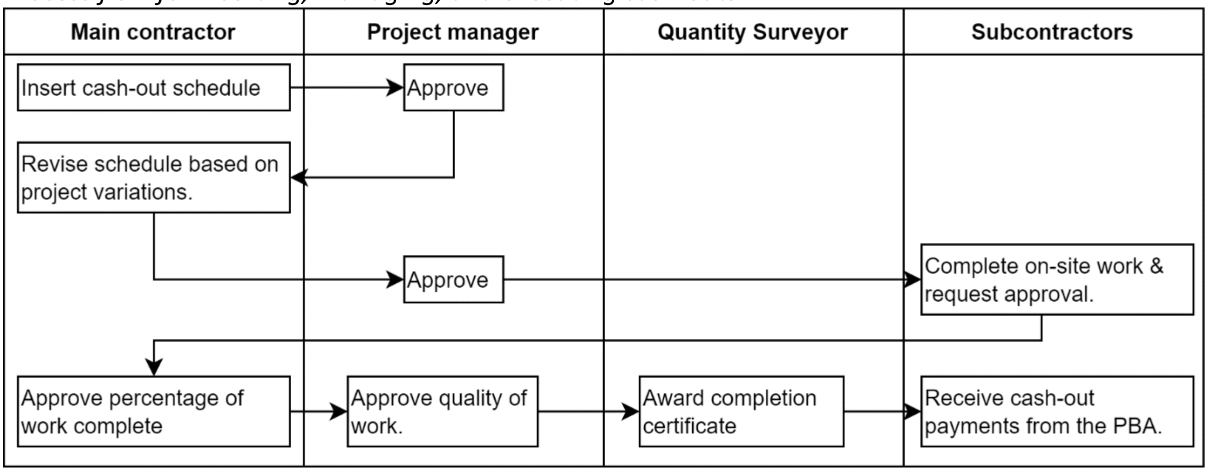
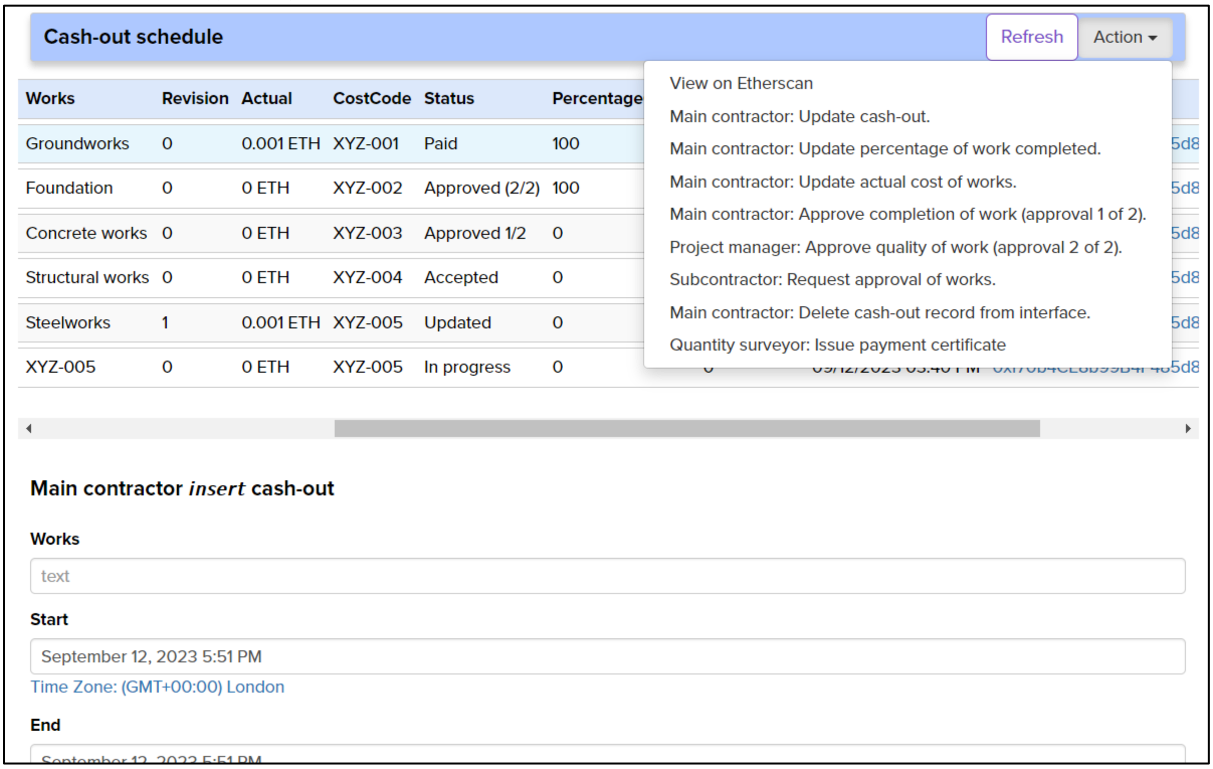


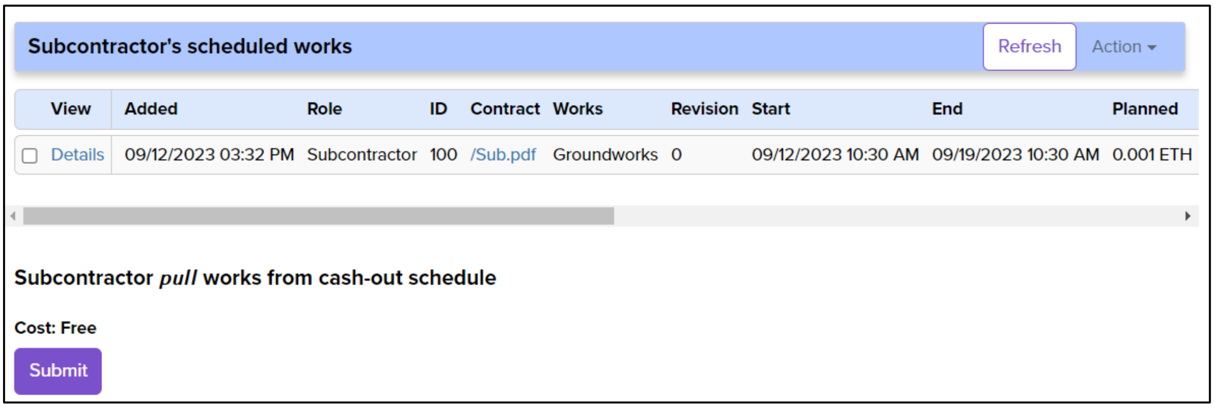
Figure 31.
The Cash-out interface of the proposed application.



4.4.4 Subcontractors Interface

Figure 32 illustrates how a subcontractor can pull their scheduled work from the cash-out smart contract. To do this, all the subcontractor would need to do is click the submit button shown in Figure 32. Afterwards, their schedule data would automatically be pulled from the Cash-out table. This was useful because subcontractors would only get schedule information relevant to them and not the full cash-out schedule. Furthermore, the subcontractor's table operated like a relational database; therefore, when the cash-out table would update, the subcontractor's table would update accordingly, and the subcontractor would be notified of the changes.

Figure 32.
The Subcontractor interface of the proposed application.



4.4.5 Retentions Interface

The Retentions user interface operated like a relational database and autonomously pulled data from the Cash-in and Cash-out smart contract tables. All the main contractor needed to do was click *submit* on the user interface displayed in Figure 34 (shown below). Afterwards, the Retentions table automatically synchronised with the Cash-in/out tables to display the retention amount due to subcontractors. Figure 31 illustrates the high-level procedures involved with the proposed application's retention process.

Figure 33.
Process flow of the retention process.

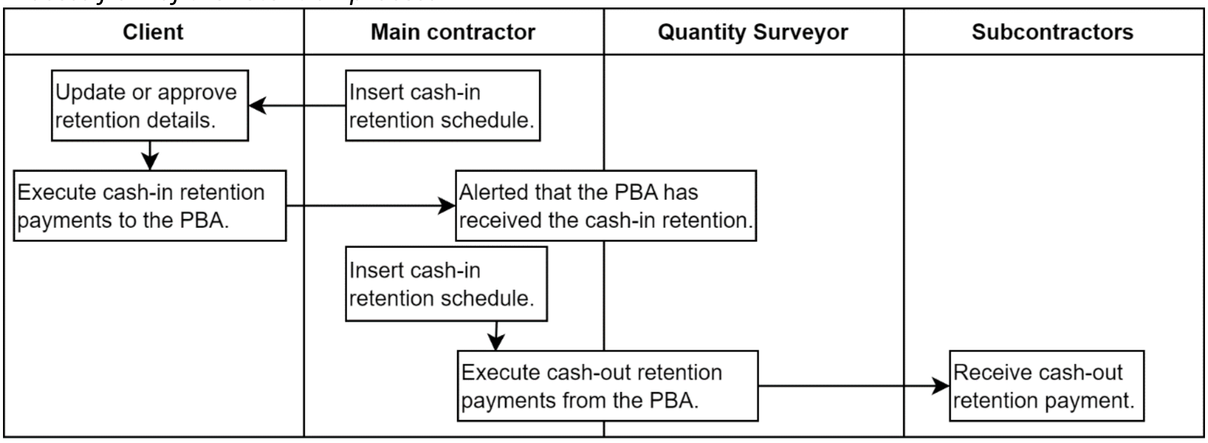
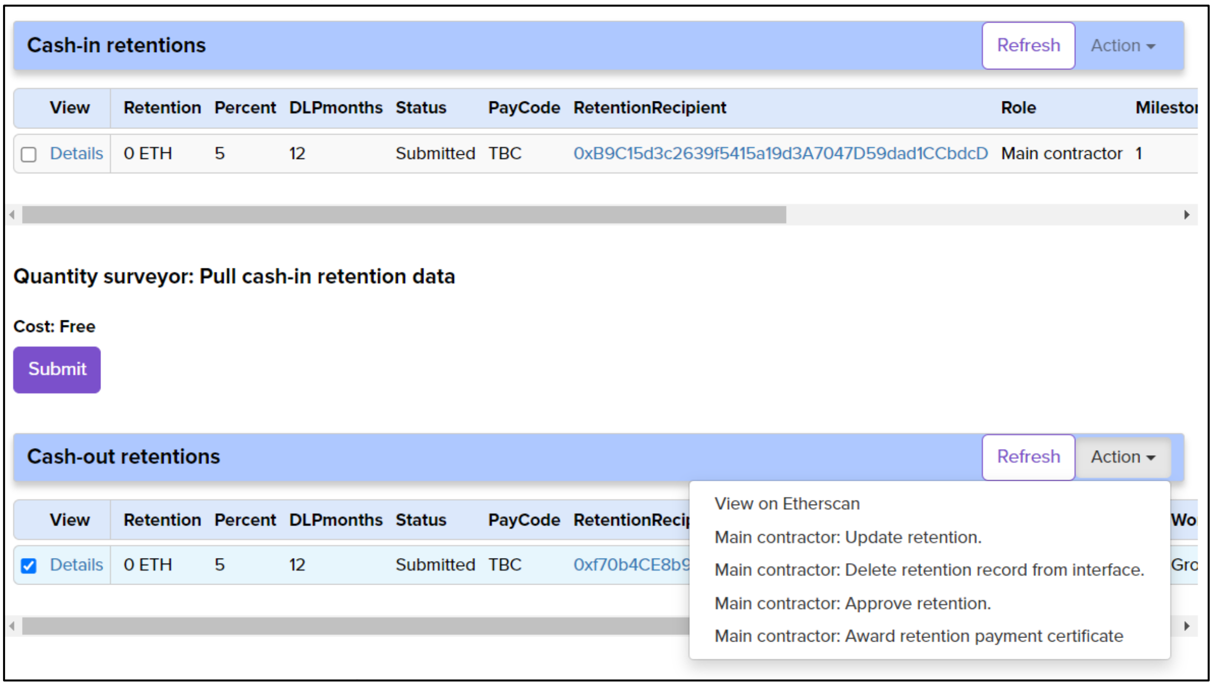


Figure 34.
The Retentions interface of the proposed application.



4.5 Cost

The deployment costs of the proposed application's smart contracts (shown in Table 8) were estimated based on a one-year project. However, smart contracts only need to be deployed once throughout an entire project; therefore, if the project duration is longer, the smart contract deployment costs will not incur additional fees. The cost breakdown comprised £326 for deploying 57 smart contracts, £851 for sending an estimated 1200 transactions, and £473 for one-year duration of Web hosting fees, altogether totalling £1,650.

Table 10.
The total cost of deploying and operating the proposed application.

Description	Unit Cost	Quantity	Total
Smart contract table deployment fee	£9.45* (each)	12	£113.40
Smart contract trigger deployment fee	£4.73* (each)	45	£212.85
Ethereum transaction fee	£0.71* (each)	1200	£851.00
Atra Cloud Platform's Web hosting services	£39.40 (per month)	12	£472.80
Total =			£1,650.00

Note. * is based on an exchange rate of £1182 per Ether (the currency of Ethereum).

4.6 Codebase

The full codebase of the smart contract tables and triggers are displayed in Table 15 in the appendix, with explanations of the functionalities and conditions preprogrammed into each smart contract. Alternatively, the codebases can also be accessed via this GitHub link: https://github.com/D-UCL/PBA-dApp (last accessed in August, 2024).

5 Data and Analysis

This chapter is organised into two sections: (1) *Focus Group Interview* and (2) *Questionnaire*. The focus group investigates the proposed PBA blockchain application from an organisational perspective by collecting responses from construction consultants with working experience of PBAs. The questionnaire investigates the application from the technical perspective by collecting responses from blockchain engineers. Investigating the proposed application's value contribution relied on the abovementioned data collection stages to qualitatively evaluate the viability of hosting PBAs on the blockchain.

5.1 Focus Group Interview

A thematic analysis was used to structure the focus group data into four primary themes: strengths, weaknesses, opportunities, and threats (SWOT). These were then organised into 16 subthemes.

The focus group format was semi-structured, and the researcher prepared a list of ten questions as a guideline (as per Table 10); however, these questions were expanded upon organically while the interview commenced.

Table 11.
Semi-structured questions of the focus group interview.

What are the weaknesses or threats of the application?
What are the strengths or opportunities of the application?
If developed more, do you see the application as a feasible solution, or do you have any suggestions for improving it?
Did the application overlook some key cash flow management processes? If so, can you explain which ones?
Do you think the application should integrate with other software? If so, which would you suggest?
Do you think the application would struggle to integrate with current systems within your organisation? If so, why is this?
Do you see any security concerns with the application?
Do you think the application demonstrated how management and cash flow processes could be integrated, and do you have any comments regarding this?
Do you see any legal or regulatory challenges with using blockchain for payments?
What are the challenges with hosting PBAs on the blockchain instead of with a bank?

Other researchers that used a SWOT analysis in their blockchain in construction papers include: (Gao et al., 2022; Tezel et al., 2020). SWOT analysis originated at Harvard Business School in the 1960s and became popular among organisations investigating the value proposition of products or services (Hill & Westbrook, 1997). Due to its simplicity, familiarity, and usefulness in reviewing applications, it was incorporated into the research to provide the initial theme for structuring the focus group data. The four primary themes are presented below, along with their subthemes.

5.1.1 Focus Group Interview Summary

Some general remarks from the focus group participants are as follows: According to one interviewee, “The proposed application may be better suited if it was more general purpose instead of targeting PBA.” Another interviewee commented that they “would like to see it tested in a more real-life setting to see how it holds up.” Furthermore, another interviewee added, “It was a reasonable effort and should be piloted in the industry”.

Concerning the reliability of responses from the four focus group interview participants, there was a mixed range of PBA and blockchain knowledge among them. One participant (i.e., the innovation consultant) had a technical understanding of blockchain and its regulatory environment but had little general knowledge of PBAs. In contrast, one participant (i.e., the company treasurer) had an advanced understanding of PBAs and had managed around 40 PBAs in his working career but had very basic knowledge of blockchain. The other two participants (i.e., the contract manager, and the legal consultant) had a general understanding of blockchain and had been involved with several construction projects where PBAs were used. The participant with a technical understanding of blockchain responded to a high majority of the author’s questions about blockchain, therefore, any feedback regarding blockchain was centred around the thoughts of one person, while a high majority of the PBA responses came from the thoughts of the other three participants.

Table 12 summarises the key points of each subtheme of the focus group interview. The author revisits these key points in Chapter 6: Discussion, Section 6.3: Discussing the Findings to elaborate on the findings.

Table 12.
Focus group interview summary

Theme	Subtheme	Summary
A. Strengths		All the application’s data flows were timestamped and permanently stored on the blockchain for easy auditing.

	A1. Data Traceability and Permanence	Blockchain prevents the issues that arise with transaction reconciliation through its single source of truth.
	A2. Event-driven Architecture	The application showcased how users receive automated e-mail notifications to remind them to complete tasks.
		Blockchain provides a trusted data layer for integrating with analytics dashboards.
B. Weaknesses	B1. Overlooked PBA Processes	Current/standard PBAs include a contract wording approval process as part of the set-up process of PBAs. The proposed application did not include this in its system.
		The PBA trust deed (TD) legal document and TD smart contract of the proposed application should be integrated rather than being separate systems.
		The proposed application did not represent how key PBA forms, such as the payment application and authorisation statement, are managed.
	B2. Overlooked Management Processes	The application should include interim valuation processes because the client relies heavily on this for approvals.
		The payment approval stages showcased in the proposed application is overly simplified and not reflective of the complexities of real-life cash flow management.
		The application's retention process is overly simplified and should include the defects liability period.
	B3.Interoperability with Existing Software	The proposed application needs an application programming interface that interoperates with the main contractor's internal spreadsheet.
		Blockchain needs more integration tools to interoperate with centralised software.
	B4. Lack of Interoperability with Existing PBA Systems	All PBA payments typically flow through a payment terminal management system (TMS) heavily integrated with traditional banks. Replacing this will be challenging.
		The UK Government does not allow PBAs to acquire finance because it increases their national debt, hampering decentralised finance (DeFi) entering the PBA space.
		Banks will not take the risk of issuing finance, such as payment guarantees, through the proposed application.
	B5. Technology Uniqueness	Blockchain was designed as a settlement layer; thus, its focus should be on transactions instead of data management.
		The application stored contracts in IPFS (a general-purpose decentralised cloud), which is inadequate because construction/NEC-specific cloud systems already exist for the commercial management of contract documents.
C. Opportunities		The application can use stablecoins as its default currency to mitigate cryptocurrency volatility.

	C1. Cryptocurrency Price Stability	The application would not intervene with standard tax duties because each transaction's final output is settled in fiat.
	C2. Systems Integration	The general-purpose protocol of the blockchain is a feasible medium for integrating data from fragmented software.
		The app demonstrated the potential of integrating the PBA trust deed (TD) smart contract and the TD legal document.
		Blockchain wallets can be linked to e-mail addresses (like PayPal) to make wallet addresses easier to use/remember.
		The proposed app demonstrated how smart contracts can be configured to operate like relational databases.
		Smart contract-based PBAs could reduce the complexities of setting up PBAs in joint venture projects.
	C3. User Accessibility	The open-source nature of decentralised applications (dApps) provides developers with more freedom, transpiring into better services for society.
		A tool called ‘signing agent’ allows multiple transactions to be batched and signed simultaneously.
		Some blockchain dApps provide white-label solutions that allow their work to be rebranded and commercialised.
	C4. Decentralised Finance (DeFi)	The Qredo dApp provides up to £470 million in insurance for any funds hacked/stolen through their wallet dApp.
		DeFi protocols exist that provide the loan underwriting services of traditional finance (TradFi) while using blockchain to settle transactions, merging TradFi with DeFi.
		Invoice finance is unregulated in the UK, making it a good entry point for DeFi protocols to offer lending to subcontractors.
	C5. Privacy	Zero-knowledge proofs (ZKPs) can be used to achieve privacy on public blockchains.
		Multi-party computation (MPC) wallets are recommended for significantly reducing the risk of hacks and theft.
D. Threats	D1. Cryptocurrency Regulations	Stablecoins are not yet considered legal tender, although their legislative bill is under review with the UK Parliament.
		Until the UK stablecoin bill is passed, stablecoins are considered capital gains and are subject to capital gains tax.
	D2. Relationship With Banks	Even if stablecoins become regulated, banks can still block off-ramping them due to potential money laundering risks.
		If banks feel threatened by blockchain taking their services, they can block interoperability between blockchain and traditional finance services.

	D3. Know-Your-Customer (KYC) Verification	The application did not provide a solution for KYC (know-your-customer), such as linking user details to wallets.
		Majority of blockchain applications do not abide by KYC regulations for businesses. Because of this, banks may reject transactions from blockchain services.

5.1.2 Theme A: Strengths

Strengths relate to the benefits of the proposed application in its present form. Since the application is a work in progress, most benefits are presented in the *Opportunities* section. Nevertheless, the *Strengths* section was organised into two subsections: (1.1) Data Traceability and Permanence and (1.2) Event-driven Architecture, as shown below. The responses were organised in this way based of the themes that organically arose while the author was re-watching the video recording of the interview and reading through its transcript.

5.1.2.1 Data Traceability and Permanence

One interviewee commented that “current systems lack traceability with payment approvals and signoffs” and that “blockchain would provide value in timestamping this data.” Regarding storing and managing PBA cash flow data, one interviewee highlighted that they “internally keep cash book records for each project but frequently suffer reconciliation issues”, which they clarified was because “data is manually entered and managed by numerous people”. They later remarked that they “see the blockchain as a potential solution to logging and timestamping cash flow events with better accuracy”. One interviewee stated, “Banks only keep PBA transaction records for six to twelve months; after that, the bank needs to be contacted manually for the records, which is an administratively laborious process.” Furthermore, they added, “Blockchain would make a good system for permanently storing transaction records.”

5.1.2.2 Event-Driven Architecture

The proposed application contains two main parts: (1) a Web application, and (2) a decentralised (blockchain) application. Part one includes the user interface (UI) and Web server, whereas part two includes the blockchain and its smart contracts. Event-driven architecture relates to part one of the proposed application. Event-driven architecture is when functionality is added to the application’s user interface and Web server to allow it to connect to an e-mail application to enable the proposed application to send e-mail notifications to users. This e-mail notification is the event-driven architecture aspect of the proposed application.

During the live demonstration of the proposed application to the interviewees, the researcher showed how project participants receive automated e-mail notifications from the application whenever actions are performed. For example, subcontractors receive an automatic e-mail notification when appointed via the application, and project managers receive autonomous notifications when work validations are required. Regarding this, one interviewee commented, “The fact that users are automatically reminded when tasks need to be performed is brilliant; it immediately mitigates having to chase people to do things.”

One interviewee commented they are “currently conducting a pilot that leverages analytics dashboard to improve their ability to measure cash performance better”. However, they also stated that “it lacks data trust because users can overwrite it any time, and it relies on people manually entering the information correctly.” Furthermore, they commented that they would like to “see the proposed application tested in a real-life project to see how it holds up.” Another interviewee mentioned that “live analytics would be highly beneficial to projects” and that “having the visibility of knowing, with pinpoint accuracy, when works were approved on-site, certificates awarded, and liabilities executed, would be useful for project analysis.”

5.1.3 Theme B: Weaknesses

The *Weaknesses* section was organised into five subsections: (2.1) Overlooked PBA Processes, (2.2) Overlooked Management Procedures, (2.3) Interoperability with Existing Software, (2.4) Interoperability with Existing PBA Systems, and (2.5) Technology Uniqueness, as shown below.

5.1.3.1 Overlooked PBA Processes

The researcher assumed that inserting PBA clauses into a PBA contract (i.e., a construction contract with PBA clauses embedded into it) came from a standardised template; however, one interviewee clarified this as incorrect and highlighted that six primary steps are required, such as: (1) “Bid manager identifies actual or potential PBA requirements from the tender documents and advises treasury lead”, (2) “treasury lead confirms PBA wording and identifies whether any changes are required”, (3) “Bid manager raises any required changes to type and wording with client at tender stage, (4) “type & wording resolution processes commences”, (5) “bid manager communicates outcome of the tender process to the commercial manager”, and (6) “commercial manager sends it to the treasury lead, who approves the PBA and trust deed wording and includes it in the contract’s document pack to be executed”. They also added that “in joint venture projects that include several head contractors and PBAs, additional approval stages are required.” Another interviewee mentioned, “due to the bespoke nature of construction contracts, PBA clauses for each contract are unique.” Another interviewee commented, “One clause that is important to note is that contractors put a termination clause that allow them to terminate the PBA and revert all cash flow to their account”. However, another clarified, “Triggering the termination clause still requires approval from multiple parties, such as the project manager and client, so the contractor cannot trigger it by themselves.”

Another critical point highlighted by one interviewee is that “PBAs are only used for payments down to tier two because they are too complicated to set up and manage and the contracts between tier two and tier three are completely different” and that “not all banks offer PBA services.” Furthermore, they added that they “have managed over 40 PBAs, and none of them was used to make payments to tier three”.

Regarding the cost of hosting a PBA, one interviewee stated, “There is no real difference in cost when opening a PBA compared to a standard account.” Another added, “The only cost associated with PBA is the additional management resource it demands from the lead contractor, such as setting up the PBA, training staff on how to use it, and managing the additional tasks it imposes”. They further clarified that these tasks include, “Managing the trust deed, joining deed, payment application, authorisation statement, and the fact that both the client and project manager have to approve every single debit from the PBA.” Furthermore, they added, “The *joining deed* is a legal document that allows the adding of new beneficiaries to the PBA trust deed, a *payment application* is a request for cash-ins sent to the client that lists all the payments due under the PBA, and the *authorisation statement* is a request for cash-outs from the PBA, which is sent to the client for approval and to the bank for execution.”

One interviewee highlighted that appointing participants through the proposed application should be “linked to standard PBA processes” and that “parties should only be appointed if they are on the PBA trust deed”. One interviewee asked the researcher whether “the application can integrate the trust deed in some way”. Another interviewee mentioned, “If a subcontractor is not on the trust deed, then they would need to apply through a joining deed and have it signed by the client, contractor, and subcontractor.” Another said, “The PBA trust deed, payment application, and authorisation statement, which are key PBA processes, were not itemised in the application.” However, they added, “This may be down to different use of terminologies” and that “the PBA payment application and authorisation statement should be clearly labelled”. The researcher explained that these forms are automated in the background; therefore, the data entry and document exchange associated with these forms are mitigated.

Concerning the cash outflow process, one interviewee remarked, “The cash outflow approval process demonstrated is more generalised and not entirely reflective of PBA”. Another elaborated, “In a PBA project, the contractor’s commercial manager would submit an authorisation statement to the PM for the amounts due to the subcontractors, then the client and the PM would sign it and forward it to the bank for settling.” Furthermore, “the bank normally notifies the subcontractor via text or e-mail when the payment is sent.” The researcher explained that the proposed application autonomously sends the project manager an authorisation statement whenever a subcontractor’s works are ready for approval, in which the project manager and any other appointed payment authoriser would check whether the delivered works match the order value and approve/authorise the work/payment to the subcontractor. This triggers the smart contract to execute a payment to the subcontractor without the main contractor needing to send an authorisation statement to the bank for processing.

Another interviewee commented, “The quantity surveyor (QS) must be included in the payment approval process. Their role includes measuring the works delivered and issuing a payment certificate or pay-less notice deeming how much to spend within the PBA.” In response, the researcher appended the QS and their responsibilities to the proposed application.

One interviewee mentioned, “Before subcontractors can be entered into the trust or joining deed, the contractor must check whether they are CIS (construction industry scheme) qualified; if not, they would need to undergo training and certification.”

One interviewee highlighted, “The problem with PBA is that the head contractor must get approval from the client before they can spend anything, unlike in traditional projects where the contractor has full control.” Another remarked how “all PBA payments are measured according to KPIs, assessed on cash receiving and outlay” and that “a good KPI score is deemed on how quickly payments to parties signed up to the PBA can be processed” and that “low KPIs are subject to penalties from the client.” Furthermore, they added that they “currently process payments within three days of the PBA receiving cash-ins”.

5.1.3.2 Overlooked Management Processes

The management processes discussed in this section differ from the previous section because they are longstanding processes that existed before PBAs emerged. Nevertheless, these processes are still exercised alongside PBA and are therefore crucial for the proposed application to examine. Concerning the proposed application’s Cash-in and Cash-out user interfaces shown in Figure 29 and Figure 31, one interviewee commented, “It should include budget cost and estimations so people can see how costs progress from estimation to actual.” Regarding the proposed application’s Cash-in interface, shown in Figure 29 from Chapter Four (Conceptual Framework), one interviewee stated that it “should include the status of the commercial manager’s interim valuation, which the client and the project manager would sign to authorise the payment.” This response was also supported by another interviewee who clarified: “The Cash-in user interface only showed two parties approving the cash-in (i.e., contractor and the client), but in a contract like NEC, there would be several other levels of signoffs by authorities such as the project manager, and any other consultants tasked with approving cash flows.” After the data collection, the researcher made an amendment to the proposed application by adding the project manager to the cash-in approval process.

One interviewee commented, “The proposed application’s Cash-in user interface displayed the client undertaking the valuator’s role and approving the works themselves, but in a realistic case, a valuator, such as the commercial manager, would be appointed to work with a quantity surveyor and project manager to process interim valuations and approve payments, then the client would execute milestone payments to the PBA based on the valuator's assessments." Furthermore, they clarified, "the interim valuator's primary duties include assessing whether project liabilities match orders and delivered works; their role also includes approximating the additional resource requirements for change orders."

Regarding the proposed application's Retention user interface shown in Figure 34 from Chapter Four (Conceptual Framework), one interviewee discussed that "when a retention payment from the contractor to a subcontractor is due, the contractor's finance team undergoes a verification process to check whether the contract manager has authorised its release and whether the liability matches the contract's order value." Furthermore, they added that "the process includes (1) verifying the recipient's payment details, (2) ensuring VAT (value-added tax) codes are applied, (3) reconciling invoices and credit notes, and (4) packaging the information for the payable team to process. The payable team also produces financial reports on the state of released retentions." Another interviewee mentioned, "Retentions are paid in two steps, one at practical completion and the other after the defects liability period, but the application only showed the first step." Another interviewee highlighted that "Retention payments are not included in standard PBAs, so if the goal is to build a PBA application, then this step is unnecessary". Another interviewee added, "Retentions are not currently covered in standard PBAs; however, NEC is starting to push for it, so implementing it in the application provides value." Another interviewee added, "Maple, a DeFi protocol, has opened a cash management pool in the form of US Treasury bills; this could easily extend to include UK T-bills, and the retention could be placed into one of these pools and earn interest over time before it is used for payments."

5.1.3.3 Interoperability with Existing Software

Concerning the Trust Deed user interface shown in Figure 26 from Chapter Four (Conceptual Framework), one interviewee stated it should "link up with the contractor's internal spreadsheet rather than having to enter the subcontractors' details twice". When they say "twice", they mean how the contractor traditionally creates the payment schedule in Excel and must manually transfer the data to the proposed application. A similar comment was made by another interviewee who said: "The demonstration showcased the contractor manually inserting cash inflow and cash outflow schedules" and suggested that "they should be automatically linked to the contractor's spreadsheet". Some spreadsheet software, such as Excel, have add-in capabilities that push data from a spreadsheet to a Web application without needing to build costly APIs (application programming interfaces); furthermore, this add-in feature is a standard function built into Excel (Hiron-Grimes, 2017).

Regarding traditional, non-blockchain-based technologies, one interviewee commented, "They tried integrating management information on SharePoint but ended up with too many bespoke systems that no one knew how to manage because data was being moved around too often." Furthermore, they added, "The problem with standard proprietary software, such as ERP (enterprise resource planning) software, is that it is too rigid, while Web applications such as SharePoint are too customisable". Another interviewee commented, "It is typical for managers of the same role to use different software even though they do the same tasks".

5.1.3.4 Interoperability with Existing PBA Systems

One interviewee commented that PBA processes are already well established and that "public-sector clients in the UK have a governmental login portal that they use to monitor and access PBAs." Furthermore, they added, "Banks are familiar with PBAs and can set them up in a few weeks." Another interviewee highlighted, "All PBA payments are made through a TMS (terminal management system) set up with the bank" and that "the client has the final say in what financial system to use for PBAs, and at the moment, it is with traditional finance, but it could be blockchain if the value proposition is big enough". When the researcher asked whether all banks offer PBA services in the UK, the interviewees agreed that not all banks offer them; however, they did not know why. The researcher also asked if PBAs are used in the private sector, to which one interviewee replied: "Not currently, but the government is considering rolling it out to include them."

Regarding whether blockchain can provide a solution for administering payment guarantees, one interviewee stated, "Banks already have a formal process for administering finance; they will not change their internal process just for one application." Another interviewee clarified, "The government does not allow PBAs to acquire finance because it increases their national debt due to interest repayments."

Another interviewee commented, “Payment guarantees for PBAs are unnecessary because the client is the government and is cash-rich.” Furthermore, they added, “It is more likely for the client to obtain a performance bond to protect against the contractor’s non-delivery.”

5.1.3.5 Technology Uniqueness

One interviewee highlighted, “There is a plethora of project management software that does management tasks better than blockchain, so it is best to use blockchain for what it is good at, which is a settlement layer.” Another interviewee agreed and stated, “The general concept of the application is fine, but it would be more effective if it were scaled back and simplified to just payments for now, then gradually improve it from there.” However, they added that they “see the benefits of putting some data on the blockchain, such as approvals.” Another interviewee expanded on the idea of a PBA blockchain application and advised, “The original idea of using a PBA in a traditional finance account is that it does not cut across any existing commercial agreements. If the idea is to develop a PBA application, then strip it down to just PBA.”

One interviewee discussed how they are “currently testing a custom-built software called the Contract Solutions Platform (CSP), which performs similar tasks as the proposed application, such as managing subcontractors, approvals, schedules, and compensation events. However, CSP is still in its piloting stage.” They added that “CSP tracks and manages the issuance and signing of contract agreements and order values in one platform, and all data flows are timestamped.” However, they highlighted, “A limitation of CSP is that it cannot execute payments, only manage them.” Another commented, “Ultimately, we will test and use whatever system is pushed onto us by our client, but, due to risk, it rarely happens because no one wants to take the blame if it all goes wrong.”

Concerning how the proposed application stores contract documents on IPFS (Interplanetary File System (i.e. a decentralised cloud)), one interview highlighted: “Standard cloud is not designed to handle the commercial complexities of contract management” and that “Cloud-based solutions for this already exist, such as CEMAR (Contract Event Management and Reporting software).” They added, “CEMAR is designed to operate with NEC and provides users with dashboards for tracking and managing contract data.” Furthermore, they said, “CEMAR automates the generation of charts, dashboards, and reports, such as percentage of early warnings managed effectively, communications dealt with on time, compensation events approved, and so on.” Another interviewee stated that “partitioning the proposed application into many small segments may be better than creating an all-encompassing solution because it is easier to test while incurring less risk and cost”.

5.1.4 Theme C: Opportunities

The *Opportunities* section was organised into five subsections: (3.1) Cryptocurrency Price Stability, (3.2) Systems Integration, (3.3) User Accessibility, (3.4) Blockchain-based Finance, and (3.5) Privacy.

5.1.4.1 Cryptocurrency Price Stability

“Cryptocurrency volatility” was an issue highlighted by one interviewee. The researcher replied that in a real-life scenario, stablecoins would be used; however, stablecoins are only available on the Ethereum main network, not the Ethereum-Goerli test network in which the application was deployed. One interviewee asked, “How can government tax duties be processed in cryptocurrencies?”. The researcher responded that the final output of payments would be in fiat currency; thus, tax duties would be the same as current procedures. The blockchain is merely used as a tool to move funds more efficiently than traditional finance. Any cryptocurrencies/stablecoins would be exchanged for fiat and deposited into the user’s bank account. However, the researcher admitted that this article did not investigate the off-ramping infrastructure. The typical method for off-ramping cryptocurrencies from the blockchain is via online centralised exchanges.

5.1.4.2 Systems Integration

One interviewee highlighted, “The problem with current systems is that data across multiple files or projects are difficult to aggregate with a high degree of trust”. Another interviewee added, “If data is stored on the blockchain with timestamps, a simple lookup application can pull the data and present it onto dashboards.” Regarding the integration of centralised and decentralised systems, another commented, “Qredo (a blockchain platform and decentralised application provider) has teamed up with Xero (an accounting software used by businesses) to bridge the gap between centralised and decentralised systems.” This is particularly useful because one interviewee stated earlier that “the problem with proprietary software, such as ERPs (enterprise resource planning) is that it is too rigid”. Another interviewee added, “ERPs have difficulty integrating with other software systems because they are not designed to be customisable”.

The proposed application’s Subcontractor user interface shown in Figure 32 in Chapter Four (Conceptual Framework) was designed to enable subcontractors to pull their scheduled work and payment data instantly without them needing to contact the contractor to retrieve the data. In response, one interviewee commented, “This reduces the number of unnecessary communications between management parties and subcontractors because much time is wasted simply relaying information.” Another interviewee stated, “In a typical large project within their company, ten people, on average, spend two full days per week answering queries related to schedules, orders, and payments.” Another interviewee added, “Enabling each subcontractor to pull the most updated version of their scheduled work is very useful for data consistency and reduces the burden on them managing this information themselves.” Furthermore, another interviewee commented that one of the problems they face is “maintaining an accurate data trail between the lead contractor and subcontractor.”

Concerning the set-up process of PBAs, one interviewee highlighted, “In a joint venture project, several interconnected PBAs, called tranches, would need to be set up, which causes unnecessary bureaucracy and delays with the bank.” A joint venture is when a construction project is cooperatively delivered by several contractors instead of one. They later added, “This could potentially be managed more easily with smart contracts.”

5.1.4.3 User Accessibility

According to one interviewee, “decentralised applications grant developers more freedom and control over what they want to build, which makes the technology easier and more inviting to use; this will eventually transpire into better services for users.” Another interviewee mentioned, “Many of the concepts for using blockchain with enterprises are well established. The next stage is developing the appropriate user interface for non-technical users to access these systems.” Furthermore, another interviewee added, “A tool called signing agent is currently being developed that mitigates signing fatigue” and clarified that a “signing agent allows multiple transactions to be batched and signed under one transaction". Another interviewee highlighted, "The proposed application should be designed so the end-user does not even know blockchain is being used; blockchain should be an invisible layer in the background."

One interviewee pointed out, "Since blockchain uses a copyleft vs copyright licence, the technology can be copied, modified, and redistributed without intellectual property issues; the same applies to decentralised applications built on the blockchain." Furthermore, they added, "Some blockchain decentralised applications take the idea of open-licence further, such as Qredo blockchain, by providing white-label solutions that enable their work to be used and rebranded in another application without risk of copyright."

5.1.4.4 Decentralised Finance

One interviewee commented, "Liquidity is one of the biggest issues in construction, and getting cash to the supply chain faster and with lower fees will be the first key application for construction." Furthermore, they added that "wallet decentralised applications such as Qredo provide insurance up to the value of £470 million for any funds lost through wallet hacks on their platform." Another interviewee commented, "The problem with many decentralised finance (DeFi) protocols, such as Aave and Compound (decentralised lending platforms), is that they do not integrate with existing centralised systems; therefore, they have no practical value in the real business world." They later pointed out that "DeFi protocols, such as Maple Finance (a decentralised lending platform that provides the loan underwriting services of traditional finance), provide a middle ground between blockchain and traditional finance, whereby they use blockchain for what it is good at (i.e., a settlement layer) while providing the loan underwriting services of traditional finance." Furthermore, they added, "There is a private blockchain platform called Lygon (a lending platform built on a private blockchain) that provides blockchain-based bank guarantees using Hyperledger Fabric, but it took them many years just to issue a single bank guarantee on the blockchain chain because they ran into many problems using a private blockchain." Additionally, they added that "Many DeFi protocols already provide institutional lending through public blockchains" and that "the problem with using private blockchains for finance is that so much time and money is wasted setting up the protocol and maintaining the network, whereas this problem is non-existent if deploying a decentralised application on Ethereum". Additionally, they added, "Ethereum is probably the best blockchain to build on because they have the brightest blockchain minds and the largest community of developers working this stuff out and they have worked through all sorts of attacks and patches that other blockchains are still yet to go through."

While discussing blockchain finance, one interviewee stated, "Invoice finance is not regulated in the UK, so providing blockchain-based supply chain finance through approved invoices is a good entry point." Furthermore, they added that "existing invoice finance providers do not look at invoices on a project-by-project basis; instead, they look at the applicant's sales ledger across an entire year and then calculate how much finance they can offer."

5.1.4.5 Privacy

One interviewee asked the researcher, "If a public blockchain is used and the data is publicly available on a webpage, how can a company maintain the privacy requirements it needs?". The researcher responded that a cryptographic protocol called zero-knowledge proofs (ZKPs) allows users to encrypt data stored on the blockchain, such as the transaction value. This enables users to transact privately on the blockchain. The researcher explained that ZKPs were not used in the proposed application due to a lack of technical expertise in implementing them; however, a decentralised application developer would program the ZKP in a real-life project.

Concerning how all project participants can view all data visible on the proposed application's user interface, one interviewee commented, "The subcontractors should not have visibility of the cash-in schedule, but the application showed that they can freely view this data". The researcher responded that for testing purposes, the cash-in and cash-out schedules were displayed under the same user interface; however, in a real-life application, these schedules would be partitioned into separate user interfaces. Furthermore, the cash-in/out schedules could store data encrypted, enabling only authorised users to decrypt it.

To increase the proposed application's wallet security, one interviewee highlighted, "If using a wallet for the PBA, then an MPC (multi-party computation) wallet is best, but if using a smart contract, then a multi-signature smart contract is best." Furthermore, they added, “An MPC is when a shared wallet’s private key is divided into several parts, with each part owned by a different user.” This allows multiple users to control the MPC wallet’s funds. For example, each user holding a fraction of the private key would partially authorise a transaction, and the transaction would only execute if all (or a predefined percentage of key holders) sign for the transaction.

5.1.5 Theme D: Threats

The *Threats* section is organised into three subsections: (4.1) Off-ramp Regulations, (4.2) Relationship With Banks, and (4.3) Know Your Customer Services, as shown below.

5.1.5.1 Cryptocurrency Regulations

Stablecoins were mentioned in the *Opportunities* section as a method for mitigating cryptocurrency volatility. However, there are some regulatory challenges to stablecoins that the interviewees identified. For example, one pointed out that “stablecoins are not yet considered legal tender, but this should be ironed out when the stablecoin bill is approved.” Furthermore, they added, “When approved, there will be a fast expansion of real-life use cases for blockchain” and that “the bill for regulating stablecoins is currently with the House of Lords”. Another interviewee highlighted, “The current problem with stablecoins is that when it is converted into fiat, it is treated as capital gains and is subject to capital gains tax.” Furthermore, they added that “when stablecoin regulations catch up, people will naturally gravitate towards blockchain applications because they are faster and cheaper than traditional finance.” Another interviewee stated, “Another problem with stablecoins is how to off-ramp them from the blockchain.” However, they clarified that “If these stablecoin regulations are successful, and if the plan is just to use the application for payments, then there should be no problem using the blockchain.”

5.1.5.2 Relationship With Banks

When the researcher asked the interviewees whether they saw any potential threats with enterprises adopting the proposed application, one mentioned, “The threat is with the bank and not the enterprises because blockchain will take business away from them.” Furthermore, they added, “Banks can indeed make it harder for crypto companies to off-ramp crypto assets if they feel threatened.” Another interviewee commented, “Banks have a strong grip on construction companies. Because of this, contractors must inform them if they plan to use the PBA services of another provider.” Another interviewee added, “Maintaining good relations with banks is crucial for business, and the banks know this and use it to their advantage.” Another interviewee remarked, “Banks seem to have reacted too slowly with blockchain, so it seems decentralised finance is filling in.”

5.1.5.3 Know Your Customer Services

Regarding the proposed application’s Trust Deed user interface shown in Figure 26 from Chapter Four (Conceptual Framework), one interviewee discussed how “the wallet addresses of users should be linked to a KYC (know your customer) registry to ensure only verified users can be entered into the application” and added, “whether the application wants to undertake the responsibility of a KYC verifier is another question.” Another interviewee highlighted, “DocuSign has been used a lot more recently since everyone has been working from home” and that “Integrating the application with a DocuSign-type system that allows users to sign the trust deed with their blockchain wallets would be useful.” Another mentioned, “Many blockchain decentralised applications provide KYC and white-listing services that enable users to limit transactions to verified wallets only.”

Regarding the set-up process of PBAs, one interviewee stated, “In the PBA trust deed, it will say which bank account to use for the PBA; there should be no problem in specifying a blockchain wallet as the PBA, provided the right KYC (know your customer) and insurance is in place throughout.” Another commented, “Several blockchain applications have gone a step further by linking human-readable aliases to KYC-approved wallets, similar to how PayPal links e-mail addresses to bank accounts.”

5.2 Questionnaire

The questionnaire included nine open-ended questions (as shown in Table 12) covering several technology components typically found in a blockchain application. Questions **one** and **two** are regarding the application’s limitations and areas of improvement. Questions **three** to **five** concern back-end systems; question **six** relates to the front-end; question **seven** investigates Web 3; Question **eight** concerns cybersecurity and wallet security; and finally, question **nine** concerns decentralised

The following video was included in the questionnaire sent to the questionnaire participants, they were instructed to watch it before starting the questionnaire: https://www.youtube.com/watch?v=mwAAAhnowxQ. The author created this video to showcase how end-users would interact with the proposed application to execute PBA activities. All the questionnaire's questions were in direct response to that video.

Table 13.
Questionnaire questions to the blockchain developers.

1	Are there any challenges or limitations of any sort that you see with the proposed application? (E.g., from a general, technical, organisational, user interface, or any other perspective.)
2	Do you have any suggestions for altering or reconfiguring the application or its components to improve its architecture or performance? (E.g., from a general, technical, organisational, user interface, or any other perspective.)
3	The application's back-end comprises Ethereum for the blockchain and Node.js for the virtual server and incorporates third-party services such as Infura for the blockchain node, MetaMask for the wallet, and IPFS as the decentralised storage provider. Do you have any comments or recommendations for improving this setup?
4	Would the application be better suited on another blockchain platform or an Ethereum layer two scaling solution? If so, which one, and why?
5	The application requires transferring data manually from centralised spreadsheets to smart contracts. What is the best solution for automating data transfer between these mediums, and what technology systems does it require?
6	The application's front-end is built from React and JavaScript. Is there an alternative user interface setup you would suggest that is more beneficial for decentralised applications (dApps)?
7	Do you think the application would benefit more if it were hosted entirely on Web 3? Moreover, what are some of the challenges and benefits of this?
8	How can the application's wallet security be improved, and what general cybersecurity precautions would you advise on?
9	Since Ethereum dApps benefit from high integration capacity because they are built on a general-purpose blockchain, are there any dApps you suggest integrating with?

A thematic analysis was used to analyse the questionnaire data; however, unlike the focus group interview (the previous data collection), the questionnaire did not use a SWOT analysis due to the framing of the questionnaire's questions. The questions were designed based on the assumption that the technical aspects of the proposed application require customisations and architecture reconfigurations before it can be considered a viable solution. This is because the researcher is not from a software engineering or computer science background; therefore, the questions were designed to extract technical insights, comments, and suggestions for improving the application.

5.2.1 Questionnaire Summary

The low response rate of the questionnaire participants created potential biases in the responses. However, the author predicted this may occur and designed the questionnaire's questions open-ended to mitigate it. Although responses to the questionnaire were anonymous, the author could make an educated guess of who the respondents were based on their responses. This is because some of the respondents were highly positive and optimistic about particular technology solutions and had little to no view about anything else. Furthermore, some of the respondents left many questions blank; therefore, the average response per question was lower than the total count of 38 respondents. The majority of candidates who were invited to complete the questionnaire were from public blockchain space, which biased the responses towards public blockchains, in particular, Ethereum. However, Ethereum dominates the decentralised application (dApp) space and has the largest number of dApp developers building dApps on their platform (Chain Stack, 2020). Therefore, if randomly selecting a dApp developer from the blockchain space, most of the time they will be from Ethereum. When the author invited candidates to participate in the questionnaire, he had no predefined filter for targeting Ethereum developers.

Table 14 displays the key points of each subtheme from the questionnaire's data collection, and is evaluated in greater detail in Chapter 6: Discussion, Section 6.3: Discussing the Findings.

Table 14.
Summary of the questionnaire findings.

Theme	Subtheme	Summary
1. Blockchain	1.1 Systems Design	Enterprise systems and process flows would need restructuring to accommodate blockchain.
		The application should be deployed as part of a larger ecosystem of services.
		Decentralised technologies suffer from a lack of centralised accountability with legal systems, making it hard for insurers.
	1.2 Tokens	The application should use a crypto-economic incentive system as part of its general framework to better stimulate user activity.
		Cryptocurrencies, including stablecoins, have not yet been approved as legal tender; thus, they face regulatory challenges.
		Stablecoins are critical to the application's success.
		A token off-ramping strategy or solution is required.
		Non-fungible tokens can be used to represent asset ownership certificates and should be leveraged in the application.
		Alchemy can be substituted for Infura for node services.

	1.3 Blockchain Services	Like Truffle and Hardhat, Foundry is a good toolkit for testing smart contracts.
		OpenZeppelin provides a wide range of fully audited smart contract templates.
	1.4 Scaling Solutions	Ethereum layer two scaling solutions are critical for scalability.
		Polygon, an Ethereum layer two (L2) sidechain, can reduce transaction fees by a factor of 10,000.
	1.5 Privacy Solutions	The Zero-knowledge proof (ZKP) L2 privacy solution can achieve private transactions on Ethereum.
		Stealth addresses (SAs) are an alternative to ZKP.
	1.6 Blockchain Selection	Hashgraph and Algorand have transaction fees of £0.01 and can scale to 10K TPS (transactions per second).
		Polkadot can scale to 1K TPS; furthermore, it solves the cross-chain interoperability problem of Ethereum.
		Internet Computer (IC) blockchain imitates the client-server model of Web 2; however, IC's servers are fully decentralised.
		Hyperledger is a private blockchain alternative; however, tokens minted on its platform have no value outside its blockchain.
2. Web services	2.1 Web 3	Web 2 has had decades of development; thus, it is faster, cheaper, and more efficient than Web 3.
		The most common Web 3 applications are decentralised storage and decentralised identifiers.
		The proposed application would not benefit from Web 3.
		Web 3 would provide value if using a decentralised autonomous organisation (DAO) or building an ecosystem of services.
	2.2 User Interface	Regarding the user interface, Vue, Angular, Pure.JS, and Svelte are alternative programming languages to React.
		Fleek and Drizzle are Web 3 user interface services built to interoperate with Ethereum and decentralised services.
		Python (instead of JavaScript) has more tools for integrating with construction software such as Revit and Dynamo.
	2.3 Oracles and APIs (application programming interfaces)	Chainlink was the first oracle provider for blockchains and is considered reputable.
		Dfinity is an organisation that provides oracle frameworks.
		Blockchain oracles can be built from JavaScript and Python.
		Amazon and IBM also provide oracle services but are centralised.
		Instead of using oracles, automating data flows to the application can be achieved through standard REST APIs.
		If using APIs, an ETL (extract, transform, and load) system should be used to reduce data inconsistencies and faults.
		Most management software (e.g., Excel) has API and plugin capabilities for pulling or pushing data from Web applications.
	2.4 Server-side Logic	Blockchain apps should integrate with centralised computer systems for improved computation performance and storage.
		The application should include logic that enables it to inform users if a transaction will fail before they send it, saving users on fees.
		The application should autonomously notify tier-one parties if project costs are on a trajectory to exceed the project budget.

		The app should use an object-relational mapper (ORM) tool to allow databases to interoperate with smart contracts.
		The application should use a batch-processing tool to allow multiple transactions to be signed together.
3. Security	3.1 Cybersecurity	Decentralisation does not equate to better cybersecurity, and relying on third-party blockchain services jeopardises it further.
		The application should host a blockchain node instead of outsourcing node services from Infura.
		Some decentralised applications already link biometric authentication to blockchain wallets.
	3.2 Wallet Security	There is insufficient evidence that third-party wallets, such as MetaMask, can provide adequate proof of their security promises.
		Multi-sig wallets, MPC wallets, or multi-sig smart contracts should be the default account for holding PBA funds.
		One way to improve blockchain wallet security is to ensure they are generated using the new Edward Curve 25519 algorithm.
		The application should have a system for performing KYC verification on the wallets of its users.

5.2.2 Theme One: Blockchain

A thematic analysis was used to organise the questionnaire responses into three primary themes: (1) Blockchain, (2) Web Services, and (3) Security. These themes were then structured into twelve subthemes, presented throughout this section. Theme one: *Blockchain*, is the largest of the three primary themes and covers everything intrinsic to blockchain technology. This theme is structured into six subthemes: (1) Systems Design, (2) Tokens, (3) Blockchain Services, (4) Scaling Solutions, (5) Privacy Solutions, and (6) Blockchain Selection.

5.2.2.1 Systems Design

System design refers to the high-level considerations of the proposed application and regarding blockchain in general, such as whether blockchain is ready for enterprise adoption and the complexities of using decentralised technologies. Concerning this, one questionee commented, “Before enterprises embark on a blockchain journey, they should assess whether they are willing to restructure their business workflows, retrain staff, and have the resources to maintain the technology long-term”. Furthermore, they highlighted that “Deploying the application as a component in a larger ecosystem of technology services would help attract collaboration from other developers”; furthermore, they added, “It mitigates having to spend resources building entirely new systems”. Another questionee mentioned, “The application can be improved by using a more general-purpose scheme, rather than focusing on payments, users should have the option to choose how they want to use it”. Another questionee commented, “Decentralised technologies are complex for the courts of law because no one party can be held liable for blockchain technology-related faults, leading to potential legal accountability issues for lost or stolen funds”.

5.2.2.2 Crypto-economics & NFTs

A cryptocurrency is the native currency of a blockchain platform, which is minted when the platform is launched. In contrast, a blockchain token is a type of cryptocurrency minted when a blockchain is already in operation, such as NFTs (non-fungible tokens) and stablecoins. One questionee commented, “The proposed application needs to incorporate a crypto-economic incentivisation system as part of its core function.” Crypto-economics is an automated rewards system built into decentralised applications, providing users with automated financial rewards for task completion

(Bao & Roubaud, 2022). Another questionee said, “Stablecoins should be implemented in the application to mitigate the price fluctuations of Ether (the cryptocurrency of Ethereum)” and that “incorporating it would ultimately decide the application’s success.” Another questionee commented, “Circle is a stablecoin provided by banks”. Furthermore, another questionee added, “Off-ramping stablecoins is where most of the challenges are”.

On the topic of NFTs (non-fungible tokens), one questionee mentioned, “NFTs would be useful to explore because many assets (digital and physical) are unique and would benefit from easy verification and transferability”. Furthermore, another questionee added, “If construction companies adopted NFTs, they could use them to represent asset ownership certificates, which can be used as a medium of exchange when providing banks collateral for finance.” Moreover, they added, “This would reduce the banks’ processing time for verifying the authenticity of data, leading to reduced processing times for financial services”.

5.2.2.3 Blockchain Services

Blockchain services are third-party applications that reduce the entry barriers for developers and users by providing infrastructure for blockchain applications. Regarding this, one questionee highlighted, “Alchemy can be substituted for Infura for hosting the blockchain node; Infura specialises in decentralised storage, while Alchemy specialises in NFTs”; however, “both offer similar services”. Another questionee mentioned, “Foundry is open-source toolkit for testing blockchain applications; it includes Forge (a framework for testing decentralised applications), Cast (a tool for blockchain smart contracts), and Anvil (a local Ethereum computer node)”. Another questionee commented, “OpenZeppelin provides a library of community-reviewed smart contract templates that align with Ethereum’s most updated standards”. Another questionee remarked, “The Graph is a blockchain platform that provides indexing and API (application programming interface) services to other blockchains”, and another highlighted, “Amazon and IBM provide blockchain-as-a-service (BaaS) for users seeking an instant blockchain solution with inbuilt services that integrate with existing enterprise systems”; however, they added “BaaS is proprietary-based and centralised”.

5.2.2.4 Scaling Solutions

Ethereum is known for having low throughput (measured in transactions per second (TPS)) and high transaction fees (anything from £0.5 to £25 based on Ethereum's network fee estimations at the time of testing the proposed application throughout 2022 and 2023). As a result, scaling solutions are required to increase TPS and reduce transaction fees. One questionee commented, "Transaction fees on public Ethereum are slow and expensive, so you need a layer 2." Layer twos are separate blockchain platforms built on top of an existing layer one blockchain such as Ethereum. Layer two benefits from high security because it synchronises its ledger with a layer one blockchain by periodically batching numerous layer two transactions and sending them to layer one as one transaction; hence, high scalability is achieved (Liang et al., 2022). Another questionee mentioned, "Polygon, a layer two scaling solution for Ethereum, can reduce transaction fees to negligible sums". For example, an Ethereum transaction fee of £20 would be reduced to £0.002 on Polygon (Besancon et al., 2022).

5.2.2.5 Privacy Solutions

Regarding achieving privacy on a public blockchain, one questionee stated that "one way to achieve privacy on public blockchains, such as Ethereum, is to use zero-knowledge proofs (ZKP)". ZKP is a cryptographic protocol that enables users to mathematically prove that a piece of encrypted data is correct without decrypting it (Li & Xue, 2021). Another questionee highlighted, "Privacy can be achieved directly on layer one using the stealth address (SA) protocol; it allows users to generate sub-addresses that are one-time-use and cryptographically linked to the user's primary wallet". A version of the SA protocol is located here: https://application.umbra.cash/ (Solomon & DiFrancesco, 2021). Once an SA is used, funds are transferred from the SA to the user's primary wallet; afterwards, the SA is deleted (Solomon & DiFrancesco, 2021). Users can generate an unlimited number of new SAs for future private transactions (Solomon & DiFrancesco, 2021).

5.2.2.6 Blockchain Selection

The popularity of Ethereum has resulted in high transaction fees due to network congestion. In response to this, the respondents highlighted several blockchain alternatives. One questionee remarked, "Hashgraph and Algorand can achieve higher transactions per second (TPS) and lower transaction fees than Ethereum". Hashgraph and Algorand can reach over 10K TPS with a £0.01 transaction fee, and both can process smart contracts coded in Solidity (Baird & Luykx, 2020; Micali, 2022). Solidity is the native programming language of Ethereum. Another questionee stated, “Polkadot solves a critical problem that most blockchains have with cross-chain interoperability and is faster and cheaper than Ethereum”. Polkadot can achieve 1K TPS (Busayatananphon & Boonchieng, 2022). Another questionee highlighted, “Internet Computer blockchain uses the same client-server model of Web 2 but decentralises them using Web 3 and blockchain.” Another questionee commented, “Hyperledger is a private blockchain with high throughput (several thousand TPS) and no transaction fees.” However, they added, “its high TPS and low fees are exchanged for low security”.

5.2.3 Theme Two: Web Services

Theme two: Web services, covers the additional components blockchain-based Web applications require to integrate with the blockchain. This theme includes four subthemes: (1) Web 3, (2) User Interface, (3) Oracles and APIs (application programming interfaces), and (4) Server-side Logic.

5.2.3.1 Web 3

The goal of Web 3 is to fully decentralise the Internet, where all software is open-source, open licence, and permissionless (Jacobs et al., 2012). One of the respondents stated, “In a pure blockchain decentralised application, the back-end would be the blockchain and smart contracts only”. Although this is true, blockchain applications typically integrate with Web systems to provide better services for users and developers. One questionee commented, “The problem with Web 2 is that technology companies monetise the data of users”; however, they added, “Its services are cheap and scalable because it has had decades of development”. Another questionee added, “Examples of Web 3 services include decentralised storage (e.g., IPFS), decentralised finance (DeFi), and decentralised identifiers (DIDs)”. Another questionee highlighted, “A hybrid approach that integrates Web 2 and Web 3 is more practical in the current environment because a full Web 3 setup offers less value to developers and customers”. Another questionee mentioned, “Making an entire application censorship-resistant by using Web 3, storing documents in IPFS, and using ENS (Ethereum name service) is excessive; These services are more catered for anonymous transacting parties". Another questionee remarked, "If the application aims to process payments with smart contracts, then using Web 3 just for the user interface would not add value". Another questionee stated, "Web 3 complements blockchain, but blockchain applications can operate fine without it". Furthermore, they added, "there is little evidence that the application can benefit from Web 3". This was supported by another questionee who commented, "Whether or not to Web 3 is a balance between complete decentralisation versus retaining some operational control over the application". However, they added, "If the plan is to build a large ecosystem of blockchain services or if planning to set up a DAO, then the rationale to use Web 3 becomes stronger". A DAO (decentralised autonomous organisation) is an entity managed by decentralised members that use smart contracts to manage the system (Qian & Papadonikolaki, 2020). Lastly, one questionee highlighted, "Web 3 is acceptable if complete decentralisation is the only goal"; however, they added, "Decentralisation is one of many factors to consider, and improving the application's business logic should take precedence".

5.2.3.2 User Interface

The proposed application's user interface was built using JavaScript and React, the most common front-end setup for Web applications. When asked about other potential approaches for the user interface, one questionee replied, "An alternative to React is Vue (a lightweight JavaScript framework) and Angular (a more technical Typescript framework)"; however, they added, "the decisin on which Web framework to choose is predominantly based on the developer's preference". Another questionee commented, "Pure.js allows developers to create simple Web apps without requiring a front-end framework, but its features are limited". Another questionee mentioned, "Svelte is a front-end framework that supports both TypeScript and JavaScript"; furthermore, they added, "it compiles code to vanilla JavaScript, making syntax easy to read"; additionally, "it performs faster than most front-end frameworks because its coding is precompiled, unlike most Web apps that compile code in the browser". Another questionee remarked, "Fleek, a decentralised Web user interface application, provides services for hosting full Web 3 applications that connect to Ethereum, Internet Computer blockchain, IPFS (a decentralised cloud storage provider), and Filecoin (a blockchain platform built for supporting IPFS services)". Another questionee stated, "Drizzle (part of Ethereum's Truffle suite) is a front-end library that integrates with

React, Web 3, and Ethereum. Alternatively, Hardhat is a similar service specialising in Web 3 application plugins". Another questionee highlighted, "Python's Web 3 library (Web3.py) provides tools for construction industry software, such as Revit and Dynamo, to connect to blockchains". Lastly, one questionee commented, "Libsodium is a software library for Web 3 that provides tools for simplifying cryptography in Web applications without compromising security".

5.2.3.3 Oracles and APIs

Blockchain oracles are application programming interfaces (APIs) that autonomously send data from the real world to the blockchain (Sonmez et al., 2022). Regarding this, one questionee mentioned, "ChainLink is a blockchain platform that originated blockchain oracles, making them a popular choice for oracles because of their first-mover advantage". Another questionee remarked, "Dfinity is a non-profit organisation specialising in decentralised services and provides oracles frameworks and templates for users to customise and deploy." Furthermore, they added, "Their framework is accessible here: https://github.com/hyplabs/dfinity-oracle-framework". Another questionee stated, "Web 3 oracles can be built from JavaScript (Web3.js) and Python (Web3.py)". Another questionee highlighted, "Oracle and API services can be outsourced to blockchain-as-a-service (BaaS) providers, but decentralisation is exchanged for convenience". BaaS is owned by centralised technology companies that charge high subscription fees and exercise vendor-lock strategies (Cai et al., 2022; Rodrigo et al., 2020). Examples of BaaS providers include Amazon and IBM (Arnold, 2021; Krishnan et al., 2021). Another questionee stated, "Instead of using oracles to automate data flows to the blockchain, semi-automation can be achieved with standard APIs, such as RPCs (remote procedure calls) or REST (representational state transfer)". Another questionee highlighted, "ETL (extract, transfer, and load) is a system used for APIs to manage and organise data to reduce inconsistencies and faults; ETL provides a central system for APIs to pull or push data from". Lastly, another questionee commented, "Management software such as Excel include plugin capabilities that can be configured to automate data flow to and from Web applications".

5.2.3.4 Server-Side Logic

In the context of blockchain and decentralised application development, server-side logic refers to how traditional Web 2 infrastructure (which is predominantly centralised) is leveraged to improve the buildability of blockchain applications in the current climate. Regarding this, one questionee mentioned, "Off-the-blockchain integration is essential because the blockchain cannot be used for computationally intensive tasks or storing data-rich files". Off-the-blockchain solutions are when data processing that typically occurs on the blockchain is transferred to an off-the-blockchain system, such as Web servers (Nawari & Ravindran, 2019b). Another questionee remarked, "One of the ways that the application's business logic could improve is by enabling it to inform users if their transaction will fail before they send it, saving users unnecessary transaction fees". Another questionee suggested it should include "automated alerts to tier-one parties when project costs exceed a threshold or if on a trajectory to exceed it; then users could react more quickly in strategising a solution to mitigate overspending". Another questionee highlighted, "An object-relational mapping (ORM) tool would improve the application's ability to interoperate smart contracts with relational/SQL databases". ORMs allow relational data to be collected from databases and presented as classes and objects in object-oriented programming languages such as JavaScript or Solidity (Colley et al., 2019). Lastly, another questionee commented, "Incorporating batch processing in the application would allow numerous transactions to be grouped and processed together with one signature, resulting in a better user experience because users would not be constantly prompted for MetaMask signatures every time they send a transaction". Furthermore, they added, "it enables the application to work in offline mode because transactions can be parsed in the background and sent when back online".

5.2.4 Theme Three: Security

Theme three: *Security* covers the proposed application's threats concerning Web security, third-party services risk, and how to ensure the correct wallet precautions are considered. This theme is organised into two subthemes: (1) cybersecurity and (2) Wallet Security.

5.2.4.1 Cybersecurity

Concerning the proposed application's cybersecurity considerations, one questionee mentioned, "Decentralisation does not automatically equate to increased security, and more emphasis must be made to ensure the application is correctly managed and maintained". Additionally, they added, "Overreliance on third-party blockchain services jeopardises security." Another questionee remarked, "Deploying a blockchain node internally within the application is more secure than relying on third-party node services such as Infura". Another questionee stated, "Some decentralised applications link biometric authentication (e.g., fingerprint and face recognition) to blockchain wallets. Incorporating biometric logins would increase the application's security". Another questionee highlighted, "E-mail logins and two-factor authentication could be used to secure the front-end, but 2FA cannot provide security for blockchain wallets because they are non-custodial, meaning users directly manage their wallets. 2FA is only used when third-party service providers manage their users' accounts but want to grant users access to the third-party system". Lastly, another questionee commented, "OAuth 2 is a technology standard for managing data trust in Web applications, which needs consideration if planning to process or store user-identifiable data".

5.2.4.2 Wallet Security

Wallet security is another critical aspect of the proposed application because, unlike centralised custodians (i.e., a bank), blockchain wallets are managed solely by their owner, and each user on the blockchain is responsible for correctly managing their wallets. Wallet security also includes how to store escrowed funds safely. Since all cash inflows and outflows are made to and from a shared blockchain wallet, ensuring project funds are protected from thefts or hacks is vital for success. One questionee stated, "There is insufficient evidence that third-party blockchain wallets, such as MetaMask, can provide adequate proof of their security promises." They added that "MetaMask operates through a Web browser that collects data on user activity, so it is vulnerable to attacks". Another highlighted, "Multi-signature wallets and multi-signature smart contracts can improve security by protecting project funds from theft". This is because wallet signatures from a predefined percentage of users are required to execute transactions from a multi-signature system (Cocco et al., 2022). Another questionee commented, “Threshold wallets are an updated version of multi-signature wallets” and that “the difference is that one private key is divided into many parts and given to multiple users”. Another questionee mentioned, “An instant way to improve the security and performance of blockchain wallets is to ensure that they are generated using the most updated algorithm, such as the Edward Curve 25519”. Edward Curve generates more secure wallets and occupies fewer bits/characters in their address length; thus, transactions are cheaper because less memory is required to store transactions on the blockchain (Brendel et al., 2021). Another questionee remarked, “Performing KYC (know your customer) verification checks on the wallet addresses of the supply chain is good practice to ensure users can be trusted and people are who they say they are”. Lastly, another questionee stated, “Decentralised identifiers (DID) have gained popularity in blockchain because it allows users to partition identity information away from third parties.” Furthermore, they added: “Users can use their wallet purely for DID verification rather than transactions.”

5.3 Application Readiness Level

Of the 27 subthemes created in the thematic analysis, 23 were converted to ARL factors for measuring the proposed application’s ARL. The four subthemes that did not transpire into ARL factors include (1) decentralised finance, (2) relationship with banks, (3) privacy solutions, and (4) Web 3. In conjunction with those four subthemes: (1) The *decentralised finance* (DeFi) subtheme investigated the potential for construction companies to obtain loans from DeFi lenders in the blockchain ecosystem. However, two focus group participants clarified that the UK Government does not allow PBA projects to obtain loans because the interest repayments of these loans would increase the government’s debt. Therefore, the potential for using DeFi loans to increase project cash flow was verified as unfeasible. (2) *Relationship with banks* was another subtheme that was not included as a factor in the ARL scale because it discusses the potential negative impact blockchain may have on the relationship between banks and construction enterprises if blockchain takes business away from banks. However, PBAs are negligible compared to the vast financial products and services offered by banks, and it is a political issue that is external to the topic of scoring applications based on their readiness for adoption. (3) Concerning *privacy solutions*, two subthemes were created for privacy because it was discussed by both the focus group and questionnaire participants and their data was analysed separately, which created two subthemes: one privacy subthemes was organisationally-focused (i.e., data privacy requirements for enterprises) and the second was technically-focused (i.e., how to achieve private transactions on a public blockchain). Nevertheless, the two privacy subthemes were merged into one ARL factor. Lastly, (4) *Web 3* was excluded as an ARL factor because the questionnaire respondents advised that Web 3 is an optional feature that is not necessary for blockchain applications to operate, and that Web 3 is better suited for decentralised autonomous organisations (DAOs) or if the transacting parties on the network are anonymous.

Table 15 displays the 23 ARL factors that determine the proposed application's ARL. It also shows the ARL score of each factor and the author's description of how that score was assigned. A full explanation of the ARL scale (i.e., ARL 1 to ARL 9) is mentioned in *Chapter 3: Methodology,* section *3.6: Data Analysis.* However, a simplified overview of the ARL scale is as follows: ARL 1: exploratory research; ARL 2: conceptual framework; ARL 3 application development; ARL 4: proof of concept (PoC); ARL 5: enterprise pilot; ARL 6: commercial prototyping; ARL 7: minimum visible product (MVP); ARL 8: end-of-project reports; ARL 9: commercial adoption.

Table 15.
Application readiness level (ARL) score of each ARL factor

ARL factors	Score	Description
Data traceability and permanence	ARL 9: Adoption	The Ethereum blockchain was deployed in the commercial environment in 2015. Since then, it has proven reliable for data traceability and permanence. Therefore, when assessing the application purely from the *data traceability and permanence* factor, it is suitable for commercial adoption because its data is immutable, and many traditional finance enterprises, such as Xero account software, are already leveraging Ethereum's ledger. Thus, from the data immutability perspective, this ARL factor is scored at ARL 9. Factors concerning privacy and regulations are covered in separate ARL factors.
Event-driven architecture	ARL 4: PoC	Event-driven architecture is when a technology application sends automated notifications to users. The proposed application sends these notifications to project participants when action is required from them. For example, when a payment is approved or sent, the relevant parties are notified of the activity. An ARL score of 4 was given for this factor because the author made assumptions about the content and format of these notifications. The application was designed to send e-mail notifications to end-users; however, e-mail may not be the correct medium for these notifications, and

		greater user customisations need to be considered before it can progress to ARL 5.
Overlooked PBA processes	ARL 2: CF	This factor concerns whether PBA processes were overlooked in the proposed application. If no PBA processes were overlooked (i.e., all PBA processes were covered in the application), it would receive a high ARL score. When the author was researching PBA processes, he did not come across any documentation that discussed its wording approval process, and he assumed that a PBA template was standardised across all projects. However, one focus group interview participant stated that a formal structure for the PBA wording approval process is a critical part of setting up PBAs. As a result, an update to the proposed application's framework or a revision of the application's scope is required in consideration of this; thus, this factor is scored at ARL 2.
Overlooked management processes	ARL 5: Pilot	This factor relates to general construction management processes rather than PBA-specific processes. The focus group participants advised that the application should notify the payment approver of the status of a construction project's interim valuation because PBA payments should not execute until the interim has been signed off. From the author's perspective, integrating the proposed application with interim valuation processes is beyond its scope. However, since interim valuations directly affect the execution of PBA payments, approaches for their integration should be considered and strategized. Other non-PBA management processes overlooked include integrating the proposed application with the construction project's estimate and budget costs to provide insight on how the various construction costs (i.e., estimated, budget, planned, and actual costs) compare as a project progresses. Nevertheless, since interim valuation and various construction cost procedures are beyond the application's scope, this factor can be scored at ARL 5 (enterprise pilot stage). The author assumed that additional overlooked management processes will become apparent at the enterprise pilot stage; therefore, the author made a conservative reservation to delimit its ARL score to 5.
Interoperability with existing software	ARL 2: CF	The focus group participants highlighted that the proposed application should pull data from the main contractor's (MC's) scheduling software, otherwise, data is being managed in two locations: (1) in the MC's scheduling software and (2) in the proposed application. This can be achieved with the design and development of APIs; however, an amendment to the proposed application's conceptual framework would be required, resulting in an ARL score of 2.
Interoperability with existing PBA systems	ARL 1: Research	The focus group participants disclosed that National Highways (a UK public sector client and the biggest user of PBAs) use a terminal management system (TMS) to monitor and issue PBA payments. Further investigation is required on whether this TMS has an API endpoint that enables third-

		party connectivity, which requires additional research and thus this factor is scored at ARL 1 until a review of this TMS is documented.
Technology uniqueness	ARL 1: Research	Technology uniqueness refers to the proposed application not duplicating an existing functional solution. The proposed application illustrated the capabilities of storing construction documentation in a decentralised cloud storage and enabling it to connect to the application. However, one focus group participant highlighted that "standard cloud is not designed to handle the commercial complexities of contract management" and that "cloud-based solutions for this already exist, such as CEMAR". Further investigation is required on the capabilities of CEMAR and whether it has an API endpoint that enables third-party applications to pull construction data from its system. Since additional research is required, this factor is scored ARL 1.
Cryptocurrency price stability	ARL 4: PoC	The exchange rate fluctuations of cryptocurrencies, such as Ether (the native currency of Ethereum), are mitigated by stablecoins. However, stablecoins have not yet been approved as legal tender, and thus, this factor is capped at ARL 4. More information on the topic of stablecoins is located in the *cryptocurrency regulations* ARL factor in this table. Despite stablecoins providing a solution against the exchange rate volatility of public blockchains, such as Ethereum, they have not been adopted yet in construction, and thus, a PoC is required to test the viability of using stablecoins as legal tender in the construction supply chain. Therefore, this factor remains at ARL 4.
Systems integration	ARL 5: Pilot	Overall, the proposed application's potential to integrate systems was received positively. One focus group participant highlighted how data trust is challenging to achieve with current enterprise systems and that blockchain's ability to store immutable records would improve data trust. Another interviewee pointed out how traditional, centralised companies, such as Xero accounting, have started bridging their services with blockchain to leverage its data trust capabilities. One focus group participant commented how the ability for subcontractors to pull their updated payment schedule information directly from the proposed application without having to request this data from the main contractor saves time in relaying schedule, order, and payment information back and forth between project participants. Despite these positive comments. This ARL factor was scored no higher than ARL 5 because project participants are required to send blockchain transactions via the proposed application to retrieve their payment schedule data. This process of retrieving data from the application should be costless and more automated for the project participants. Therefore, the application needs to improve its business logic before it can progress. The *server-side logic* ARL factor in this table

		discusses solutions for improving the application's business logic.
User accessibility	ARL 5: Pilot	User accessibility is loosely defined and can incorporate end-users (such as the client or contractor) or blockchain developers. In the context of this factor, it refers to blockchain developers and their access to open-source and open-licence codebases for building decentralised applications (dApps). DApps are open-source, and the blockchain itself is an open-source and open-licence technology, thus, developers benefit from an abundant and costless information-sharing environment. Even though blockchain dApps exist in the commercial enterprise landscape, this factor cannot progress to ARL 6 (commercial prototyping) until it has been first validated at ARL 5 (enterprise pilot).
Privacy	ARL 2: CF	Concerning how to achieve private transactions on a public blockchain, the questionnaire respondents proposed two options: (1) zero-knowledge proofs (ZKPs), which allow users to encrypt blockchain transactions, and (2) stealth addresses (SAs), which enable users to encrypt blockchain wallet addresses. However, these solutions were not incorporated in the proposed application, therefore, this factor is limited to ARL 2 because an amendment to the conceptual framework is required to accommodate ZKPs or SAs.
Cryptocurrency regulations	ARL 2: CF	If testing the proposed application with construction companies, a legal tender currency would be required for settling payments. The proposed application used cryptocurrency stablecoins as its currency. Stablecoins can be converted to legal tender, such as the British Pound, at blockchain exchanges; however, requesting UK construction companies to exchange stablecoins for British Pounds via a blockchain exchange is not a practical approach. One focus group respondent advised that a cryptocurrency stablecoin bill is with the UK Parliament for approval. Until this bill is approved, additional application infrastructure will be required to bridge the blockchain and traditional finance landscape. Therefore, from the cryptocurrency regulation perspective, this factor was awarded an ARL score of 1 because additional research is required on stablecoin conversion services.
Know-your-customer services	ARL 1: Research	The proposed application provided a solution for digitising the PBA trust deed but did not provide a solution for KYC verification. This is because the author was aware that decentralised KYC services for blockchain applications exist and was planning to leverage their services to provide KYC for the application. Nevertheless, additional research is required to investigate KYC services.
Systems design	ARL 2: CF	Regarding the proposed application's general systems design, the key feedback from the questionnaire respondents was as follows: one advised to consider redeploying the proposed application as a component of an existing decentralised

		ecosystem of services, and another mentioned that the application should be designed general-purpose and not restrict itself to PBAs. These suggestions are conceptual framework considerations and are, therefore, scored at ARL 2.
Crypto-economics & NFTs	ARL 2: CF	The c*rypto-economics & NFTs* ARL factor refers to token economics and the use of non-fungible tokens (NFTs) in the proposed application. Regarding token-economics, one questionnaire respondent advised that an algorithmic reward and penalty system is a key component of blockchain systems and that it should be inbuilt into the proposed application. Concerning NFTs, two questionnaire respondents discussed how the construction industry has many unique digital documents (e.g., invoices, contracts) and that using an NFT to digitally manage and exchange these with high traceability and trust could be a valuable addition to the application. Token-economics and NFTs are useful recommendations; however, appending them would require modifying the proposed application's conceptual framework. Therefore, this factor is scored at ARL 2.
Blockchain services	ARL 5: Pilot	Regarding blockchain services, the questionnaire respondents provided helpful suggestions, such as decentralised toolkits and community-reviewed smart contract templates, for providing technical assistance to the application's development team. These suggestions are documented in section *5.2.1.3: Blockchain Services* of this chapter. Nevertheless, these suggestions require no update to the application's framework, as they are predominantly resources for optimising and accelerating the application's development. The score of this ARL factor is delimited to 5 until all minor application customisations are finalised. No major alterations are required for this factor.
Scaling solutions	ARL 2: CF	High transaction fees used to be one of the primary barriers for adopting a public blockchain, such as Ethereum. However, public blockchains have advanced to include scaling solutions to mitigate this. Several questionnaire respondents advised using the Ethereum Polygon layer two scaling solution to reduce transaction fees significantly. For example, an Ethereum transaction fee of £20 would be reduced to £0.002 on Polygon (Besancon et al., 2022). Configuring the proposed application to include Polygon would require updating its conceptual framework; therefore, this factor is scored at ARL 2.
Blockchain selection	ARL 5: Pilot	Selecting the correct blockchain platform is crucial for ensuring the proposed application's success. *Table 7. Blockchain selection matrix* in *Chapter 4: Conceptual Framework* outlined the application's requirements for selecting the blockchain platform. This factor was scored at ARL 5 (pilot) because other factors, namely *privacy* and *scaling solutions,* require validation before this factor can

		progress to ARL 6 (commercial prototyping). If privacy and transaction scaling cannot be achieved, this would revert this factor to ARL 1 (research) or ARL 2 (conceptual framework) because a new blockchain would need to be selected.
User interface	ARL 4: PoC	The proposed application's user interface (UI) is a standard Web application built using standard Web development tools: Javascript and React. These tools are also the most compatible with blockchain wallets, which the author was aware of while designing the application's conceptual framework. The author developed the application's UI by using a React template for decentralised applications. However, preparing the UI for ARL 5 (i.e., pilot testing) would require hiring the services of a Web developer to update the application's UI and back-end to display and operate more similarly to a fully working application. For example, standard UI features such as user logins, page layouts, and application logic require formalising, which is beyond the technical expertise of the author.
Oracles and APIs	ARL 2: CF	In the context of blockchain, an oracle is an API that pulls or pushes data directly to the blockchain instead of a Web server. The focus group participants advised that integrating with CEMAR software is crucial for integrating management flows with payments. Currently, the application can only integrate with spreadsheet software, such as Microsoft Excel. However, extending its functionality to include construction software, such as CEMAR, would require the development of additional APIs. This factor is therefore scored at ARL 2 because an amendment to the application's framework would be required to accommodate the additional API functionalities for integrating with CEMAR.
Server-side logic	ARL 2: CF	The questionnaire respondents recommended several application logic improvements for the proposed application, such as fail-safe functionalities (i.e., notifying users if their transactions will fail before they send it), and batch processing (i.e., the ability to combine multiple blockchain transactions into one single transaction). These additions require alterations to the proposed application's business logic and an amendment to its conceptual framework. Therefore, this factor is scored at ARL 2.
Cybersecurity	ARL 4: Prototype	Implementing cybersecurity is beyond the scope of this research to investigate, and it is a specialised skill suited for cybersecurity engineers. This factor is scored at ARL 4 (PoC) because more sophisticated cybersecurity is required before it can be piloted with construction companies at ARL 5. This is to maintain good ethical practice when putting private enterprise data at risk. Nevertheless, regarding cybersecurity precautions, two questionnaire respondents advised reducing reliance on third-party blockchain services, such as running an instance of the blockchain node internally rather than relying on Infura. Furthermore, regarding user logins for the

		application, one respondent advised using biometric authentication, while another suggested two-factor authentication.
Wallet security	ARL 1: Research	In conjunction with the questionnaire respondents, the actions concerning wallet security include selecting a blockchain wallet service that provides better enterprise security guarantees (see section 5.2.3.2: Wallet Security for details), adopting a multi-signature wallet for the PBA wallet, and ensuring all wallets in the application are generated using the most updated wallet algorithm (which is currently the Edward Curve 25519). This factor was scored at ARL 1 because additional research is required on which enterprise blockchain wallet provider would be most suitable for the application.

The total ARL score of the proposed application was calculated as follows: All the ARL scores of the 23 ARL factors in Table 15 were tallied and divided by 23, equating to an average ARL score of 3.09. This average ARL score is the application's total ARL score.

Of the 23 ARL factors shown in Table 15, 5 count (22%) received an ARL score of 1, 8 count (35%) received an ARL score of 2, 4 count (17%) received an ARL score of 4, 5 count (22%) received an ARL score of 5, and 1 count (4%) received an ARL score of 9. Based on this, 57% of the ARL factors have an ARL score equal to or less than 2, 39% of the ARL factors have an ARL score of 4 (PoC) or 5 (enterprise pilot), and 4% have an ARL score equal to or greater than 6. When an ARL factor is scored with a particular ARL score, it means that the ARL factor has achieved that level of maturity. For example, the s*ystems integration* factor received an ARL score of 5; therefore, it is in a state that can be prepared for commercial testing at ARL 6. However, before it can progress to ARL 6, it needs to be validated by an enterprise pilot at ARL 5, which means inviting construction companies to partake in an industry pilot and collecting primary data to validate the solution. The terminology PoC and pilot are used interchangeably in research; however, from the perspective of this research, a pilot relates to developing a full working application and deploying it for a sample of construction companies to test with real (not simulated) enterprise data flowing through the application.

Even though the proposed application was tested at ARL 4 (PoC), it does not mean its total ARL score is 4. In fact, the total ARL score of the application equates to 3.09. This is because several ARL factors, such as *interoperability with existing PBA* *systems, technology uniqueness, cryptocurrency regulations, know-your-customer services, and wallet security,* as shown in Table 16, encountered application issues identified in the data collection, resulting in these ARL factors receiving an ARL score of 1. Furthermore, many of the technical ARL factors, such as privacy, scaling solutions, oracles and APIs, server-side logic, etc., (as shown in Table 16) received an ARL score of 2 and require further development to improve the application's maturity.

Table 16.
ARL factors in ascending order of ARL score

ARL score	**ARL factor**
1 (5 count, 22%)	Interoperability with existing PBA systems
	Technology uniqueness
	Cryptocurrency regulations
	Know-your-customer services
	Wallet security
2 (8 count, 35%)	Overlooked PBA processes
	Interoperability with existing software
	Privacy
	Systems design
	Crypto-economics & NFTs
	Scaling solutions
	Oracles and APIs
	Server-side logic
4 (4 count, 17%)	Event-driven architecture
	Cryptocurrency price stability
	User interface
	Cybersecurity
5 (5 count, 22%)	Overlooked management processes
	Systems integration
	User accessibility
	Blockchain services
	Blockchain selection
9 (1 count, 4%)	Data traceability and permanence

6 Discussion

Blockchain has three dimensions that affect its implementation in the construction industry: (1) Socio-technical, (2) process, and (3) policy (Li et al., 2019). This research overlaps with all three dimensions because it investigates how construction managers can engage with blockchain to improve project performance (i.e., the socio-technical dimension); furthermore, the research also integrates management flows with cash flows to reduce process redundancies and improve automation (i.e., the process dimension), and it incorporates the UK Government's PBA strategy in its framework design (i.e., the policy dimension). The management flows mentioned above include scheduling and work approval stages, while cash flows include the movement of money from payers (e.g., the client) to payees (e.g., the subcontractors). The blockchain provides a shared, general-purpose protocol layer that enables management flows and cash flow to interoperate with minimal technology infrastructure (Tezel et al., 2020).

The proposed application responds to the challenges centralised software faces with data interoperability. The focus group interview provided insight into the application's organisational feasibility, whereas the questionnaire provided feedback on the application's technical feasibility. PBA was targeted for this study because it is a system enforced by the UK Government, and contractors are mandated to implement it in public sector work; thus, it has a solid practical foundation. However, PBA shares a common problem with construction: systems and data fragmentation. From the literature review, only one academic publication by (Chong & Diamantopoulos, 2020) provides evidence of a blockchain application used in a real-life construction project; however, that application was closed-source, its technology components were not itemised, and there was no evidence that the solution was commercialised; thus, it cannot be externally verified and lacks credibility.

Existing literature suggests that PBAs suffer from improper adoption due to the additional workload it imposes on main contractors; furthermore, PBAs are hampered by the same challenges that plague the construction industry: (1) System fragmentation that causes unnecessary data duplication and (2) lack of process flow automation. The research aim is to thoroughly investigate, through a proof of concept (PoC), whether the cited benefits of blockchain and smart contracts, such as disintermediation, programmability, and automation, can contribute to mitigating the abovementioned problems (i.e., systems fragmentation and lack of automation) concerning the management and operations of PBAs. The research questions (RQs) were used as the foundation for achieving the research aim. A reiteration of the RQs mentioned in the Chapter One (Introduction) are as follows:

1. How can a blockchain application improve the delivery of PBAs through systems integration and process flow automation, and how would end-users interact with the system?
2. From the perspective of construction practitioners experienced in PBAs, what are the potential advantages and disadvantages of using blockchain and smart contracts for managing PBAs?
3. By collecting data from blockchain engineers experienced in developing decentralised applications, what are the technical concerns for using the proposed application in the commercial environment?

This chapter is organised into four primary sections: (1) Discussing the Framework, (2) Discussing the Findings, (3) Improvement Proposals, and (4) Key Findings. Section one, Discussing the Framework, assesses the proposed application’s conceptual framework and how it was influenced by ideas examined in the Related Works section of Chapter Two (Literature Review). Section two, provides an evaluation of Chapter Five (Data and Analysis) and Chapter Six (Discussion). It is also the most voluminous of all the sections in this chapter because it thoroughly assesses and discusses the research findings across several subsections. Section three, Improvement Proposals, aggregates all the suggestions from the findings for improving the proposed application’s functionality from the enterprise and technical perspective. Lastly, section four, Key Findings, highlights the most impactful research findings and organises them into the benefits and challenges of using blockchain for PBAs in the commercial climate. RQ 1 is answered in the Discussing the Framework section by proposing a PBA blockchain application that leverages and builds upon ideas from existing literature. RQ 2 and RQ 3 are answered in section two (Discussing the Findings) and section three (Improvement Proposals) by presenting the focus group interview and questionnaire findings.

This researcher uncovered thirteen test applications proposed by other researchers that overlap with the topical area of blockchain for payments, as shown in the Related Works section of Chapter Two (Literature Review), which includes the following publications: (Ahmadisheykhsarmast & Sonmez, 2020; Chong & Diamantopoulos, 2020; Das et al., 2020; Elghaish et al., 2020; Elghaish et al., 2022; Hamledari & Fischer, 2021b, 2021c; Ibrahim et al., 2022; Perera et al., 2021; Sigalov et al., 2021; Sonmez et al., 2022; Tezel et al., 2021; Yang et al., 2020). However, the blockchain applications shown in those publications lacked extensibility from the perspective of being able to use sections of their codebase to build a new blockchain application. Furthermore, they did not provided access to their user interface despite them all using a Web application for it. Web applications are websites that allow users to interact with them (e.g., Facebook is a Web application). Due to the ubiquitous nature of Web applications in the current environment, they require little to no infrastructure to set up. For example, the research's proposed application is hosted online at no cost due to the availability of free infrastructure/Web services; thus, its user interface is openly available online for external users to browse and test. Of the 13 above-mentioned related works of blockchain payment applications for construction, five displayed screenshots of their open-source code (Elghaish et al., 2020; Elghaish et al., 2022; Sigalov et al., 2021; Sonmez et al., 2022; Yang et al., 2020). To maximise replicability, the proposed application also displayed its open-source codebase on GitHub (a code hosting site). The reason for not showcasing its entire codebase in the appendix is that it contains over 8000 lines of code, which equates to over 200 pages if displayed in a Word document.

Using blockchain to integrate management flows with cash flows was inspired by Hamledari Hamledari and Fischer (2021c), who linked standard documents with the blockchain through a Web application user interface. In their proposal, they presented payment schedule data in a smart contract table, and project participants would interact with it to insert, approve, and execute payments (Hamledari & Fischer, 2021c). This feature was replicated in the proposed application. The researcher initially wanted to integrate with existing software, starting with Microsoft Excel, and uncovered that Excel has add-in capabilities that enable users to pull/push data to/from Web applications without needing to install/download additional tools (Hiron-Grimes, 2017). One strategy for pushing spreadsheet data to the blockchain was demonstrated by

Ahmadisheykhsarmast and Sonmez (2020), who built a plugin that enabled data to be exported from Microsoft Projects to a text file; afterwards, the text file was manually imported into smart contracts through a user interface. However, the problem with that approach is the risk of file manipulation, such as a hacker altering its data. To mitigate this, the file could be encrypted with the public key of its recipient, enabling only the recipient to decrypt the data with their private key; however, that process requires numerous intermediary stages that detract from the purpose of using blockchain to automate data flows. One of the challenges when using a public blockchain is achieving private transactions. A private blockchain was not used for the proposed application because it does not accommodate stablecoins. A stablecoin is a crypto token that can be converted to fiat (GBP or USD etc.) at online exchanges; thus, tokens on public blockchains have value outside their network and can be used for payments. In contrast, cryptocurrencies on private blockchains have no monetary value outside their network and thus cannot be used for payments. A public blockchain was used for the proposed application because payments are its primary purpose. Furthermore, the researcher came across a paper by (Das et al., 2020) that established how to achieve privacy on public blockchains using a key-sharing algorithm, whereby multiple parties merge their public keys to produce a new shared wallet (Das et al., 2020). In that example, data would be stored encrypted on the blockchain, and only authorised users with access to the shared wallet would have access to decrypt the data (Das et al., 2020).

The researcher only knows one other publication by Tezel et al. (2021) that developed a PBA blockchain application. Some of the ideas of his application were used for developing this dissertation’s proposed application. The proposed application extends the work of Tezel by using smart contracts (SCs) to manage the access controls of project participants. Access control is crucial because it allows multiple users to interact with the proposed application’s SCs to perform specific tasks while delimiting their access rights to specific functions. For example, the subcontractor would interact with the cash-out SC to notify the project that their work is ready for approval; afterwards, the project manager and contractor would approve the work through the same SC, and then the payment would autonomously execute when all approvals are received. Access controls also operate like a safety mechanism by ensuring that SC payments can only execute to the wallet addresses of the PBA trustees, which is crucial because if funds are mistakenly sent to anonymous wallets (because of a data entry error or hacks), they will not be retrievable due to the pseudo-anonymous nature blockchain wallets. Therefore, the proposed application embeds access controls into SCs as a crucial aspect of its design. Furthermore, the proposed application extended the work of (Tezel et al., 2021) by designing it to accommodate multi-user functionalities that enable multi-stage payment approvals that more closely replicate existing construction workflows.

6.1 Key Findings

The key benefits of the research are: (1) The proposed application reduces the management workload of main contractors due to automating workflows using smart contracts, (2) blockchain and smart contracts include the potential to democratise PBAs, (3) a blockchain-based PBA can be set-up within a day (vs weeks with banks) and stores transactions permanently (vs a one year cap with banks), and finally, (4) blockchain provides a trusted data later for project reports and analytics dashboards. These four points are elaborated below.

1. Cash flows to and from PBAs are controlled by two forms: (1) Payment applications and (2) authorisation statements. The former is used for cash-ins, while the latter is used for cash-outs. The proposed application automates the main contractor's (MC's) responsibility for managing these forms. Figure 37 from Chapter Six (Discussion) illustrates this in greater detail.

2. Blockchain and smart contracts could democratise PBAs by making them more accessible to a wider percentage of the construction supply chain. PBAs in the UK are only used for payments down to tier-two subcontractors, not tier-three or below. This is due to several reasons:

    - The UK Government PBA strategy mandates the client, project manager (PM), and MC to authorise all cash-outs from the PBA. However, the contracts between tier-one and tier-two subcontractors are entirely different from the contracts between tier-two and tier-three subcontractors; therefore, the MC cannot directly approve the works of tier-three subcontractors, and thus, the MC cannot send a PBA authorisation statement to the client and PM to approve payments to tier-three subcontractors. An amendment to the

PBA strategy is required to allow lower-tier subcontractors to submit authorisation statements directly to the client and PM without the authorisation statement going through the MC. However, this amendment would substantially increase the workload of the client and PM because they would be tasked with approving all cash-outs to the lower-tier subcontractors. For example, extending PBAs to include payments down to tier-three subcontractors could increase the transaction processing workload of all parties by up to tenfold. For example, suppose a main contractor has ten tier-two subcontractors, and each tier-two subcontractor has ten tier-three subcontractors. In that case, 100 *PBA authorisation statement* approval signatures (instead of 10) would be required to enable payments between the tier the one contractor and tier three subcontractors. Unfortunately, the construction supply chain can include many tiers (e.g., tier three, four, and five subcontractors). Therefore, amendments to the UK government's PBA strategy and greater payment automation are required to democratise PBAs across all supply chain tiers.

- Lastly, since beneficiaries of the PBA must be signatories to the PBA trust deed, including lower-tier subcontractors would substantially increase the trust deed’s signatory count from tens to hundreds, causing data processing delays when collecting and managing PBA trust deed signatures.

3. The findings highlighted several limitations with hosting PBAs with banks, such as (1) banks only store PBA transaction records for one year, and (2) banks take several weeks to set up and deploy the PBA. In contrast, all transactions on the blockchain are stored permanently with no time limitations, and the proposed application’s PBA smart contract can be deployed within a working day.

4. The findings suggest that the automated logging and timestamping of payment approvals, certificate awarding, and liability executions on the blockchain could increase the traceability of cash flow data in project performance reports. Furthermore, blockchain ledgers provide a suitable and trusted data layer for interoperating with analytics dashboards, for example, using APIs (application

programming interfaces) that pull project data from the blockchain and presenting the data on a Web application.

6.1.1 Key Challenges

The key challenges of the proposed application include: (1) The proposed application needs to interoperate more effectively with existing construction software, (2) blockchain solutions are costly to develop in the current commercial climate, (3) there is a lack of off-ramping infrastructure for withdrawing cryptocurrency assets to commercial banks, and finally, (4) decentralised technologies suffer from a lack of legal accountability. These points are elaborated below.

1. The findings revealed that the proposed application needs to interoperate more effectively with existing software, such as enterprise resource planning (ERP), contract event management and reporting (CEMAR), and spreadsheets (e.g., Microsoft Excel) to improve its extensibility with current management tools. Furthermore, the proposed application should avoid duplicating the functionalities of existing software so as not to unnecessarily waste resources building new systems.

2. The findings suggest that despite the blockchain providing cost-free technology infrastructure by being open-source and open-licence, it suffers from a lack of formal adoption frameworks and skill shortages in blockchain engineers, making the technology expensive to utilise in the commercial climate. However, the research also suggests that this cost will gradually reduce and normalise as more blockchain developers enter the market.

3. Another crucial finding is that banks can block cash deposits from cryptocurrency service providers if they deem them high-risk. This is problematic because the construction supply chain relies on banks for essential financial products and services. The risk of subcontractors not having access to funds due to blockchain being high risk is a significant deterrent for construction companies. However, the approval of the stablecoin bill that is currently under review by the UK Parliament would mitigate this problem.

4. Enterprises are centralised entities that rely on centralised accountability when doing business. Because blockchain is decentralised, it cannot be held legally accountable or responsible for potential damages caused by hacks or system

malfunctions. Nevertheless, some decentralised applications have addressed this problem and offer insurance against funds lost or stolen from their service

6.2 Discussing the Framework

This section relates to research question one: “How can a blockchain application improve the delivery of PBAs through systems integration and process flow automation, and how would end-users interact with the system?” Section 2.6 Related Works of Chapter 2: Literature Review identified 13 academic publications that most closely align with the ambitions of using blockchain to automate cash flow in construction. Of those 13 publications, two gaps in the literature were identified: (1) there was a lack of literature that discussed how the immutable code of blockchain smart contracts (SCs) can adapt to construction change orders (a change order is when a signed construction contract requires revising); And (2) there was a lack of evidence in the literature that demonstrated how payment schedules, approvals, and executions can be integrated into one system to achieve increased payment automation.

Regarding how blockchain smart contracts (SCs) can adapt to construction change orders, the ability of digital construction contracts to adapt to change orders is crucial because project variations and change orders are commonplace in construction projects. When designing SCs to operate like digital construction contracts, the system must be able to account for potential human errors in writing SC code, and adapt to change orders. One of the principal features of blockchain is its immutable code. SC code is stored on the blockchain and is thus immutable. The problem is that redeploying a SC is not a straightforward task because before it can be deployed, it must be audited by a SC auditor to ensure its code is secure from cyberattacks (Hedera Hashgraph, 2025). The cost of a SC audit typically ranges from £4,000 to £12,000 but it can cost more depending on the SC's complexity (Hedera Hashgraph, 2025). This is a high price to pay for change orders. The challenge here is how a SC’s code can adapt to a construction contract’s change orders without altering the SC’s immutable code. What is needed is a redesign of the SC’s architecture. Figure 35. *Relational conditions in smart contracts* and its surrounding text explains how SCs can be designed to accommodate change orders while abiding by the blockchain’s immutable code. However, just because the code of a SC can be manipulated, it does not mean their hard-coded conditions can be altered. The hard-coded conditions of SCs are immutable because they are stored on the blockchain, but a variable called a pointed function can be embedded into a SC that allows it to point to the conditions of another SC and integrate those conditions as part of its own. This is illustrated in Figure 35. *Relational conditions in smart contracts* and Figure 36. *Relational data in smart contracts*. SC pointer functions are variables within a SC, this variable is hard-coded and immutable; however, these variables store values which can be updated. For example, in the statement ‘X = 1’, ‘X’ is the variable and ‘1’ is the value. In an append-only system such as blockchain, a SC’s value can be updated while preserving historic values. In the case of a SC pointer function, the value it stored is the SC address of another SC, and that value can be updated. This allows the conditions of one SC to affect the conditions of another SC. A SC can update its conditions by updating its pointer function to point to another SC. Thereby, allowing SCs to accommodate change orders.

Since this research established that the codified conditions of a smart contract (SC) can be manipulated without altering its underlying code, this created the opportunity to append more complex functionality in SCs to leverage their process integration capabilities. Chapter 2: Literature Review, Section 2.6: Related Works reviewed 13 publications whose research closely aligns with the topic of this thesis (i.e., blockchain for payment automation in construction). Of those reviewed literature, none was able to integrate construction payment schedules, approvals, and executions into one system. However, the aim of this thesis (i.e., process integration for PBAs) is different from the aim of the 13 reviewed literature, therefore, the author is not discrediting their work. The author integrated payment schedules, approvals, and executions by configuring SCs to accommodate two diverse functionalities: a relational database, and a digital contract. Since this research uncovered that SCs can be persistent in the context that they do not need redeployment when change orders occur, it allows SCs to store other persistent project data, such as payment schedules or any project data stored in tabular format like spreadsheets. On the contrary, if a SC stored schedule data and it needed redeploying because of a changer order, then all the schedule data would need rewriting into the redeployed SC. However, since this research proved that a SC can adapt to change orders without requiring redeployment, it can be used to store payment schedules while also having the ability to be used as a payment approval tool and payment execution system. Thereby, the solution for the gap in the literature, namely the lack of proof for the ability to integrate payment schedules, approvals, and executions in one system, was provided in this research.

Analysing how blockchain can improve existing PBA workflows was tested by developing a PBA blockchain application and presenting the works to construction practitioners and questionees for thorough qualitative analysis. No evidence exists of commercial adoption of blockchain in the construction industry; thus, the research area is still in its exploratory stage with no complete model for how a construction company can adopt blockchain for commercial use. Therefore, the author sought to develop the proposed application as a test model. The proposed application exemplifies how blockchain, smart contracts, and a Web application can integrate project scheduling, supply chain management, and payment executions in one system to improve process automation. PBA was selected as the test case because it aims to achieve greater cash flow transparency and auditability, which are inherent properties of the blockchain; thus, they are harmonious to integrate. Furthermore, PBA uses a ring-fenced bank account to safeguard project funds, which smart contracts can achieve without needing the services of a bank. This study demonstrates how payment activities can be hard-coded into smart contracts to reduce process redundancies. Additionally, no construction research provides a live user interface for external users to test a blockchain application; thus, this is provided in the proof of concept (PoC).

The smart contracts in the proposed application are used like spreadsheet software rather than mimicking digital contract documents. This is because, despite terminology ambiguity, smart contracts are not smart and are not contracts; instead, they are miniature pieces of software. Because of this, changes in the wording of contract agreements do not affect the functionality of the proposed application’s smart contracts. Any contract documentation in the application is stored in IPFS in standard PDF format. IPFS is a decentralised cloud storage provider typically used alongside blockchain applications. Entire payment clauses are unnecessary to program into smart contracts; only crucial process flows, such as approval stages and payment executions, are necessary to program. This mitigates the complications of converting contract wording into coding syntax. The problem with the terminology *smart contract* is that they are not contracts. The terminology derived from computer scientist, and their understanding of a contract is different compared to the construction industry.

Smart contracts are miniature pieces of software with ‘if and then’ statements programmed into them, such as ‘if X happens then execute Y’. In the case of the proposed application, its smart contracts carry the business logic to automate payments, but they are not used in replacement of a construction contract document. The traditional construction contract document would continue to exist while the proposed application automates process flows.

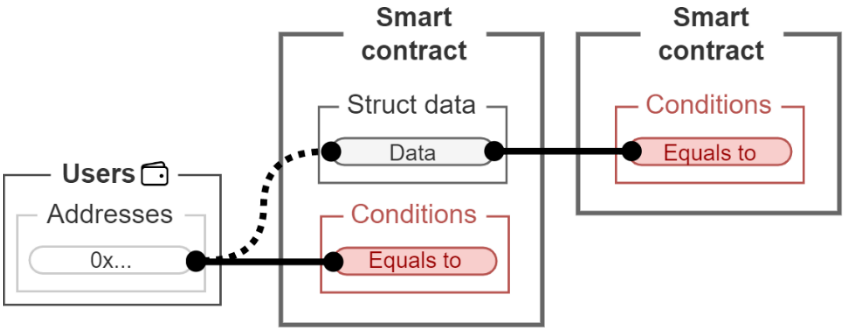
A benefit of using the proposed applications is that when dispute resolutions arise, each data flow, such as updates, approvals, and payment executions, is stored on the blockchain with full traceability. For example, suppose a dispute between two transacting parties arises; in that case, the blockchain can provide quantitative and irrefutable proof of occurred events.

Decentralised applications use blockchain to achieve technology decentralisation; however, smart contracts can be configured for centralised management. For example, approving payments is a centralised activity performed by tier-one project participants. Therefore, the proposed application leverages the data immutability of blockchain/decentralisation while programming smart contracts to suit centralised construction workflows.

An area deficient in academic literature is the cost implications of developing a blockchain application. Therefore, this was carefully considered in the proposed application’s framework design. Whenever a smart contract requires redeploying because of change orders or project variations, it incurs costs such as auditing and transaction fees. Auditing a smart contract is complex because it involves stress testing code for security flaws, which blockchain developers can only conduct with extensive experience; however, even junior blockchain coders are in short supply, contributing to resource scarcity that can potentially transpire to increased project delays and cost. Auditing a small to medium-sized smart contract on the Ethereum blockchain can range from £4,000 to £25,000, whereas a large one can reach over £400,000 each (Hacken, 2022). The proposed application’s smart contracts would fall into the small category due to its simplicity, substantially reducing deployment and auditing fees. For example, Table 8 in Chapter Four (Conceptual Framework) shows that the proposed application’s smart contract deployment costs ranged from £4.50 to £10 each on the Ethereum blockchain. An example of a complex smart contract is one deployed by (Sonmez et al., 2022), which pushes building information modelling object data into smart contracts and costs £400 to £1,600 each in Ethereum transaction fees.

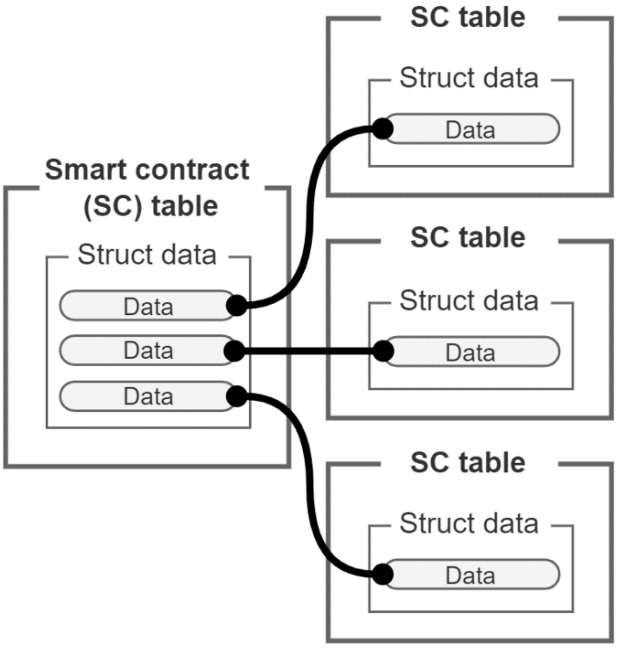
Conditions are the hard-coded syntax of a smart contract that controls who and how users interact with it. Typically, these conditions cannot be altered once a smart contract is deployed; however, the proposed application bypassed this problem by using a pointer function stored in the conditions of a smart contract that points to the data field of another smart contract (as shown in Figure 35). The pointer function is hard-coded in a smart contract; therefore, a hacker cannot compromise it. For example, Figure 35 demonstrates how one smart contract's variable is used as the condition of another smart contract. Therefore, the smart contract’s variable can be updated while its logic remains immutable.

Figure 35.
Relational conditions in smart contracts



Two types of databases exist: relational and non-relational. Relational databases have existed for over 50 years and are the standard format for storing structured data in tables (Batra, 2018). Since blockchain is a decentralised ledger database, it carries the same inherent properties as a relational database. The main difference is that the blockchain is decentralised. Since the blockchain is one extensive global database, its functions are not customisable. However, smart contracts can be deployed and converted into miniature relational databases customisable with centralised or decentralised functions. Using a smart contract as a centralised database may sound counterintuitive since blockchain is a decentralised ledger. However, leveraging the data immutability of blockchain reduces the cybersecurity cost of data persistency, while converting smart contracts into relational databases is useful because it enables data from numerous smart contracts to map together and synchronise (as per Figure 36). Furthermore, when data in one smart contract is updated, it autonomously updates the state of the other smart contracts in the network, reducing manual data entry and reconciliation.

Figure 36.
Relational data in smart contracts.



Despite blockchains' association with decentralisation, a company can deploy a centralised private blockchain and manage all of its nodes internally; however, this jeopardises the most critical feature of blockchain: data immutability. An alternative is using a private permissioned blockchain; however, the Table 7 blockchain selection scoring matrix if Chapter Four (Conceptual Framework) identified that the Hyperledger Fabric private blockchain did not score as high as the Ethereum public blockchain. This was predominantly down to Hyperledger Fabric not having stablecoin capabilities. A qualitative study with a sample of participants who work for investment banks revealed that some banks use a centralised internal blockchain to reduce costs associated with ledger reconciliations across multiple internal bank branches (Vedapradha & Ravi, 2021). However, a centralised blockchain is highly limiting because it cannot integrate with the vast ecosystem of decentralised services; furthermore, it requires an internal team to manage the system, whereas public blockchains are maintained by its decentralised blockchain miners or blockchain stakers, core developers, and decentralised application contributors (Chain Stack, 2020).

Integrating the blockchain with centralised systems is challenging because blockchain is infrastructurally immature in comparison; therefore, additional services are required to bridge the centralised and decentralised landscapes. In comparison, centralised technologies have spent decades maturing. Nevertheless, developing construction applications built on Ethereum's protocol layer could hypothetically reduce the number of APIs (application programming interfaces) required to integrate software. For example, the proposed application integrates payment approvals with payment executions. In contrast, integrating approvals with payments on a centralised system would require building APIs between management and banking software/applications, which is costly, technical, and reliant on the bank's cooperation. For example, the bank will likely not want a third-party application company sending API calls to their banking system. All Ethereum decentralised applications have the inbuilt capability to interoperate because they share the same protocol infrastructure. Since Ethereum's blockchain protocol operates on a general-purpose data layer, it could be used as a medium for receiving data inflows from various software, which hypothetically reduces the complexity of building APIs because all data is transferred to a single system that is not under the authority of a centralised entity. Thus, software licence restrictions and proprietary fees are mitigated because public blockchains are permissionless (i.e., they're open for anyone to use). In the early stages of blockchain, decentralised applications deployed on one blockchain were restricted to that platform only; however, as the technology advanced, cross-chain interoperability became possible (Lu et al., 2021). The main fees associated with blockchain are transaction fees; however, scaling solutions make these negligible (e.g., £0.002 per transaction) (Kravenkit & So-In, 2022). More on scaling solutions will be discussed later in this chapter.

The idea of incorporating retentions into the proposed application was inspired by a paper by Elghaish et al. (2022), who used smart contracts (SCs) to manage retentions and defects liability periods (DLPs). In that example, the project's closeout stage was autonomously controlled by a retention SC that calculates the sum due to each subcontractor; furthermore, any unpaid invoices would result in the end date of the closeout being autonomously deferred (Elghaish et al., 2022). DLPs provide the client with a timescale (typically six to twelve months) for identifying and rectifying building defects, which grants them the authority to recall the contractor back to the project to rectify any construction problems. After the DLP period expires, contract administrators are scheduled to revisit project documentation to verify the value of retentions owed to subcontractors. According to one interviewee, “When a retention payment from the contractor to a subcontractor is due, the contractor’s finance team undergoes a verification process to check whether the contract manager has authorised its release and whether the liability matches the contract’s order value.” Furthermore, they added that some of the key processes include, “verifying the recipient’s payment details”, “reconciling invoices and credit notes”, and “packaging the information for the payable team to process”. The proposed application attempted to automate these processes by connecting the cash in/out SCs to a retention SC to mitigate (1) having to verify recipient details, (2) reconciling payment data, and (3) having to send the data to the payable team to process. The proposed application achieved point one because when subcontractors are inserted into the cash-out SC, it automatically copies their details to a retention SC; thus, subcontractor details do not require re-verification. Furthermore, the retention value is calculated according to a contractually agreed percentage, which is autonomously calculated by the retention SC since it is connected to the cash-out SC, thus achieving point two. Point three was achieved because when the contractor manager authorises the retention’s release via the retention SC, payments automatically execute to the subcontractor without the payable team having to process the payment manually.

6.3 Discussing the Findings

This section relates to research questions two and three: “By collecting data from construction practitioners experienced in PBAs, what are the potential advantages and disadvantages of using blockchain and smart contracts for managing PBAs?” and “By collecting data from blockchain engineers experienced in developing decentralised applications, what are the technical challenges for developing the proposed application further?” The data collection from the focus group interview participants was used to answer question two, while the data collection from the questionnaire participants was used to answer question three. However, despite the focus group interview being focused on the narrative of construction companies and the questionnaire being focused on the narrative of blockchain engineers, both spectrums share strong overlapping themes and are thus amalgamated in this discussion as one narrative: the organisational and technical benefits and barriers of using blockchain for PBAs in construction. This is the primary section of this chapter because it discusses the results of Chapter Five: Data and Analysis, and is structured into nine subsections: (1) Supply Chain Coverage of PBAs, (2) Process Flow Automation, (3) Systems Integration, (4) Interoperability Issues, (5) Cost, (6) Stablecoins, (7) Private Transactions, (8) Wallet Security, (9) Banks, and (10) Managing Identities.

The primary benefits of PBAs are transaction traceability, prompt payments for tier-two subcontractors, cost savings for the client, and insurance against main contractor insolvency. For example, one interviewee mentioned, “At any time, the client can view how much money is in the account and how much is being moved around to each subcontractor”. Another interviewee stated, “The client can directly see any unspent funds, allowing them to make savings on what would normally go to the contractor as extra profit.” Furthermore, one interviewee commented that “Payments from tier one to tier two are processed within three days”, and that “tier two subcontractors are protected if the contractor becomes insolvent”.

Blockchain and PBAs share overlapping values because both systems aim to achieve greater transparency and auditability (Scott et al., 2022b, p. 149). The primary difference between the existing vs proposed PBA system is that the latter disintermediates from having to use the services of a bank, has the potential for automating cash flow via smart contracts, and has better systems integration potential with other applications due to it being built on a general-purpose technology layer. However, a blockchain-based PBA has many benefits and limitations, which are covered throughout this chapter and summarised in Table 17.

Table 17.
Benefits and limitations of this section’s themes.

Theme	Topic	Benefits or limitations	Description
Process flow automation	Automating standard PBA forms	Benefits	Two standard PBA forms were automated: the Payment Application and the Authorisation Statement.
		Limitation	Even though these forms are automated, they need to be downloadable for formality purposes
	Automated transaction execution	Benefit	Banks are no longer required to process PBA payments.
		Limitation	Although payments are automated, formal pay documents, such as invoices, are still required.

Systems Integration	Open-source	Benefit	All dApps (decentralised applications) are open-source, which makes integration with them easier.
		Benefit	DApps do not have copyright restrictions.
	Resource	Benefit	Blockchain has a wide selection of dApps and free tools to integrate with.
		Limitation	Skills shortage of dApp developers in the blockchain ecosystem.
Interoperability issues	Web 3	Benefit	Web 3 is not required for blockchain dApps.
	Legal accountability	Limitation	Legal accountability is challenging with decentralised technologies.
	Document management	Limitation	The application needs to integrate with CEMAR, a contract management and reporting software.
Cost	Cost	Benefit	The blockchain ecosystem is abundant with free technology infrastructure, smart contract templates, tools, and information.
		Limitation	DApps provide no customer support.
	Transaction fees	Benefit	Polygon can reduce Ethereum's transaction fees to £0.002, making transaction fees negligible.
	Funding	Limitation	Enterprises must be aware that blockchain is a technology that requires long-term funding.
Stablecoins	Stability	Benefit	Stablecoins mitigate the price fluctuations of cryptocurrencies.
		Limit	Stablecoins have not yet been approved as legal tender; therefore, withdrawal services for stablecoins are required.
Wallet security	Wallet security	Benefit	Multi-signature options are available for wallet security.
		Limitations	The Metamask wallet is not secure enough for enterprises.
Banks	Set up time of PBAs	Benefit	PBAs can be set up in a day with blockchain vs. weeks with banks.
		Benefit	A blockchain PBA mitigates using the bank for the PBA trust deed.
	Withdrawal issues	Limitation	Banks can block or freeze deposits from cryptocurrency service companies.
		Limitation	A good relationship between the bank and cryptocurrency service providers is crucial for withdrawing cash from the blockchain.
	Regulation	Limitation	Anti-money laundering (AML) regulation is tough on blockchain.
Managing identities	Know-your-customer (KYC)	Benefit	Third-party KYC services are available for dApps.
		Limitations	The application did not provide any KYC services.

Another interviewee mentioned that one of the stark differences of using a PBA vs. a non-PBA payment process is that the "Head contractor must get approval from the client before they can spend anything, unlike in traditional projects where the contractor has full control.” This states that according to standard PBA procedures, the client oversees all cash-outs from the PBA, which places greater surveillance on the contractor. In a non-PBA project, the contractor is responsible for all cash-outs to subcontractors, which the client has no traceability over. In contrast, in PBAs, the client and PM are mandated to approve all cash-outs to the supply chain, giving the client’s team full traceability over project payments to subcontractors.

6.3.1 Supply Chain Coverage of PBAs

A critical point highlighted by one interviewee is that “PBAs are only used for payments down to tier-two subcontractors because they are too complicated to set up and manage and the contracts between tier two and tier three are completely different” and that “not all banks offer PBA services.” Furthermore, the interviewee added that they “have managed over 40 PBAs, and none of them were used to make payments down to tier-three subcontractors”. Since most of the supply chain exists below tier two (i.e., tier three, four, and so on) a solution is needed that provides greater accessibility of PBAs to the lower-tier subcontractors. This is crucial because the lower-tier subcontractors are at greater risk of financial adversity due to their lower working capital.

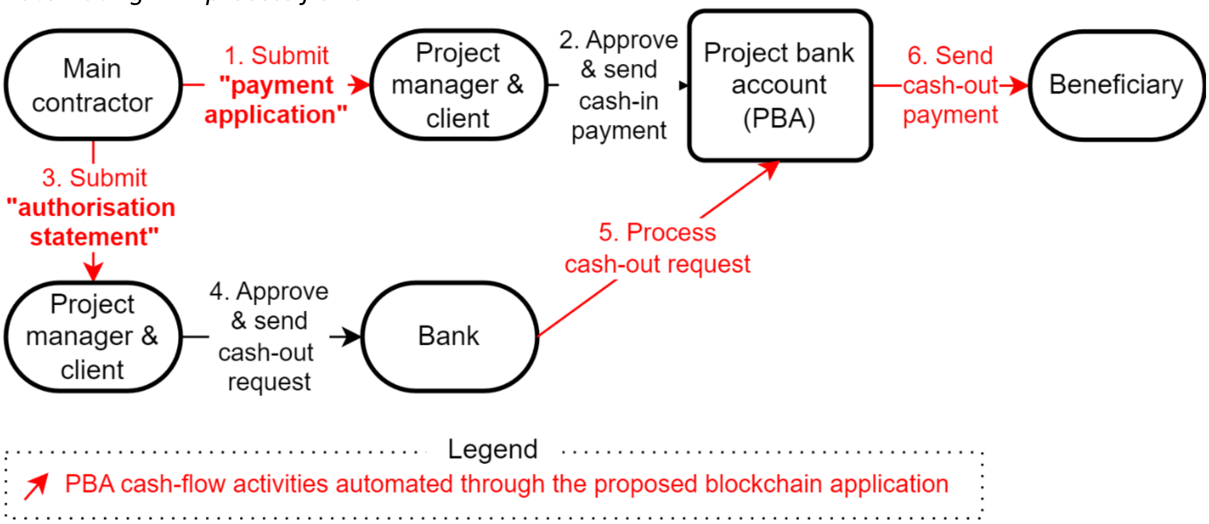
One of the challenges of PBAs in the current environment is that they cannot be used to process payments to tier-three subcontractors despite this being a major component of the UK Government’s PBA strategy (i.e., (UK Government, 2012a)). This is because the contractor is not responsible for managing tier-three contracts; consequently, they cannot approve the works/payments of tier-three subcontractors. An amendment to the UK Government’s PBA guidance document would be required to include tier-three subcontractors into the system, such as allowing tier-one project participants (i.e., the main contractor, project manager, and client) to authorise payments to tier-three subcontractors based on payment approval certificates from tier-two subcontractors. However, this has several challenges: The PBA trust deed currently only stores the signatures of tier-one and tier-two subcontractors. Amending the trust deed to include tier-three subcontractors would substantially increase its management workload. For example, suppose the main contractor employs 20 tier-two subcontractors, and each tier-two subcontractor employs 10 tier-three subcontractors. In that case, the main contractor must collect and manage hundreds of trust deed signatures, causing delays in data processing. This problem becomes exponentially more complicated when considering the inclusion of tier-four and tier-five subcontractors. The UK PBA strategy mandates that all cash-outs from PBAs require approval/authorisation from the client, project manager, and main contractor (UK Government, 2012a). Therefore, the bank must verify these signatures every time a payment is executed from the PBA. Processing payments via the PBA method also increases the bank's payment processing workload as payment authorisation statements, which are paper-based documents submitted by the main contractor to the bank at interim stages, are required to authorise cash-outs from the PBA. Main contractors already have an aversion to using a traditional PBA in its current form because it increases their management workload; therefore, adding additional complexities, such as incorporating lower-tier subcontractors into the traditional PBA payment system, is not a proposal they would support. From the perspective of subcontractors, the primary reason subcontractors do not request main contractors to use PBAs is because of fear of potential exclusion from future work (Griffiths et al., 2017, p. 331).

6.3.2 Process Flow Automation

This section discusses two of the most crucial forms in PBAs: (1) the *payment application* and (2) the *authorisation statement*. The *payment application* is a request for cash-ins to the PBA, whereas an *authorisation statement* is a request for cash-outs from the PBA. The *payment application* is a form the contractor submits to the tier-one payment approvers (i.e., the client and project manager (PM)), stipulating the amounts due to the PBA. These payment approvers then check whether the amount requested matches the project’s order value, and once approved/signed, the client executes the cash-in to the PBA. Similarly, the *authorisation statement* is a form the main contractor (MC) signs and submits to the client and PM, requesting approval to debit cash from the PBA. Once all three tier-one project participants (the client, MC, and PM) approve/sign the *authorisation statement*, the MC sends it to the bank for processing. Technically, the MC’s signature also comprises signatures from the quantity surveyor, commercial manager, and contract manager; however, these signatures are managed by the MC and are thus grouped under the MC’s signature for simplification.

Figure 37 shows a sequence of how the PBA *payment application* & *authorisation statement* are processed. The proposed application automates the *payment application* process when it sends a cash-in request notification (via e-mail) to the payment approvers whenever cash-ins are due; thus, the main contractor (MC) is no longer required to manually submit the *payment application* because it is automated in the proposed application. One interviewee advised that "even though it is automated, publishing a formal document would still be required for management and archiving purposes". Regarding the *authorisation statement* mentioned above, the proposed application also automated this form because when a subcontractor sends a notification to the proposed application that works are ready for approval, the application's payment authorisers (i.e., the client, MC, and project manager) receive an automated e-mail with a link directing them to the location on the user interface where an approval signature is required; therefore, the MC no longer needs to manage the *authorisation statement* form manually. The proposed application executes autonomous cash-outs from the PBA to the subcontractors when all payments are signed by the payment authorisers.

Figure 37.
Automating PBA process flows.



One interviewee commented, "The quantity surveyor (QS) would need to be included in the payment approval process before the authorisation statement is even sent to the PM. Their role includes measuring the works delivered and issuing a payment certificate or payless notice suggesting how much to spend within the PBA." The proposed application was designed to allow configurations, and adding the QS as a payment approver in the proposed application was easily accommodated after the data collection. In the proposed application, subcontractors are no longer required to submit invoices because payments are directly linked to approval signatures; however, the proposed application could automate the publishing of invoice documents to satisfy current, standardised, administrative workflows. Hypothetically, the invoice data could automatically generated based on the information in the proposed applications cash-in and cash-out smart contract tables displayed in Figures 29 and Figure 31 in Chapter Four (Conceptual Framework). However, the researcher understands that additional information, such as tax codes, must be appended to the invoice to make it more legally and formally acceptable. Nevertheless, the proposed application has not yet reached the stage where details like this are being designed into the system, as the focal point is the general framework design of a PBA blockchain application.

In standard PBAs, only the bank has the authority to debit cash from the PBA, hence the need for an authorisation statement instructing them to execute cash-outs. Since the proposed application disintermediates from using a bank, the process of sending them a PBA authorisation statement is irrelevant because cash-outs from the blockchain PBA are automatically triggered when payment approvers (such as the client, MC, and PM) sign and approve cash-outs via the proposed application. In the current version of the proposed application, the approval certificate is a blockchain signature rather than an official document; however, a future iteration of the proposed application could append these signatures directly onto standard payment certificate documents, extending the use of blockchain for certificate authentication.

Two interviewees highlighted that existing construction processes lack traceability. One said, “Current systems lack traceability with payment approvals and signoffs”, and another mentioned that they “frequently suffer reconciliation issues” regarding managing cash book data. All actions performed through the proposed application are recorded on the blockchain as transactions, allowing management parties to query and trace data flows from origin to completion with an intact data trail. This was supported by another interviewee, who discussed how they “see the automated accounting of blockchain as a potential solution to logging and timestamping cash flow events”. Blockchain automates the logging of transactions through its network of nodes that run a consensus algorithm that validates data. All data on the blockchain is immutable, making it a suitable medium as a single source of truth; furthermore, it mitigates reconciliation errors when project managers synchronise data across interim stages. According to one interviewee, banks only keep PBA transaction records for “six to twelve months”. Since all transactions on the blockchain are permanently stored, they can be instantly queried after many years; as one interviewee highlighted, “Blockchain would make a good system for permanently storing transaction records.”

6.3.3 Systems Integration

Blockchain can achieve management and cash flow integration easier than traditional software because it does not partition general data from financial transactions, unlike traditional software, where financial transactions can only occur in FinTech or banking systems. For example, one questionee discussed how blockchain integrates “decentralised identity”, “decentralised indexing and API (application programming interface) services”, “decentralised cloud”, “decentralised servers”, and “decentralised finance”. These services can all interoperate on the blockchain, unlike traditional software systems that are more specialised in functionality. Since blockchains operate on a transparent and shared protocol layer, all applications built on them can naturally interoperate.

The proposed application sends automated e-mails to parties when tasks require performing rather than relying on them to communicate manually. For example, when a subcontractor registers through the proposed application that their works are ready for approval, the main contractor is sent an automated e-mail stating that a review of the works is due. Furthermore, since data flows are immutably recorded on the blockchain, harmful practices, such as late payments, are easy to identify and penalise. One interviewee commented, “The fact that users are automatically reminded when tasks need to be performed is brilliant; it immediately mitigates having to chase people to do things.” The automated e-mail notification feature is not an invention of the blockchain; it is a function already implemented in standard Web applications.

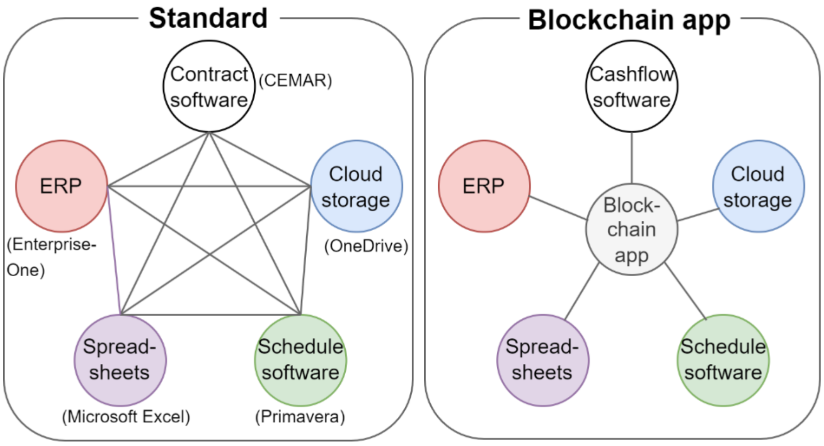
Integrating Web applications with the blockchain is easier than integrating them with proprietary software. This is because Web applications are the default user interface for end-users to interact with the blockchain. Therefore, the infrastructure requirements of blockchain applications are lightweight and require no infrastructure prerequisites (i.e., downloading software is not required to interact with blockchain applications). The implications of this are potentially significant because many decentralised applications (dApps) for construction could be made available to end-users (i.e., the construction supply chain) at no cost or technology barriers.

Furthermore, end-users would have the ability to integrate dApps with each other without interoperability issues because all the dApps on the blockchain share the same platform infrastructure, and the blockchain wallets that users use to exchange data and sign transactions in one dApp would be the same across all dApps. Additionally, because no one owns the blockchain, there would be no risk of vendor-lock, such as when software companies making it challenging for their customers to integrate with the applications of their competitors to maximise software sales.

Regarding the use of application programming interfaces (APIs) and oracles, one questionee advised, "Instead of using oracles to automate data flows to the blockchain, semi-automation can be achieved with standard APIs" by pushing data from construction software into the proposed application's user interface, then pushing the data from the user interface into the blockchain, thereby using the proposed application as an intermediary system for integrating management data with payments. Since Web APIs have existed since the emergence of Web 2 (i.e., around the year 2000), they have existed for over two decades and are used ubiquitously, and thus Web APIs have substantial resources and templates for how to integrate with software. In contrast, oracles (i.e., blockchain APIs) are a relatively nascent Web tool with limited resources and integration capabilities. For example, Microsoft Office has a plugin that enables data from it to integrate with Web applications. The author tested this API integration capability and was able to push data from Excel to the proposed application. Therefore, if a user has a payment schedule on an Excel spreadsheet and they want to transfer that data immediately to the proposed application, it can be achieved with existing Web tools. This API can also operate vice versa, where the API pulls data from the proposed application and displays it on Excel.

Traditional PBA payments are processed via a terminal management system (TMS), as advised by one interviewee who stated, "All PBA payments are made through a TMS set up with the bank." However, TMS is a legacy system that is closed-source, licenced and does not offer programmable payments. Similarly, one type of software system used regularly by large construction companies is enterprise resource planning (ERP) software. One interviewee mentioned they use "an ERP for managing orders and payment data, but it cannot integrate with other software systems". ERP software is more specialised and technical, unlike spreadsheet software, which is general-purpose and straightforward to integrate. Similarly, another interviewee discussed how they "tried integrating management information on SharePoint but ended up with too many bespoke systems that no one knew how to manage." The technology siloing of legacy, centralised systems makes data integration challenging. Due to the general-purpose properties of blockchain and the programmability of smart contracts, they could be used as intermediary systems for integrating data from fragmented software, as shown in Figure 38.

Figure 38.
Using blockchain to reduce the complexities of APIs.



Accessibility is critical for an application's success. One perspective for evaluating accessibility is how easy it is for anyone to access and benefit from the technology. Due to the open-source nature of blockchains, copying technology is normalised and encouraged within the blockchain ecosystem. For example, Litecoin is a fork of Bitcoin, and Feathercoin is a fork of Litecoin. A 'fork' is when the codebase of one blockchain is copied, edited, and deployed as a new blockchain. One interviewee remarked, "Since blockchain is open-source and legally backed by a copyleft vs. copyright licence, the technology can be copied, modified, used, and redistributed without intellectual property issues." They added, "The same applies to any decentralised applications built on public blockchains." Blockchains differ from centralised software because they place free and permissionless information sharing as the top priority over profit. For example, the Ethereum Foundation (EF) is a non-profit organisation comprising hundreds of decentralised core developers managing and maintaining the Ethereum blockchain (Ethereum Foundation, 2023). Furthermore, anyone can submit an Ethereum Improvement Proposal for consideration by the EF. The business model of public blockchains is vastly different from any organisation that existed before them because they operate through a transparent and publicly verifiable system, unlike centralised companies, which rely heavily on privacy and profit. One interviewee commented, “Some blockchain decentralised applications, such as Qredo, take the idea of open-source further by providing white-label solutions that enable their work to be copied and rebranded without risk of copyright infringement”. Construction companies can leverage the services of a white-label decentralised applications (dApps), rebrand it as a new product, and even profit from it without the risk of copyright breach. Furthermore, since decentralised applications are hosted on the blockchain, their codebase is open-source and openly replicable. An example of how the proposed application can benefit from a white-label dApp is copying the codebase of another white-label dApp, such as a wallet provider, and deploying it as a new product/service to reduce reliance on third-party wallet providers. The white-labelling of dApps is a potential solution to an area of caution advised by one questionee who stipulated, “Overreliance on third-party blockchain services jeopardises security.” The benefit of white-label dApps is that they provide cost-free infrastructure for anyone that wants to exploit their codebases. This provides opportunities for construction companies seeking an economical alternative to testing new systems without incurring technology licence fees. However, blockchain currently suffers from skill shortages in dApp development, which inflates the cost of outsourcing their services and potentially offsets the free and open-source infrastructure of the blockchain. Nevertheless, since the technology is relatively new, the influx of new dApp developers entering the space over the coming years should reduce the cost of outsourcing dApp services.

6.3.4 Interoperability Issues

Since blockchain and Web 3 are decentralised technologies, they are typically coupled in decentralised applications. However, one questionee advised, "A hybrid approach that integrates Web 2 and Web 3 is more practical in the current environment because a full Web 3 setup offers less value to developers and customers”. Another questionee supported this by saying, “If the application aims to process payments with smart contracts, then using Web 3 just for the user interface would not add value”. This dissertation’s author can identify with the above comments concerning how Web 3 offers less value to users because when the proposed application was in development, the researcher’s initial plan was to host it in Web 3; however, due to a lack of services, a hybrid solution that incorporates both Web 2 and Web 3 was used. Therefore, for particular use cases, such as the proposed application, Web 3 is at a disadvantage to Web 2 due to a lack of technology maturity; however, if managing multiple decentralised applications that interoperate, the justification for using Web 3 increases, as per one questionee who stated, “If the plan is to build a large ecosystem of blockchain services or if planning to set up a DAO, then the rationale to use Web 3 becomes stronger”. A decentralised autonomous organisation (DAO) is a system operated by smart contracts and managed by a decentralised network of participants/stakeholders that vote on decision points (Dounas et al., 2021).

One questionee discussed that one of the risks of blockchain is the lack of “legal accountability” if project funds are stolen due to wallet hacks. For example, MetaMask (the wallet provider used in the proposed application) cannot be liable for damages caused by theft because decentralised wallets are self-owned rather being managed by a third-party custodian such as a bank. Despite that, one interviewee advised, “Wallet decentralised applications such as Qredo provide insurance up to the value of £470 million for any funds lost through wallet hacks on their platform.” Therefore, despite the self-ownership of funds being a risk of using the blockchain, some wallet decentralised applications provide services that mitigate this issue.

Each payment schedule in the proposed application includes a weblink that directs users to the contract associated with the work. The contracts are in PDF format, stored in a decentralised cloud (i.e., IPFS), accessed via a weblink, and uploaded by the main contractor. Technically, the documents can be stored using whatever cloud storage is preferred, as all that is needed is a weblink to the repository. Furthermore, although the proposed application improves systems integration, it is not a document management system; thus, traditional data hygiene (i.e., managing and organising files) is essential. Concerning how the proposed application stores contract documents in IPFS, one interviewee stipulated, “Standard cloud is not designed to handle the commercial complexities of contract management”, and that “Cloud-based solutions for this already exist, such as CEMAR.” They added, “CEMAR is designed to operate with NEC and provides users with dashboards for tracking and managing contract data.” Furthermore, they clarified, “It automates the generation of charts, dashboards, and reports, such as percentage of early warnings managed effectively, communications dealt with on time, compensation events approved, and so on.” An easy and indirect way to instantly link CEMAR files with the proposed application is to store a hyperlink of CEMAR's contract repository in the proposed application (as shown in Figure 39) while also storing a similar Web link in CEMAR, allowing the two systems to be indirectly connected. The word 'indirect' is used because changing data in one system does not autonomously change the state of the other because they are only connected via hyperlinks.

Figure 39.
Screenshot of the application's Cash-out table.

Role	ID	Contract	Works	Revision	Start	End	Planned	Actual	CostCode	Status	PercentageCo
Subcontractor	100	/Sub.pdf	Ground	0	01/03/2023 09:00 AM	01/10/2023 06:00 PM	0.1 ETH	0.14 ETH	XX-001	Paid	100

One interviewee advised, "There is a plethora of project management software that does management tasks better than blockchain, so it is best to use blockchain for what it is good at, which is a settlement layer." The proposed application did not intend to imitate or replicate another software. Instead, it is a tool that integrates payment approvals with executions. For example, when on-site works are approved (via the proposed application's user interface), it triggers an autonomous payment to the subcontractor. Currently, no centralised software has the same programmability capabilities as blockchain smart contracts; thus, this is one of the key technical areas this research explores.

6.3.5 Cost

Construction companies are in a continual state of low cash liquidity caused by a lack of project profitability (Lowe & Moroke, 2010). From the perspective of cost, the proposed application's potential benefits include reduced cost for setting up and managing PBAs, reduced labour for processing payments, and reduced time for synchronising project data across the supply chain.

Transaction fees on Ethereum only apply if transacting on its main network. The Ethereum-Goerli test network was used to deploy the proposed application without incurring transaction fees. Test networks mirror the functionality of the main network entirely; thus, they are suitable testing environments. When testing the proposed application, the transaction fees ranged from £0.7 to £24 for each transaction depending on network demand. Since the test network mimics the cost of transacting on the Ethereum main network, users can get a realistic estimation of the cost implications of deploying smart contracts and sending transactions in a real-life application.

If a blockchain application is commercialised, the application’s team keep 100% of the revenue generated from it and 0% goes to the blockchain platform. This is because, technically, no one owns the blockchain and thus there is no entity that can claim commission (the founders of a public blockchain get their funds from selling cryptocurrencies they minted when the blockchain was launched). However, if an organisation builds an application on blockchain, that application provider can charge whatever fees they want. However, because all applications deployed on the blockchain are open-source, any application provider that charges high fees would get their codebase copied and redeployed by another application provider. This is acceptable behaviour on the blockchain and it stops application providers behaving overly capitalistic. In contrast, Google charges 15% to 30% commission on revenue generated through their services (Google, 2023). However, centralised technology companies provide comprehensive customer support. In contrast, the blockchain platform itself provides no customer support.

Although blockchains charge mining/staking fees paid by each transaction’s sender, one questionee highlighted, “Polygon, a layer two scaling solution for Ethereum, can reduce transaction fees by a factor of 10,000”, making transaction fees negligible. For example, an Ethereum transaction fee of £20 would be reduced to £0.002 on Polygon (Besancon et al., 2022). Another questionee highlighted other types of layer-two scaling solutions that exist alongside Polygon, such as “Validium” (e.g., Starkware), “state channels” (e.g., Raiden), and “rollups” (e.g., zkSync). As complicated as this sounds, a layer two (L2) scaling solution, such as Polygon, is a blockchain platform that is built on top of another blockchain platform such as Ethereum. Therefore, Polygon has its own native cryptocurrency and blockchain nodes, but it leverages the security of Ethereum by grouping many transactions together and sending them on Ethereum as one transaction. This is how Polygon reduces the transaction fees on Ethereum. Polygon is entirely reliant on Ethereum because it reconciles its transactions with Ethereum to increase its security. Therefore, Ethereum provides Polygon with security and Polygon provides Ethereum with scalability.

One questionee commented, “Before enterprises embark on a blockchain journey, they should assess whether they are willing to restructure their business workflows, retrain staff, and have the resources to maintain the technology long-term.” Obtaining the resources to manage and operate these additional blockchain services is a long-term commitment that will be costly, time-consuming, and require ongoing technical maintenance that construction companies must be prepared to absorb if planning to adopt blockchain. The construction industry already suffers from low investment in innovation; therefore, relying on them to fund blockchain applications may be overly ambitious unless the business model is cost-effective and easy to implement. Table 7 from Chapter Four (Conceptual Framework) displayed that deploying and operating the proposed application’s smart contracts on Ethereum costs roughly £1,200 per project. However, this cost could be reduced to less than £1 if deployed on a scaling solution such as Ethereum-Polygon. The user interface of the proposed application (i.e., its website) costs £40 per month in Web hosting fees. However, the maintenance costs of a full-feature Web application can range from £250 to £2,500 per month (Web FX, 2023). Due to the novelty of how blockchain uses cryptography and consensus to achieve data immutability, financial institutions such as J.P. Morgan and Bank of America use an internal private blockchain to reduce costs associated with transaction reconciliation and auditing (Ullah et al., 2022).

6.3.6 Stablecoins

On the topic of stablecoins, one questionee commented, “Stablecoins should be implemented in the application to mitigate the price fluctuations of cryptocurrencies”. The only reason the proposed application did not implement stablecoins is that it was deployed on an Ethereum test network, and stablecoins are only available on the Ethereum main network. In a real-life project, the proposed application would include stablecoins issued by a stablecoin provider. One questionee advised, “Circle is an example of a stablecoin provider developed by financial institutions” with their “USDC coin”. A reputable stablecoin in the UK is Pound Token with their GBPT stablecoin (Pound Token, 2023a). GBPT is fully regulated, with monthly audits from KPMG attesting its legitimacy (Pound Token, 2023a). An example of a country that adopted stablecoins is the Marshall Islands (Republic of the Marshall Islands, 2018, p. 4). They passed a bill in 2018 to use the SOV stablecoin as their country’s national currency (Republic of the Marshall Islands, 2018, p. 5). Blockchain adoption at the governmental and national level is more straightforward in less developed countries because they are less entrenched with layers of traditional financial technology infrastructure.

Although stablecoins mitigate cryptocurrency price volatility, one interviewee stipulated, “stablecoins are not yet considered legal tender, but this should be ironed out when the stablecoin bill is approved”. Furthermore, they added that “The bill for regulating stablecoins is currently with the House of Lords”. The *Queen’s Speech: Economic Affairs and Business Report* highlighted regulating stablecoins as a matter of high legislative consideration (Smith, 2022). However, until the abovementioned stablecoin bill is approved, a solution for off-ramping stablecoins is required. One interviewee cautioned that “off-ramping ramping stablecoins is where most of the challenges are”. To convert stablecoins to fiat, the beneficiary (i.e., subcontractors receiving payments from the PBA) would exchange them via the stablecoin provider’s platform and then deposit the fiat to their commercial bank. However, due to the high-risk profile of blockchain services, banks can freeze deposits from stablecoin providers due to governmental controls with anti-money laundering (AML) regulations. Banks are cautious about accepting money from stablecoin providers due to the numerous frauds that have taken place regarding cryptocurrencies. For example, FTX Trading Limited was considered one the most reputable and regulation-abiding cryptocurrency services provider until it filed for bankruptcy in 2022 (Palma et al., 2022). FTX lost an estimated £25 billion worth of customer and creditor funds and was labelled “one of the biggest US financial frauds in history” (Palma et al., 2022). This is why banks are cautious about accepting deposits from cryptocurrency services companies. When asked about the viability of paying taxes with cryptocurrencies, the researcher explained that using cryptocurrencies/stablecoins for payments would not affect standard tax duties because beneficiaries would still receive payments in fiat after they convert their stablecoins. Therefore, the existing method of managing and filing taxes remains unchanged. Furthermore, the blockchain transactions would include reference codes that enable auditors to track and verify the origin and destination of payments that take place on the blockchain.

Central bank digital currencies (CBDCs) are an alternative to stablecoins; however, at best, they are still in the piloting stage and have not reached adoption. CBDCs and stablecoins are similar in that they are both blockchain tokens. The primary difference is that CBDCs are issued by the central bank, whereas private organisations and institutions issue stablecoins. Nevertheless, the demand for blockchain-based currencies caused the UK Government to set up the CBDC Taskforce to investigate whether the Bank of England can use blockchain to improve the management, issuance, and tracking of British Pounds in the form of CBDCs (Bank of England, 2020; HM Treasury, 2021). Although blockchain is challenging to regulate because of its decentralised nature, it is being tested at a multi-sector and governmental level, and bodies such as ISO include 26 registered blockchain standards; however, most of those standards are still under development (ISO, 2022).

6.3.7 Private Transactions

Private transactions are a minimum requirement for enterprises considering blockchain. Permissioned/private blockchains, such as Hyperledger, provide privacy as part of their default setup (Hyperledger, 2017). However, advances in cryptography have enabled public blockchains to achieve private transactions (Robinson, 2020). Layer two (L2) is when additional infrastructure is built atop the blockchain to improve its performance (i.e., L2 privacy or L2 scaling solutions). One privacy solution, as mentioned by one questionee, includes “zero-knowledge proofs (ZKPs)”. The researcher was aware of ZKPs before the data collection but did not incorporate them into the proposed application because of a lack of technical expertise in implementing them. Nevertheless, in a real-life project, configuring the application to include ZKPs would be outsourced to a decentralised application developer. ZKP allows data within a transaction to be stored encrypted on the blockchain (Li & Xue, 2021). This data can only be decrypted in the form of a mathematical proof attesting to the correctness of the information (Banerjee et al., 2020). An example of a ZKP is attesting (via a boolean response) that a transaction value is precisely £1234.56 without having to decrypt the blockchain data, whereby the response would be either true or false. ZKPs can only be generated by the transacting parties because revealing the proof requires a private-key signature from them. More layers of verification would be included in the ZKP to make it relatively impossible (based on current encryption methods) for any external party to breach its encryption. ZKPs incur less blockchain computation than standard transactions; thus, they are lower in transaction fees (Ma et al., 2020). ZKPs existed before the invention of the blockchain, are mathematically proven reliable, and have been used in applications such as privacy-preserving online public auctions, whereby a person's identity can be anonymously verified online without them publicly revealing any personal data (Li & Xue, 2021).

Another privacy solution, as advised by another questionee, includes "stealth addresses" (SAs). How SAs work: Blockchain wallets can produce sub-addresses cryptographically linked to their primary wallet address (Solomon & DiFrancesco, 2021). These sub-addresses are kept private and are never disclosed to anyone apart from the transacting parties (Buterin, 2023). After the transaction executes, the SA is disposed of, and an unlimited number of new SAs can be generated for future private transactions (Buterin, 2023). To withdraw funds from an SA, the user would send them to a cryptocurrency exchange; afterwards, the user would log in to the exchange and withdraw the funds to their primary wallet (Solomon & DiFrancesco, 2021). Exchanges are intermediaries that do not disclose the provenance of their transactions; thus, privacy is maintained (Umbra, 2023). Umbra is a Web application that enables users to use the SA protocol on Ethereum without needing to manually write code, whereby private transactions can be sent or received via the Umbra protocol (Umbra, 2023). When using SAs, users would only use their primary wallet for decentralised identity (DID) verification, while their SA wallet would be used for transactions. This idea was motivated by one questionee who commented, "Users can use their wallet purely for DID verification rather than transactions." Using primary wallets for DIDs and SAs for payments enables DID wallets to be openly stored in databases without the risk of disclosing the transactions received through the SAs (Solomon & DiFrancesco, 2021). For example, a contractor can safely store the DID wallets of their subcontractors in a project database without the risk of exposing their transaction histories. However, the researcher found no literature discussing the potential auditing problems of SAs or ZKPs. For example, if mass data is stored on the blockchain encrypted (due to ZKPs) or untraceable (because of SAs), it may cause traceability problems for auditing authorities. For example, the auditing authority would need to request mathematical proofs from the transacting parties every time they want a transaction decrypted, which is data processing intensive. Nevertheless, analysing scalable solutions for the auditing problems of ZKPs and SAs is beyond the scope of this research to investigate.

Private blockchains are an alternative method for achieving private transactions; however, they require setting up infrastructure and deploying a private network (Quasim et al., 2020). Public blockchains, such as Ethereum, already come preconfigured and are maintained by hundreds of decentralised core developers that contribute to managing and maintaining it; therefore, users can transact, build applications, or deploy smart contracts on it without having to set up any infrastructure (Chain Stack, 2020; Shen et al., 2021).

6.3.8 Wallet Security

The researcher decided to host the PBA as a blockchain wallet rather than a blockchain smart contract because wallets are not affected by blockchain protocol updates. While the proposed application was being developed, the Ethereum Foundation (EF) publicly announced that it would be transitioning the Ethereum blockchain's consensus algorithm from proof of work (PoW) to proof of stake (PoS), which is a significant protocol update that requires the redeployment of all smart contracts on its network. However, the EF did not release a precise date for when Ethereum would transition from PoW to PoS. At the time of developing the proposed application, Ethereum PoW was still active, although the researcher was aware that the PoS transition was on the horizon. If the project PBA was deployed as a smart contract under Ethereum PoW, it would eventually need redeployment to accommodate Ethereum PoS, which would require moving the entirety of the PBA's funds to a new smart contract. Since the proposed application was designed to simulate a real-life project, real-life considerations were considered to ensure the highest safety of PBA funds throughout the proposed application's testing phase. Since cryptocurrency wallets are not a product of the blockchain despite them playing a critical function as a medium of account for cryptocurrencies, they are not affected by blockchain protocol updates; thus, using a blockchain wallet as the PBA mitigates any risk of externalities that occur within the blockchain ecosystem (e.g., externalities such as the Ethereum's PoS update). This is why a blockchain wallet was selected for hosting the PBA over a smart contract. However, the primary security risk with standard blockchain wallets is that a single entity controls it. Nevertheless, one questionee stipulated how this can be mitigated using "multi-signature wallet" and "multi-signature smart contracts". A multi-signature wallet is when several predefined parties control its funds. For example, to debit funds from a multi-signature wallet, several parties must sign/authorise the transaction's execution. The multi-signature mechanism is a longstanding component popularised in blockchains over a decade ago and is used ubiquitously in the blockchain ecosystem for safeguarding wallet funds (Ledger Academy, 2023). However, due to the time and cost restrictions of this research, multi-signature wallets were not implemented as they require programming or outsourcing. With more time, the researcher would manually build it following the instructions of existing multi-signature wallet templates (such as the one provided by (Allmendinger, 2017)) or outsource the responsibility to a blockchain developer. Nevertheless, substantial evidence exists on the effectiveness of multi-signature wallets (Cocco et al., 2022). Thus, the researcher relied on this evidence as theoretical proof of its implementation capabilities without formally adopting it in the proposed application. One questionee advised that "threshold wallets are an updated version of multi-signature wallets" and that "the difference is that one private key is divided into many parts and given to multiple users". In a multi-signature wallet, users sign for transactions with a separate private-key. In contrast, in a threshold wallet, users sign for transactions with a fraction of a shared private key (Bai et al., 2019). Despite the threshold wallet's private key being divided into several parts, users can still conduct signatures separately (Gennaro & Goldfeder, 2018). This results in lower transaction fees because only one full signature is logged on the blockchain when a transaction executes (Gennaro & Goldfeder, 2018). One questionee recommended using "MPC" (multi-party computation) wallets, although, upon further investigation, they are precisely the same as threshold wallets (Wiener, 2020). Threshold/MPC wallets offer more security features than multi-signature wallets because the wallet's conditions can be added to the threshold wallet even after deployment, unlike in multi-signature wallets, where all the wallet's conditions (such as how many people share the wallet) must be predefined and cannot be altered after deployment. Updating the proposed application to include threshold wallets, as advised by the questionees' responses above, would improve its security and performance while reducing transaction fees. However, a more thorough comparative analysis of multi-signature vs threshold is required to assess its suitability for the proposed application. Regarding the leveraging of third-party wallet decentralised applications in the proposed application, one questionee advised, "There is insufficient evidence that third-party blockchain wallets, such as MetaMask, can provide adequate proof of their security promises." Furthermore, they added that "MetaMask operates through a Web browser that collects data on user activity, so it is vulnerable to attacks". Therefore, hosting the wallet service internally or outsourcing it to a wallet provider specialising in enterprise security is the best approach.

6.3.9 Banks

The proposed application initially investigated whether banks could offer payment guarantees to PBA projects via the proposed application; however, the interviewees advised against this, which will be discussed throughout this section. In traditional construction projects, the client and the contractor can obtain payment or performance guarantees from banks to reduce financial risk (Chovancova et al., 2019). The payment guarantee protects the contractor if the client cannot pay liabilities, and the performance guarantee protects the client if the contractor cannot deliver work (Chovancova et al., 2019). Payment guarantees are only triggered/activated in extreme cases, such as if the client or contractor becomes insolvent, because they can take over a year to process (Wu et al., 2019). Thus, although payment guarantees provide construction projects with assurances, they are ineffective at improving general cash liquidity. One interviewee stipulated, “Payment guarantees for PBAs are unnecessary because the client is the government and is cash-rich”, and another added, “The government does not allow PBAs to acquire finance because it increases their national debt due to interest repayments.” Before the focus group interview, the researcher was unaware that PBAs imposed restrictions on finance. Therefore, obtaining payment guarantees or loans (e.g., supply chain finance) is not permissible with PBAs. The only time finance would be permitted for PBAs is if the government extends them to include the private sector. In response to a question asked by the researcher regarding whether PBA is also used in the private sector, one interviewee replied, “Not currently, but the government is considering rolling it out to include them.”

One interviewee pointed out that “the client has the final say in what financial system to use for PBA, and at the moment, it is with traditional finance, but it could be blockchain if the value proposition is big enough”. Therefore, from the perspective of that interviewee, contractors are open and willing to experiment with alternative solutions for PBA if requested by their clients. One interviewee added, “Public sector clients in the UK have a governmental login portal that they use to monitor and access PBAs”. Another interviewee mentioned how “banks are familiar with PBAs and can set them up in a few weeks.” Despite this, the proposed application could reduce PBA set-up delays from weeks to within a day. Once all trustees sign the PBA trust deed, the trust deed smart contract can be instantly deployed on the blockchain. Furthermore, in case of human errors, the PBA smart contract can be amended and redeployed anytime with minimal processing delays versus the bank having to spend another several weeks redeploying the amended PBA. A PBA trust deed is a legal document that lists all the PBA's trustees (the client, contractor, subcontractors, etc.) and is the most crucial document in PBAs. Concerning this, one interviewee added, “Waiting for the bank to initialise the PBA is one factor that causes delays in PBA projects, but it is not one of the main ones”. Therefore, although setting up a traditional PBA does not cause significant project delay risks, a blockchain-based PBA could prevent this entirely.

When the researcher asked the interviewees whether they saw any potential threats with enterprises adopting the proposed application, one replied, “The threat is with the bank and not the enterprises because blockchain will take business away from them.” Furthermore, they added, “Banks can indeed make it harder for crypto companies to off-ramp crypto assets if they feel threatened.” For example, banks can block/freeze funds from cryptocurrency companies if they deem them high risk under regulatory controls such as anti-money laundering (AML). Another interviewee highlighted that “stablecoins are not yet considered legal tender”; therefore, in the current environment, any blockchain applications must cooperate with traditional banking systems until the government approves stablecoins as legal tender. According to one interviewee, if the government approves the “bill for regulating stablecoins, there will be a fast expansion of real-life use cases for blockchain”. However, until then, cooperation between cryptocurrency/stablecoin services and traditional finance (i.e., banks) is fundamental for construction companies considering blockchain for payments.

6.3.10 Managing Identities

Know-your-customer (KYC) regulations are procedures for verifying the identity of users to ensure people are who they say they are and can be trusted (Arner et al., 2019). For example, when a customer opens a bank account, the bank is legally obliged to conduct KYC (Arner et al., 2019). Trusted authorities, such as banks, are prime providers of KYC services (Chai et al., 2020). UnionPay is an example of a Chinese financial technology company that leverages a commercial bank’s KYC services to verify the blockchain wallet addresses of its cryptocurrency customers (Chai et al., 2020). Centralised entities can exist within the blockchain ecosystem to circumvent the lack of centralised accountability with decentralised technologies

(Wong et al., 2020). The type of KYC required in the proposed application is verifying that the wallet addresses of project participants are owned by real identities. One interviewee highlighted, “The wallet addresses of project participants should be linked to a KYC-approved registry to ensure only verified users can be entered into the application.” This would mitigate the risk of data entry errors or malicious actors entering fraudulent wallets into the proposed application to commit theft. The challenge with the main contractor internally managing the KYC of their supply chain is that they would be held legally accountable for authenticating users and maintaining privacy against hacks. Furthermore, subcontractors may not feel comfortable with the main contractor having visibility of their blockchain identities. Due to the complexity of user authentication systems, it is best outsourced to FinTech (financial technology) or CeFi (centralised finance) organisations that specialise in this field (Nath, 2023). CeFi is more regulated and is used for managing assets such as mortgages, stocks, and bonds, whereas FinTech is less regulated and is focused on providing services for moving money faster and cheaper between people and businesses (Nath, 2023). Both FinTech and CeFi can provide KYC services, although CeFi is more reputable because the government more closely monitors them for regulatory purposes (Nath, 2023). One interviewee stipulated, “In the PBA trust deed, it will say which bank account to use for the PBA; there should be no problem in specifying a blockchain wallet as the PBA provided the right KYC and insurance are in place throughout.” That comment speculates that banks are not necessarily mandatory for the operations of PBAs. Regarding decentralised solutions for KYC, one questionee commented, “Some decentralised applications link biometric authentication (e.g., fingerprint and face recognition) to blockchain wallets.” Therefore, decentralised KYC is also an option. Another interviewee highlighted how KYC should be accompanied by “white-listing” to “enable users to limit transactions to verified wallets only.” White-listing is when the wallet addresses of project participants are placed into a smart contract to validate them as safe to use in a project (Tezel et al., 2021). In the case of PBAs, the white-listed wallets would include the signatories of the PBA trust deed, ensuring that only those parties can approve or receive payments from the proposed application’s smart contracts. The difference between KYC and white-listing is that the former is used for identity authentication only and managed by a trusted third party, whereas the latter would be managed by the main contractor on a project-by-project basis.

White-listing and KYC form a two-stage verification process for ensuring the safety of user wallets and project funds.

6.4 Improvement Proposals

Part of adopting a design science research (DSR) strategy is using the data collection to feed back the results to the research's conceptual framework for iterative improvements. Regarding this, one interviewee advised that the Trust Deed user interface shown in Figure 26 from Chapter Four (Conceptual Framework) should "link up with the contractor's internal spreadsheet rather than having to enter subcontractor details twice" (i.e., once in the contractor's spreadsheet and again in the proposed application). One questionee stipulated that this can be "achieved with standard APIs (application programming interfaces), such as RPCs (remote procedure calls) and REST (representational state transfer)". Additionally, general-purpose management software, such as Microsoft Excel, includes add-in capabilities that allow spreadsheets to integrate with Web applications, mitigating users from having to set up APIs manually (Hiron-Grimes, 2017). Since Web applications are lightweight and accessed via a standard webpage, they provide a highly accessible medium for transferring spreadsheet data to the blockchain and vice versa.

Concerning the proposed application's cash-in and cash-out smart contract (SC) tables (a screenshot of the proposed application's cash-out table is shown on Figure 40, below) one interviewee advised that it "only showed planned vs actual costs; why not extend it to include budget and estimated costs?". This can be achieved by adding additional data columns to the cash-in and cash-out SC tables to include estimated and budget costs and providing access rights for additional parties, such as the estimator, to access the cash-in/out SC tables to insert cost data. Regarding this, one interviewee commented, "If these costs are in one place, linking them to analytics dashboards would be straightforward." Linking the cost data to analytics dashboards would be highly effective because it allows cost performance data to be displayed in real-time rather than waiting for the publication of month-end reports. Since the data would be timestamped, immutable, and with a complete record of when it was revised and by whom, an intact data trail would be available for project analysis, which responds to the comment of one interviewee who stipulated how current systems "lack data trust because users can overwrite it any time, and it relies on people manually entering the information correctly”. Another interviewee added, “Live analytics would be highly beneficial to projects” and that “having the visibility of knowing, with pinpoint accuracy, when works were approved on-site, certificates awarded, and liabilities executed, would be useful for project reporting.”

Figure 40.
Cash-out table displaying planned and actual costs.

Works	Revision	Start	End	Planned	Actual	CostCode	Status	PercentageComp
Ground	0	01/03/2023 09:00 AM	01/10/2023 06:00 PM	0.1 ETH	0 ETH	XX-001	Paid	100
Foundations	0	01/06/2023 02:30 PM	01/12/2023 03:30 PM	0.15 ETH	0.1 ETH	XX-002	Approved (2/2)	100
Concrete	0	01/15/2023 02:00 PM	01/18/2023 07:00 PM	0.2 ETH	0.11 ETH	XX-003	Approved 1/2	100
Footing	1	01/09/2023 02:30 PM	01/16/2023 07:00 PM	0.14 ETH	0.15 ETH	XX-004	Updated	0
Blockwork	0	01/23/2023 01:30 PM	01/31/2023 05:45 PM	0.18 ETH	0.11 ETH	XX-005	In progress	80

Since the proposed application has an event-driven architecture that sends users automated e-mail notifications, one questionee suggested this should extend to include “automated alerts to tier-one parties when project costs exceed a threshold or if on a trajectory to exceed it; then users could react more quickly in strategising a solution to mitigate overspending”. Blockchain can store a timestamped history of these project alerts, which places greater responsibility on tier-one parties to act proactively because each data flow is traceable (Elghaish et al., 2020; Hunhevicz & Hall, 2020).

Concerning the proposed application’s cash-in smart contract table, shown on Figure 29 in Chapter Four (Conceptual Framework), one interviewee advised how it “should include the status of the commercial manager’s interim valuation, which the client and the project manager would review prior to signing for the cash-in.” Another interviewee added that a quantity surveyor (QS) must also be included in the valuation process to “measure the works delivered”. The PBA guidance document published by the UK Government stipulates that “A PBA does not cut across contractual provisions governing the preparation and submission of interim applications or the valuation, authorisation or certification of interim payments” (UK Government, 2012a). Because of this, the proposed application’s framework excluded interim valuation certificates from its design. However, upon reconsideration, including interim certificates in the proposed application would not interfere with existing interim valuation processes because the proposed application digitises current workflows rather than alters them.

Concerning how all project participants can view all payment data on the proposed application's user interface, one interviewee commented, "The subcontractors should not have full visibility of this". The researcher responded that for testing purposes, the cash-in and cash-out schedules were displayed under the same user interface; however, in a real-life application, these schedules would be partitioned into separate user interfaces. Furthermore, privacy solutions such as zero-knowledge proofs or stealth addresses (highlighted by several questionees in Chapter Five (Data and Analysis)) can be used to encrypt the data. The proposed application's Subcontractor user interface, shown on Figure 32 in Chapter Four (Conceptual Framework), was designed to enable subcontractors to pull their project data (such as scheduling, approvals, and payment data) instantly without needing to query it directly from the main contractor. This saves unnecessary communications and delays in data retrieval, as per one interviewee who stated, "This reduces the number of unnecessary communications between management parties and subcontractors because much time is wasted simply relaying information." Another interviewee added, "In a typical large project, ten people, on average, spend two full days per week answering queries related to schedules, orders, and payments." These comments suggest that main contractors spend substantial time relaying information and answering subcontractor queries. Time wastage could be reduced by leveraging the proposed application as a single source of truth for storing project data. Regarding this, one interviewee commented, "Enabling subcontractors to pull the most updated version of their scheduled work is very useful for data consistency, and it reduces the burden on them managing this information themselves." This comment highlights how time savings can be made from the subcontractors' perspective since their schedule data would be automatically synchronised with the main contractor's project schedule. Regarding data consistency, one interviewee commented that one of the problems they face is "maintaining an accurate data trail between the lead contractor and subcontractor." The proposed application mitigates this because each data entry, revision, approval, and payment performed through it is documented on the blockchain and can be audited.

Initially, the proposed application included a Payment Guarantee user interface; however, this was removed upon feedback from the findings. Concerning this, one interviewee mentioned: “Banks already have a formal process for administering finance; they will not change their internal process just for one application.” The findings also suggested that PBAs are disallowed from accessing bank finance because doing so increases the UK’s national debt due to interest repayments, invalidating the ability of PBA projects to access bank finance. Furthermore, one interviewee advised, “Payment guarantees for PBAs are unnecessary because the client is the government and is cash-rich.” Based on the above feedback, the payment guarantee function was removed from the proposed application.

The researcher assumed that inserting PBA clauses into a PBA contract (i.e., a construction contract with PBA clauses embedded into it) came from a standardised template; however, one interviewee clarified this as incorrect and stipulated that six primary steps are required, such as: (1) “Bid manager identifies actual or potential PBA requirements from the tender documents and advises treasury lead”, (2) “treasury lead confirms PBA wording and identifies whether any changes are required”, (3) “Bid manager raises any required changes to type and wording with the client at tender stage”, (4) “type & wording resolution processes commences”, (5) “bid manager communicates the outcome of the tender process to the commercial manager”, (6) “commercial manager sends it to the treasury lead, who approves the PBA and trust deed wording and includes it in the contract’s document pack to be executed”. The PBA contract approval process requires many engagements with many parties revising and exchanging documents over e-mail. The problem with exchanging documents via e-mail is that people can read or approve an outdated version, and someone needs to manage the version control process (i.e., printing, scanning, storing, revising, recirculating, etc.), which creates unnecessary process redundancies. This process could be improved using existing electronic document management systems, such as DocuSign, and the data trust of the system can be enhanced by using blockchain to timestamp signatures, updates, and approvals. The idea of digitising the PBA trust deed was suggested by one interviewee who commented, “Integrating with a DocuSign-type system using smart contracts is an interesting concept.”

6.4.1 Business Logic Improvements

Business logic is any back-end code that improves the proposed application's performance. For example, when a button is pressed in the application's user interface , the business logic processes the request. The findings uncovered several strategies for improving the proposed application's business logic, such as batch processing, offline mode, fail-safe features and object-relational mappers (ORMs). These will be discussed throughout this section.

The problem with using MetaMask (the wallet provider used in the proposed application) is that a popup notification appears on the screen/user interface every time a user sends a transaction. Concerning this, one questionee suggested a solution called "signing agent", which "allows multiple transactions to be batched and signed under one transaction". This was also mentioned by one questionee, who called it something similar, "batch processing", and added that "It enables the application to work in offline mode because transactions can be parsed in the background and sent when back online." This is a critical feature for user accessibility because it enables the proposed application to operate in areas with no/low internet connectivity, such as new-build construction sites.

One questionee pointed out how a fail-safe feature, such as "enabling the application to inform users if their transaction will fail before they send it", is one strategy for mitigating unnecessary transaction fees. How this fail-safe function would work is that an API (application programming interface) would query the balance of the sender on the blockchain, query the codebase of the application's smart contracts, and simulate the transaction in a centralised, cloud-based environment where processing speeds are significantly faster compared to the blockchain; afterwards, if the transaction is successful in the simulated system, then the proposed application would permit the transaction to send on the blockchain. Due to the fast processing speeds of centralised systems, this simulation would take less than a second to process.

One questionee advised, "If the intention is to integrate with centralised relational databases, an ORM should be used." An ORM allows object-oriented data (such as the data in smart contracts) to communicate directly with relational databases without using a structured query language (SQL) system such as PostgreSQL.

6.5 Application Maturity

This section to relates to research question three: “Through analysing the data collection, how mature is the proposed application for commercial adoption in the construction industry?” Analysing the proposed application’s maturity during its early stages of development was challenging because of the vast number of processes, technologies, and configurations still required to progress it. However, this analysis was necessary to understand its stage of maturity. For example, suppose the author is seeking funding to develop the application further; in that case, a clear outline of its readiness for commercial adoption would be crucial information to present. The terms *readiness* and *maturity* are used interchangeably; however, in the context of this research, they are synonymous in definition. Readiness refers to the application’s ability to be commercially adopted, while maturity is its current state across its lifecycle and is not delimited to commercial adoption. However, since the utmost stage on the application readiness level (ARL) scale is commercial adoption, both readiness and maturity are equivalent when discussing the application’s progress. The method used to analyse the proposed application’s readiness was the ARL scale, which was an adaptation of the technology readiness scale by John Mankins (1995, p. 1). The Mankins readiness scale was conceived as a method to measure the technology readiness of spacecraft at NASA (National Aeronautics and Space Administration); therefore, its objectives and end-users are different than developing digital applications for the construction industry; however, its methodology for analysing technology readiness is compatible with construction. Both the Mankins readiness level and the proposed ARL use a nine-point scale, with the primary difference being that stages six to eight on the Mankins scale focus on aerospace testing, while stages six to eight on the ARL scale focus on commercial application testing.

Quantifying the ARL score of the proposed application was as follows: The 23 ARL factors in Table 15 were individually scored from ARL 1 to ARL 9 based on their readiness for commercial adoption. Afterwards, the ARL scores of the 23 factors were summed, and the average ARL score was calculated, equating to a total of 3.09 out of 9, or 34% when expressed as a percentage. This 3.09 is the total ARL score of the application, and 34% is its readiness for commercial adoption. Therefore, substantial work is still required to complete its development. Nevertheless, the research scope was to provide a proof of concept (PoC); therefore, any development beyond this was beyond its scope. A PoC on the ARL scale is 4, and the total score of the application after the data collection was 3.09. This is because 13 of 23 (57%) of the ARL factors were scored at ARL 1 or ARL 2, as shown in Table 16 in Chapter 5: Data and Analysis. The term estimation must be emphasised when declaring the application's total ARL score. This is because only one approach (i.e., the ARL) was used to measure its maturity. Extending the research to include more technical quantitative analysis or parameters of measurement for the ARL would have overburdened the research scope. The research scope already included application development, PoC testing, thematic analysis, and ARL analysis; therefore, a straightforward approach to analysing its maturity via the ARL approach was suitable within the boundaries of the research timeframe.

The ARL factors are dependent on each other in the context that one ARL factor cannot progress in maturity without the help of the other ARL factors. For example, the *systems integration* ARL factor is reliant on the progress of these four ARL factors: (1) *server-side logic*, (2) *user interface*, (3) *oracles and APIs*, and (4) *cybersecurity*. The *systems integration* ARL factor comprises the business process aspect of the application and how the different technology components interact, while the *server-side logic* and *user interface* ARL factors are used to the technical feasibility of the *systems integration* factor (i.e., whether information cannot flow from one component to another and can be displayed informatively on a user interface). Likewise, the *APIs and oracles* ARL factor cannot be built unless the end-point (i.e., the system it connects to) is clarified in the *systems integration* ARL factor. For example, the proposed application used an API to pull data from the blockchain to present it on its user interface. Lastly, the application cannot progress beyond ARL 5 (enterprise pilot) until cybersecurity is appended onto the application. Implementing cybersecurity is beyond the scope of this research to investigate, and it is a specialised skill suited for cybersecurity engineers.

Another example of the dependencies of the ARL factors includes how the *data traceability and permanence*, *privacy*, and *scaling solution* factors are connected to the *blockchain selection* ARL factor. Incorrect choice of the blockchain platform in the early stages of the application's development (i.e., ARL 1 to ARL 3) will impede its progress in the later stages (i.e., ARL 6 onwards). This is because, despite the data immutability claims of blockchain, smaller blockchains, such as Bitcoin Gold, which is an imitation of Bitcoin, have suffered double-spend attacks on numerous occasions, causing hundreds of millions of GBP worth of damages (Lovejoy, 2020). Double-spend is when a cryptocurrency coin is spent twice and logged on the blockchain as validated transactions even though it should have been rejected by the blockchain (Lovejoy, 2020). Therefore, choosing a blockchain with a good reputation for transaction immutability, such as large public blockchains, is critical for the application’s financial security because PBAs are used on large public sector construction projects. At the time of developing the proposed application in 2022, privacy and scaling solutions were a nascent feature of public blockchains, and Ethereum were the frontrunner in this. Therefore, due to the positive reputation of Ethereum and based on the results from *Table 7. Blockchain selection matrix* in *Chapter 4: Conceptual Framework,* Ethereum was selected as the blockchain for the proposed application. The other ARL factors affected by the *blockchain selection* factor comprise *cryptocurrency price stability* and *cryptocurrency regulations*. The blockchain selected for the proposed application must have adequate stablecoin services because the exchange rates of the native cryptocurrencies of public blockchains, such as Ethereum and Bitcoin, are unstable. A stablecoin is a blockchain cryptocurrency pegged at a one-to-one ratio with a standard fiat (government-issued) currency like the USD or GBP. Private blockchains do not have ready-to-use stablecoins at their disposal; therefore, if using a private blockchain, a stablecoin application would need to be built and set up, which requires developing an entirely new application. In contrast, public blockchains are already equipped with stablecoin services. Regarding the *cryptocurrency regulations* ARL factor, the UK Government announced in 2022 that it intended to regulate stablecoins as a means of payment in the UK (HM Treasury, 2022, p. 2), which would have enabled it to be used as legal tender. However, fast forward to 2024, and the UK Government changed its stance on stablecoins, citing that they will regulate it when demand for it increases (HM Treasury, 2024). Therefore, concerning the proposed application, additional application infrastructure, such as integrating the application with a third-party cryptocurrency exchange or stablecoin provider, will be required to facilitate the conversion of stablecoins to fiat currency. Pound Token is the stablecoin provider that the author planned to integrate with because their GBP-T token is a reputable stablecoin in the UK, and the circulation of the GBPT tokens is audited monthly by KPMG (Pound Token, 2023b). However, a review of their services compared to other stablecoin providers is required, and thus, the *cryptocurrency* *regulations* ARL factor was assigned an ARL 1 score because additional research is required.

Using the ARL nine-point scale and compartmentalising the proposed application's components into 23 factors was useful for analysing the application's readiness for commercial adoption. Before the ARL scale was introduced to the research, the author generalised the proposed application as being either in the early, middle, or late stages of development, with the early stage comprising the conceptual framework and proof of concept, the middle stage comprising enterprise pilots, and the late stage comprising commercial prototyping (commercial prototyping is when an application undergoes final testing with end-users to validate it for commercial readiness). The initial view of judging the application as being in the early, middle, or late stages was ambiguous and subjective in contrast to any formal structure. Because of this, the author was influenced by the widely used nine-point technology readiness level scale of John Mankins (1995, p. 1) and adapted it to suit the proposed application.

Compartmentalising the application into ARL factors and scoring them based on the ARL's nine-point scale provided clarity in itemising which factors were the least mature and warrant further development. For example, Table 16 in Chapter 5: *Data and Analysis* identified five ARL factors with a score of 1. Therefore, additional research would be required to investigate these issues further. These five ARL factors are (1) *interoperability with existing PBA systems*, (2) *technology uniqueness*, (3) *cryptocurrency regulations*, (4) *know-your-customer services*, and (5) *wallet security*. The five issues associated with the five abovementioned ARL factors are as follows: (1) The proposed application overlooked the PBA wording approval process, which requires additional research to understand the complexities of this approval process and whether the application should accommodate or descope it. (2) The application attempted to use decentralised cloud storage as its system for storing construction project documents; however, the two focus group interview participants clarified that general cloud storage does not accommodate the commercial complexities of construction contract management and that the application should integrate with CEMAR. The application was designed to interoperate with one software system (i.e., Microsoft Excel) to prove its capability for systems integration. However, this should extend to include construction-specific software that is widely used by construction companies, such as CEMAR. (3) Regarding the *cryptocurrency regulations* ARL factor, at the time of when the proposed application's conceptual framework was being designed in 2021, the author was hopeful that the UK Government would regulate stablecoins as legal tender by time this research reached completion in 2025, however, this regulation is still in progress, and thus additional off-ramp infrastructure would be required to enable the application to convert stablecoins to standard fiat currencies such as GBP. Off-ramping is the ability to withdraw cryptocurrencies from the blockchain and deposit them as fiat in a standard bank account. (4) Regarding the *know-your-customer services* ARL factor, KYC is a service the questionnaire participants indicated must be incorporated in the proposed application, and thus, additional research is required to investigate its feasibility as either part of the application or outsourced to a third-party provider (the topic of KYC was previously discussed in section *6.3.9: Managing Identities* of this chapter). Lastly, (5) concerning the *wallet security* ARL factor, the data collection uncovered that the blockchain wallet used in the proposed application is not secure for enterprise adoption, and thus a blockchain wallet provider with better enterprise security guarantees is mandatory (the topic of wallet security was discussed in greater detail in section *6.3.7: Wallet Security* of this chapter).

7 Conclusion

This chapter summarises the value contribution this research and is organised into the following four sections: (1) *Summary of the Findings,* which provides an overview of the evaluation of the data collection, and includes three subsections dedicated to answering this dissertation's research questions; (2) *Contribution*, which identifies how the research impacts the topical area (i.e., blockchain for cash flow in construction) by addressing the problems identified in current literature and how the this thesis contributes new knowledge; (3) *Research Limitations,* which discusses this dissertation's constraints from the research design and data collection perspective and highlights the proposed application's primary challenges; And, (4) *Further Work,* which provides a guideline for how this research can be progressed and expanded upon in the future.

7.1 Summary of the Findings

This section includes three subsections: (1) *The Framework*, which summarises the primary points of discussion regarding the proposed application's development and analysis; (2) *Organisational Findings*, which provides an overview of the data collection regarding the enterprise considerations for adopting the proposed application, and (3) *Technical Findings*, which highlights the key points of the data collection collected from the blockchains regarding how the proposed application can be improved from a business logic perspective.

7.1.1 The Framework

Research question one, "How can a blockchain application improve the delivery of PBAs through systems integration and process flow automation, and how would end-users interact with the system?" was critical in providing the foundation for investigating the feasibility of blockchain for PBAs from the application perspective. The steps that enabled the development of the proposed PBA blockchain application are discussed at high-level below.

Based on the research investigated in this thesis, no existing academic literature on the topical area of blockchain in construction has provided a suitable theoretical foundation for developing a PBA blockchain application. Therefore, this research sought to investigate the practical feasibility of this by testing it through a proof of concept (PoC). The proposed application's development began with identifying the essential process flows necessary for a PBA blockchain application to operate, of which 12 were identified on Figure 21 in Chapter Four (Conceptual Framework). Afterwards, the decision on which blockchain to choose was made based on comparing seven blockchain platforms across six key parameters, as shown on Table 7 in Chapter Four (Conceptual Framework). These parameters included: (1) Extensive ecosystem of decentralised applications; (2) supports stablecoins; (3) provides high security and data trust; (4) supports smart contracts; (5) supports privacy; and (6) consensus is low in CO2 emissions. Ethereum scored the highest based on those parameters. In 2022, the Ethereum blockchain updated its consensus algorithm from proof-of-work to proof-of-stake, reducing its CO2 footprint by 99.992%, making Ethereum environmentally sustainable (CCRI, 2022). After selecting the blockchain suitable for the proposed application, the next step was to itemise its technology stack. This was organised into four primary technology layers: The data layer, back-end, services, and front-end. Figure 16 in Chapter Four (Conceptual Framework) itemised the technology components within each of these technology layers. After assembling its core components, the functionality and extensibility of smart contracts were examined. Figure 17 in Chapter Four (Conceptual Framework) illustrated how the proposed application's smart contracts were configured to operate like relational databases. This is because, despite terminology ambiguity, smart contracts are not smart and are not contracts. Instead, they operate more similarly to miniature software programs. Relational databases have existed for over 50 years and are the standard method for storing voluminous data in tabular format (Batra, 2018). Thus, converting smart contracts into relational databases and configuring them to execute payments was the key strategy for integrating management flows with cash flows. The proposed application deployed 57 smart contracts. Figure 22 in Chapter Four (Conceptual Framework) compared existing PBA process flows with the proposed application and uncovered that roughly half of the tasks can be automated by using blockchain and smart contracts integrated with a Web application. The cost of deploying the proposed application's smart contracts, executing an estimated 1000 transactions, and Web hosting services totalled £1,643, as shown in Table 8 from Chapter Four (Conceptual Framework). However, the findings revealed that these costs could be reduced significantly by using Ethereum layer two (L2) scaling solutions. The open-source codebase of the proposed application's smart contracts are displayed in Table 14 and

Table 15 in the appendix, along with Web links to where the smart contracts are deployed on Etherscan (Etherscan is a website that provides live updates of Ethereum transactions) to provide proof of successful deployment of the proposed application's smart contracts on the blockchain.

7.1.1.1 Reason for Choosing Ethereum

One of the key reasons for choosing Ethereum was the availability of free resources and codebase templates for users with relatively little coding experience, such as the author, to customise and deploy decentralised applications (dApps). Another key factor for choosing Ethereum was that they supported stablecoins at the commercial adoption level, whereas Hyperledger's stablecoins were still in the proof of concept stage at the time when the author was developing the proposed application circa 2021. The motivation for choosing to settle payments via stablecoin cryptocurrencies is to achieve full payment automation of PBAs. In contrast, using the blockchain for data management but settling payments via standard bank transfers requires the need for a payment processing team, and relies on the bank to settle PBA payments manually. In PBA projects, the bank is required to authorise the release of PBA funds from the PBA to the supply chain. One of the problems with PBAs in the current environment is that they are transaction processing-intensive and thus are only used for settling payments to tier-one project participants and tier-two subcontractors. Extending the use of PBAs to include tier-three and tier-four subcontractors would substantially increase the transaction processing burden of tier-one project participants and the bank because banks have to authorise each PBA payment.

Another factor the author contemplated when deciding between public vs. private blockchain was the potential corporate influence that could jeopardise the future roadmap of construction dApps for construction. The private blockchain Hyperledger is funded by the Linux Foundation, and Hyperledger is financially supported by large technology companies, such as Microsoft, Google, Oracle, and several other large technology companies (Linux Foundation, 2025). Whoever funds a project can directly or indirectly influence, restrict, or capitalise on its development; therefore, the freedom of autonomy is always in question when large corporate entities loom in the background. However, this is a sceptical view of the Linux Foundation and its financial supporters, and it is not supported by evidence. Nevertheless, whether choosing between a public or private blockchain, they both share a commonality with digital public goods (DPGs). A DPG is an open-source and open-licence platform that is built and supported by a collaborative team that allows unrestricted replication, configuration, and dissemination of their work (DHIS2, 2025). DPGs provide a foundation infrastructure for anyone who wants to leverage free technology. Building a series of DPG construction services, whether it be with or without blockchain, would be a valuable contribution to the construction industry.

7.1.2 Organisational Findings

Regarding research question two, (i.e., “From the perspective of construction practitioners experienced in PBAs, what are the potential advantages and disadvantages of using blockchain and smart contracts for managing PBAs?”), the key organisational findings that were collected in the Focus Group Interview section of Chapter Five (Data and Analysis) were as follows: Although blockchain can improve systems integration, process flow automation, data traceability, and cash flow programmability in PBA projects, there are several critical concerns that hamper its adoption in the current environment, such as a lack of interoperability with existing construction software, services for off-ramping cryptocurrencies to traditional banks, legal accountability for disputes that occur over smart contracts faults or cryptocurrency hacks, and the lack of ability to use stablecoins as legal tender in the commercial climate (i.e., paying bills or buying groceries using cryptocurrency-stablecoins). Nevertheless, the organisational findings demonstrated how traditional PBA procedures can be substantially automated in the proposed PBA blockchain application to reduce the workload of managing PBAs in construction projects, as shown on Figure 22 in Chapter Four (Conceptual Framework).

One of the complications of PBAs is that each PBA contract is bespoke, and each construction project can customise the terms and conditions of the PBA, creating PBA contract management complications due to a lack of standardisation. Nevertheless, there are standard paper-based forms that all PBA projects must include, such as the *payment application* and *authorisation statement*. The former is used for cash inflows to the PBA, while the latter is used for cash outflows from the PBA. The proposed application mitigates main contractors from having to fill in and send the *payment application* and *authorisation statement* to payment approval parties because these forms are automated in the proposed application. For example, when a cash-in approval is required by the client, they are sent an automated e-mail that includes a link to the location in the proposed application where the approval signature is required. Similarly, subcontractors in the proposed application are no longer required to submit invoices to their employer because payments are directly linked to cash-in/out authorisation signatures. For example, when a subcontractor’s works are approved by project validators, such as the main contractor validating the percentage of work completed and the project manager (PM) validating the quality of the work, it triggers an automated payment from the blockchain-PBA to the subcontractor. However, invoices serve other purposes besides just a request for payments, and the researcher addressed this by suggesting that standardised documents, such as invoices, could be automatically generated for users to download for storage and archiving. Payment certificates in the proposed application are showcased as wallet signatures rather than official paper-based documents. However, payment certificate documents could also be automatically generated for users to download with the appropriate blockchain approval signatures appended to the document as proof of the certificate’s validity.

Traditional PBAs impose additional workloads on the main contractor, such as adding additional payment approval stages that enable the client to audit all project cash-outs. The client and PM are mandated to approve all cash-ins and cash-outs to and from the PBA. In contrast, in standard, non-PBA projects, the contractor has full autonomy to spend project funds without supervision from the client. The client in PBA projects benefits from cash flow transparency and can exercise pay-less notices to save on unspent project funds that would typically go to the contractor as extra profit. In contrast, contractors are at a disadvantage using PBAs because it increases their management workload. Therefore, the PoC investigated how to reduce the burden of PBAs on main contractors, potentially resulting in improved democratisation of PBAs across the lower-tier supply chain.

Research shows that existing construction processes lack traceability and that use of a blockchain could provide a solution for autonomously storing an accurate record trail of events, such as logging and timestamping payment approval stages and certificate awarding. Furthermore, blockchain simplifies the process of transaction reconciliation because it maintains a single source of truth. For example, if a payer and payee disagree regarding the sum of liabilities paid, the transaction and its metadata can be queried instantly on the blockchain. The metadata would store any project and contract references, payment codes, and any parties involved in the transaction's approval process. One of the problems with PBAs is that banks typically only store cash flow records for six to twelve months. After that timescale, the PBA's trustees are responsible for its storage. Technically, the bank still holds the transaction records, but they archive them and disconnect them from their central system. In contrast, blockchain transactions are permanently stored on the blockchain ledger without timescale limitations and can be queried at any time, mitigating the responsibility of manual transaction storage and reconciliation for all project participants.

Systems integration and data trust are significant problems in construction. For example, data from scheduling, contract management, and payment software are challenging to integrate due to technology siloing. This is compounded further by a lack of assurance and traceability that data was not manipulated or overwritten as it passes from one software to another. When data is inserted, updated, or removed from a smart contract, including data pushed via APIs (application programming interfaces) from centralised software, the data flow is timestamped and permanently recorded on the blockchain. Some spreadsheet software, such as Microsoft Excel, include add-in capabilities for pushing data to Web applications (Hiron-Grimes, 2017). Since the proposed application is a Web application connected to smart contracts, data can indirectly flow from Microsoft Excel to the blockchain. However, for more technical systems, such as ERP (enterprise resource planning) software, APIs would be required to pull or push data to and from decentralised applications. To fully automate data to the blockchain, blockchain oracles, which are blockchain APIs, would be required to pull data from the real world and push it to the blockchain. The data immutability of blockchains provides a reliable foundation for displaying project information on analytics dashboards. For example, project performance reports could stream in real-time based on the data flows to and from the proposed application, and project participants could query transaction details at any time using a lookup tool that scans events on the blockchain. Therefore, company executives or any project leads would not need to wait for the publication of end-of-month reports to view the performance of a project, and the data from the analytics dashboards would include high traceability and reliability since it is stored on a blockchain ledger.

Stablecoins, a type of cryptocurrency token that pegs fiat currency (GBP, USD, etc.) at a one-to-one ratio, were discussed several times in the findings as a crucial component to mitigate the price fluctuations of cryptocurrencies such as Ether. The only reason the proposed application did not implement stablecoins is that the application was deployed on Ethereum-Goerli, a test network that does not accommodate stablecoins. Nevertheless, if the proposed application were deployed on the Ethereum main network, stablecoins would be its default currency. Test networks replicate the functionalities of the Ethereum main network without incurring transaction fees; otherwise, the researcher would have spent thousands of GBP in Ethereum network fees. Pound Token is an example of a regulated GBP stablecoin audited by KPMG (Pound Token, 2023a). One of the downsides of stablecoins is that they have not been approved as legal tender and thus cannot be used in standard commercial environments. Nevertheless, the bill for approving stablecoins as legal tender in the UK is under consideration by the UK Parliament (as mentioned by one of the focus group participants). Approving the stablecoin bill would allow stablecoins to be used as commercial money. Until then, the biggest challenge with stablecoins is off-ramping them from the blockchain to traditional banks. Due to blockchain being high-risk in the context of regulation, many banks do not accept deposits from stablecoin providers due to anti-money laundering (AML) uncertainties. Nevertheless, if the abovementioned stablecoin bill is approved, it would mitigate having to use banks for checking accounts, and users would be able to pay for goods directly from their blockchain wallets. PayPal announced in July 2023 that they now offer the Ethereum PY-USD (PayPal USD) stablecoin to customers and that customers can exchange fiat for PY-USD and vice versa on PayPal (PayPal, 2023). An alternative to stablecoins is CBDCs (central bank digital currencies). CBDCs are cryptocurrencies minted and issued by a country’s central bank (Bank Of England, 2021, p. 6). However, they are predominantly in the proof-of-concept stage and not mature for widespread adoption. Nevertheless, the leverage CBDCs have is that they are a governmental initiative; thus, they would not face the same regulatory pushback as all other cryptocurrency assets or services. Even though banks generally have an aversion to doing business with blockchain service providers, it does not mean they are against blockchain. For example, several banks, such as J.P. Morgan and Bank of America, use an internal private blockchain to reduce auditing and reconciliation costs across many bank branches (Ullah et al., 2022).

Construction companies have configured their standard workflows to accommodate traditional PBAs. Changing this to include a blockchain-based PBA will require altering existing systems and retraining staff on the new method. Furthermore, public-sector clients already have a PBA Web application that integrates with the bank's payment terminal management system (TMS) for executing liabilities. Nevertheless, that application's user interface can be redirected to smart contracts instead of the bank's TMS, as Web applications are simply user interfaces with customisable API (application programming interfaces) endpoints. Some of the challenges of hosting PBAs with banks include: (1) Paymasters, such as the client, project manager, and main contractor, cannot directly execute payments from the PBA; instead, they must send an authorisation statement instructing the bank to execute liabilities to subcontractors; and (2) banks take several weeks to set up the PBA once they are handed a fully signed trust deed, which increases project delay risks. The PoC demonstrated how paymasters can execute PBA payments directly from the proposed application (due to the programmability of smart contracts), and the PBA blockchain smart contract can be deployed within a day. In contrast, the banks take several weeks to deploy a traditional PBA. The findings revealed that the UK Government disallows banks from offering other financial products (i.e., loans) to PBAs because it increases the government's national debt due to interest repayments. Therefore, escrows (in the form of PBAs) are the primary service banks offer PBA projects. Nevertheless, the UK Government is considering extending PBAs to include private-sector projects, which would allow banks to offer loans to private-sector PBAs.

7.1.3 Technical Findings

This section covers research question three (i.e., "By collecting data from blockchain engineers experienced in developing decentralised applications, what are the technical concerns for using the proposed application in the commercial environment?"). That question was answered by highlighting the open technology aspects of blockchain and how it provides low-cost technology infrastructure that construction companies can leverage to test new services. Another key point that was uncovered in Chapter Five (Data and Analysis) was the practical considerations for how new companies adopting the proposed PBA blockchain application would need to substantially restructure their internal workflows, and the resource (time and money) implications of transitioning from a centralised to a decentralised system. Other points of deliberation from the questionnaire respondents included privacy and scaling solutions for public blockchains that enable private transactions and make transaction fees negligible, know-your-customer (KYC) verification solutions, and business logic recommendations for improving the proposed application's technical functionalities.

Centralised accounting software companies are already bridging their services with the blockchain to leverage its data trust capabilities. One of the areas in which centralised companies can benefit from blockchain and decentralised applications (dApps) is leveraging their open-source codebase to copy, modify, and redistribute the technology without copyright issues. Most dApps provide their code open-source, as open-source software proliferates faster than closed-source and because closed-source lacks data trust due to a lack of codebase transparency. Some dApps extend the open-source and open-license aspect of blockchain further by white-labelling their technology. From the perspective of blockchain, a white-label dApp is when the codebase and functionality of one dApp can be copied and redeployed as a new dApp (under a different name) without making any changes to it. For example, the proposed application can leverage an existing white-label dApp by copying its back-end (i.e., smart contract codebase) and deploying it in a new application without having to write any new code.

Despite blockchain's reputation for traceability, it lacks traceability in being able to identify malicious actors who have committed cryptocurrency theft, because, by default, all wallet addresses on the blockchain are owned by anonymous users. Nevertheless, this problem was addressed by several blockchain wallet application providers. For example, the Qredo cryptocurrency wallet application provides users with insurance coverage up to £470 million for any theft-related hacks that occur while using a Qredo wallet (as mentioned by one respondent in the focus group interview).

All activities performed through the proposed application are logged on the blockchain as transactions. These transactions can be financial (i.e., payments) or non-financial (i.e., data entries or approval signatures). In contrast, management software and banking applications cannot interoperate unless complex and costly application programming interfaces are built to bridge the two landscapes. Bridges such as these can cost hundreds of thousands to initiate, and the infrastructure would be bespoke and only serve one particular function. Additionally, the intellectual property of that infrastructure would be owned by a centralised technology provider that can charge high proprietary and maintenance fees. The difference between the economic structure of blockchain-based systems vs. centralised technology companies is that the former provides cost-free and open-source technology infrastructure but no customer support, whereas the latter provides costly and closed-source infrastructure but prioritises customer support as fundamental to its services. Therefore, if a construction company is looking to explore and test blockchain solutions, hiring a blockchain expert internally or outsourcing a blockchain consultant is crucial for providing general feedback and technical support. An alternative is outsourcing blockchain-as-a-service from technology companies, such as Amazon or IBM; however, these services are centralised, defeating the original purpose of using blockchain for decentralisation. Another critical feature of blockchain is that decentralised applications keep 100% of the revenue generated from their application. In contrast, centralised technology platforms charge up to 30% commission on revenue made through their services (Google, 2023). Other resource considerations for companies adopting blockchain include whether they are prepared to (1) restructure internal workflows, (2) retrain staff on how to use it securely, and (3) willing to fund its management and operations long-term, such as hiring or outsourcing blockchain experts over many years.

Scaling (i.e., throughput) and privacy can be achieved on Ethereum layer two (L2). Polygon is a popular L2 scaling solution that can reduce transaction fees by a factor of 10,000. For example, a typical transaction fee of £10 would be reduced to £0.001. Furthermore, redeploying all the proposed application's smart contracts on Polygon would reduce its deployment fees to £0.15, making network fees on Ethereum negligible. L2 is also used for achieving private transactions through systems such as zero-knowledge proofs (ZKPs), which enable transactions to be stored on the blockchain encrypted, with only the transacting parties able to decrypt it. Another method for achieving privacy that is not reliant on L2 is using the stealth address (SA) protocol. Each blockchain wallet address can produce an unlimited number of SAs, which are sub-addresses that are cryptographically connected and controlled by the primary wallet address they are connected to. The term "stealth" is used because, by default, only the payer and payee would know who the owner of the SA is. When a user wants to withdraw funds from their SA, they send the SA's funds to an exchange;

afterwards, they will transfer the funds from the exchange to their primary wallet, thereby achieving privacy. Exchanges do not disclose the provenance of transactions; thus, there would be no possibility for any external party to link the SAs to the recipient's primary wallet. Since private transactions can be achieved on public blockchains, using a private blockchain just for private transactions is unnecessary.

Blockchain wallets and smart contracts have multi-party functionalities that enable numerous users to share the permission required to send a transaction from a multi-party wallet. For example, a multi-signature wallet or smart contract can be designed to execute payments when a predefined number of payment approvers sign for it. The most sophisticated type of multi-signature wallet is a multi-party computation (MPC) wallet, synonymously threshold wallet. MPCs give users greater flexibility to control their parameters/conditions, and transaction fees cost less than standard multi-signature wallets. A third-party provider such as MetaMask was used for the proposed application's wallets; however, the findings suggest that MetaMask lacks proof that their wallets are secure enough for enterprise adoption. For example, since MetaMask is a Web browser application, it collects data on user activity. Therefore, leveraging a more secure wallet decentralised application catered for enterprises is recommended.

Wallet precautions such as know your customer (KYC) verification and whitelisting were highlighted as critical features the proposed application should include. KYC verifies that a user's wallet address is owned by a real identity, whereas whitelisting is when an organisation, such as a main contractor, creates a list of wallets/accounts that they deem safe for transacting with. Centralised and decentralised entities can offer KYC services, which typically include a combination of biometric authentication, QR code scanning that links devices to blockchain wallets, and user private-key signatures that prove that the particular user controls a specific wallet. Regarding whitelisting, the proposed application achieves this by enabling users to sign the PBA trust deed with their blockchain wallets. When a user's wallet address is registered in the PBA trust deed smart contract, it grants them permission to send or receive payments from the blockchain PBA.

Lastly, the primary business logic recommendations suggested by the questionees include (1) batch processing and (2) fail-safe functionalities. Batch processing enables multiple transactions to be clustered and signed under one transaction. It also allows the application to operate offline because transactions can be signed offline and autonomously pushed to the blockchain when back online. Fail-safe functionality is when the proposed application autonomously notifies users if transactions will fail before they send it, saving users from paying fees for transactions that will fail.

7.2 Contribution

The researcher's contribution to academic publications includes (1) "Exploratory literature review of blockchain in the construction industry", which explored 33 application categories of blockchain within the topical area, and (2) "Conceptual model utilising blockchain to automate PBA payments in the construction industry", which proposed a PBA blockchain framework and provided the foundation for developing the proposed application in this thesis (Scott et al., 2021, 2022b). The idea of using blockchain for PBAs did not originate from the researcher. A 2019 academic publication collected interview data from senior construction practitioners' knowledge of PBAs, which concluded that the programmability of smart contracts could be leveraged to automate payments in PBA projects; however, this was only discussed hypothetically (Li et al., 2019). Another paper in 2021 explored the viability of using blockchain for PBAs and deployed a test application that managed PBA payments with smart contracts (Tezel et al., 2021). However, three key gaps were identified in that literature: (1) it did not consider how various payment authorisers would interact with the system to conduct various types of approvals, such as the main contractor approving the percentage of works complete and the PM approving the quality of works; (2) it was not reflective of how PBA obligates the use of a trust deed and that all payment approvers or recipients must be signatories of this deed; and (3) it lacked general user interface functionality from the perspective of managers having the ability to insert or update smart contract data to accommodate change orders. The proposed application addressed point one by customising its smart contracts to accommodate multi-stage payment approvals by the client, PM, main contractor, and quantity surveyor. Point two was addressed by deploying a PBA trust deed smart contract that integrates with the proposed application's cash-in/out tables. For example, when a participant signs the trust deed smart contract, it grants them permission to send or receive through the proposed application. Point three was achieved because the proposed application provided a graphical user interface (i.e., a Web application) that mimics management software and enables non-technical users to interact with smart contracts to insert, update, and approve PBA payment schedule data.

The inspiration for integrating management flows with cash flows came from a paper demonstrating how management software and smart contracts can integrate to automate payments (Hamledari & Fischer, 2021c). However, their codebase was not open-source; therefore, their innovation could not be externally replicated or verified. Similarly, integrating spreadsheet software with smart contracts was inspired by a paper by (Ahmadisheykhsarmast & Sonmez, 2020), who demonstrated how data can be exported from scheduling software and imported into smart contracts using a spreadsheet plugin. Likewise, Microsoft Excel has inbuilt add-in capabilities that enable users to push data from an Excel spreadsheet to Web applications (Hiron-Grimes, 2017). Since the proposed application is a Web application, interoperating smart contracts with spreadsheets via a Web application requires little to no middleware (middleware is software that bridges two systems together). Lastly, the proposed application implemented retentions into its framework, which was inspired by a paper by (Elghaish et al., 2022), who showcased using smart contracts to manage the defects liability period of construction projects at the closeout stage (Elghaish et al., 2022).

The proposed application’s smart contracts include relational database functionalities that reduce process redundancies and improve data synchronicity. For example, if the main contractor updates the payment schedule logged in one of the project’s smart contracts, users affected by the update would receive an automated e-mail alerting them of the change. Furthermore, due to the relational properties of the smart contracts deployed in the proposed application, all project participants would be guaranteed that project data is synchronised with all supply chain participants.

Literature suggests that blockchain in construction overlaps with three dimensions: Socio-technical, process (e.g., construction workflows), and policy (e.g., governmental legislation) (Li et al., 2019). The socio-technical and process dimensions were addressed by demonstrating how the programmability of smart contracts can be configured to integrate management flows and cash flow to improve PBA delivery through process flow automation. The policy dimension was addressed by adopting the UK Government’s PBA strategy as the foundation layer of its functionality to ensure it reflects government guidelines. For example, PBA mandates using a trustee system to delimit cash flow between verified parties and implementing multi-stage payment approvals, which are features addressed and incorporated in the proposed application.

7.3 Practical Implications

The application readiness level (ARL) examined in Chapter 5: Data and Analysis, Section 5.3 Application Readiness Level was used to analyse the proposed application's maturity. This created a more structured approach for analysing and estimating the application's readiness for commercial adoption. Compartmentalising the application's analysis into ARL factors and scoring them individually allowed for fewer biases when analysing the application's overall ARL score. The subthemes created in the data collection's thematic analysis provided a suitable approach for categorising the ARL's key factors, of which 23 of the 27 subthemes from the thematic analysis were converted into ARL factors that determine the proposed application's total ARL score. Assigning each ARL factor an individual ARL score enabled better clarity in itemising the underdeveloped factors of the application. For example, Table 16 in Chapter 5: Data and Analysis displayed five ARL factors with an ARL score of 1, these are (1) interoperability with existing PBA systems, (2) technology uniqueness, (3) cryptocurrency regulations, (4) know-your-customer services, and (5) wallet security. These are the areas that would require immediate attention if planning to develop the application post-research. The overall ARL score of the proposed application equated to 3.09 out of a maximum score of 9, which is 34% ready for commercial adoption when translated as a percentage.

The solutions for the two major gaps identified in the literature review have strong practical implications for improving the commercial viability of using blockchain smart contracts (SCs) for payments in the commercial environment; therefore, they will be briefly discussed below. The first research gap is that the immutable code of blockchain SCs poses a barrier to the changing nature of construction contracts, namely the immutable, hard-coded conditions of SC cannot be changed to accommodate construction change orders. The second research gap was that there was a lack of proof, based on the findings from the literature review, that payment schedules, approvals, and executions could be integrated into one system. Concerning the first research gap, one of the problems with redeploying SCs to accommodate change orders is the SC auditing costs associated with it. Auditing a SC can cost over £12,000 each, and any SC deployed for commercial use needs to be audited by a blockchain engineer to ensure its code is cybersecurity safe (Hedera Hashgraph, 2025). Change orders occur frequently in construction projects; therefore, the high SC auditing cost associated with them is not feasible for the construction industry to absorb. Chapter 6: Discussion, Section 6.2 Discussing the Framework discoursed how the proof of concept in this research proposed and validated a solution that enables SCs to adapt to change orders without the SCs needing redeployment. Regarding the second research gap, Chapter 2: Literature Review, Section 2.6: Related Works reviewed 13 academic publications that built and tested blockchain applications for managing payments. In those examples, none managed to integrate payment schedules, approvals, and executions into one system. The proposed application addressed this gap to increase the practical viability of using SCs to improve payment automation in construction. The solution for this is discussed in Section 6.2 Discussing the Framework.

Regarding the solutions for the two research gaps identified, namely (1) configuring smart contracts to accommodate change orders, and (2) integrating payment schedules, approvals, and executions in one system; and the application readiness level (ARL) evaluation, all contributed to increasing the practical adoption potential of using blockchain SCs to increase payment automation in construction. The results from the ARL evaluation suggest that the proposed application is 34% ready for commercial adoption. This aligns with the scope of the research in testing a proof of concept, and the next immediate steps towards continuing the progress of this research are itemised in Section Chapter 7.5: Further Work, Subsection 7.5.1: Continuing Development.

7.4 Research Limitations

Although a more extended research period is more beneficial for design science research, longitudinal research was not feasible due to the four-year time constraint of this research. Because of this, data was only collected on two occasions, one from interviewees and the other from questionees. The nature of the data collection was also qualitative, and all the questions asked to the study participants were open-ended; thus, the responses covered a wide range of topics, which has limitations, such as a lack of consensus in the results. Consensus with the focus group was more apparent because they were all on the same call and engaged in discussions with the researcher and amongst themselves. However, only four participants participated in the focus group; thus, generalisations could not be realised due to the small sample. Nevertheless, there were some areas that the interviewees strongly agreed upon, such as the need for better interoperability between current systems and blockchain systems, and removing payment guarantee processes from the proposed application since banks already have their own established systems for administering finance. Although the questionnaire included 38 responses, its questions were also open-ended because of the exploratory nature of the questions, which were aimed at extracting key technical insights regarding the viability of the proposed application in the construction enterprise landscape. Since the questionnaire respondents were experts in the field of blockchain and the questionnaire's purpose was to extract general feedback regarding the technical aspects of blockchain application development, an open-ended question format was more beneficial for the questionnaire. Since the proposed application is in its early developmental stage, an exploratory vs descriptive or confirmatory approach was deemed a more suitable strategy for the data collection.

The proposed application covered the primary tasks associated with PBA processes, such as payment approvals and executions. However, many processes were overlooked, such as the wording approval process of setting up the PBA’s terms and conditions, interim valuations, and linking approval certificate signatures to standard construction documents.

Integrating the proposed application with decentralised finance (DeFi) protocols to automate cryptocurrency to fiat conversions was also not investigated. Instead, subcontractors are required to navigate the DeFi landscape to exchange their cryptocurrency for fiat and then deposit the fiat in a commercial bank. However, banks have an aversion to accepting deposits from cryptocurrency companies because cryptocurrencies are considered high risk under anti-money laundering regulations; thus, the proposed application does not have a frictionless solution for off-ramping cryptocurrencies to standard bank accounts. Nevertheless, one interviewee mentioned: “The bill for regulating stablecoins is currently with the House of Lords”. The UK House of Lords is part of the UK parliament and is where governmental legislation is reviewed. Approving the stablecoin bill would mitigate the off-ramping problem because users would no longer need to exchange stablecoins for fiat. Instead, users could use their blockchain wallets to pay for commercial goods.

The design science research (DSR) method was used to provide structure to this research's proof of concept (PoC). DSR typically incorporates many stages of data collection (Collatto et al., 2018). However, only two stages of data collection were used in this research (i.e., the focus group interview, and the questionnaire), which limited the effectiveness of DSR as a research methodology. Nevertheless, when the author was balancing the scope of this research, which incorporated the design and development of a PBA blockchain application, PoC testing, two data collection stages, thematic analysis, and application readiness analysis. The author made a rational decision to focus on quality rather than quantity, which meant sacrificing the quantity of DSR data collection stages for increased research efficacy. Retrospectively, the author was satisfied with this decision because the completion of the research thesis and all of its contents extended beyond the four-year full-time research programme.

The proposed application's total application readiness level (ARL) score is calculated as follows: the sum of all 23 ARL factors is calculated and then divided by 23 to equal the average ARL score of the application. The problem with this calculation approach is that the result is an estimated value and does not represent the application's actual maturity. Similar to how a construction project's estimated cost is different to its planned or actual cost. Therefore, the application's ARL score is reserved for informative rather than confirmatory purposes. The author perceives one scenario where the ARL scoring method returns impartial results. For example, in the unlikely event that 22 of 23 ARL factors are scored at 9 while one ARL factor is scored at 1, the average ARL score of the application would equate to 8.7. Stating that the application's maturity is at 8.7 on the ARL scale would indicate that it is close to commercial adoption. However, it would be highly improbable for the application to be close to adoption if one of its ARL factors were scored as low as 1. Nevertheless, this example (i.e., where 22 factors are scored at 9 and one is scored at 1) would be highly unlikely to ever occur because of the relationship of the ARL factors with each other. For example, in a realistic application development environment, if one of the ARL factors, such as *cybersecurity*, remained at ARL 1, the team developing the application would not waste resources continually advancing the other ARL factors. Therefore, in most cases, the method for calculating the application's ARL, as is done in this research, is suitable as an estimation.

7.5 Further work

The proposed application's proof of concept (PoC) included two data collection stages: (1) a focus group interview and (2) a questionnaire. Further work comprises appending the changes highlighted in the Improvement Proposals section of Chapter Six (Discussion) and collecting a third round of data to verify the findings. Reusing the focus group interview participants for the third round of data collection is a potential approach because of the constructive feedback attained so far from the interviewees and their familiarity with the project. Alternatively, although a questionnaire was suitable for technical data collection (as opposed to the organisational data collected from the interviewees), a more action research approach, such as working directly with blockchain developers, would be more beneficial for formalising the application for enterprise adoption. After that, the research could progress onto an enterprise pilot by testing it with a construction company. A main contractor would be the preferred candidate for the pilot as they are responsible for setting up and managing PBAs. Reasons a contractor may reject the request include resource constraints (i.e., lack of time, money, or skilled talent), low perceived return on investment, or a fear that it may increase their management workload. Alternatively, piloting directly with a public sector client also has benefits because they have greater authority and influence over the supply chain for testing new systems. For example, one interviewee stated earlier that they are willing to "test and use whatever system is pushed onto us by our client."

Due to the research's exploratory approach, a qualitative multi-method strategy was used for data collection. However, as the PoC becomes more formalised, quantitative data collection can be introduced to measure the potential time or cost savings of the proposed PBA application versus traditional PBAs. For example, as previously mentioned by one interviewee: "In a typical large project, ten people, on average, spend two full days per week answering queries related to schedules, orders, and payments." Time is a more reliable and universal unit of measurement than cost; therefore, time savings would be a practical next step for measuring the proposed application's efficiency. From the perspective of a company executive considering piloting the proposed application, time savings translates to cost savings, and a cost-benefit analysis could be used to calculate whether the proposed application warrants resource investment.

7.5.1 Continuing Development

Table 16, titled *Application readiness level (ARL) factors in ascending order of ARL score* in Chapter 5: *Data and Analysis*, displayed five ARL factors with an ARL score of 1. These ARL factors are *(1) interoperability with existing PBA systems, (2) technology uniqueness, (3) cryptocurrency regulations, (4) know-your-customer services, and (5) wallet security.* In particular, the issues within these five factors are as follows:

(1) This research uncovered that National Highways, a UK public sector client and the biggest user of PBAs, uses a PBA terminal management system (TMS) for managing and sending PBA payments. An investigation is required on the functionalities of this TMS and whether it could benefit from increased cash flow automation using blockchain smart contracts. Alternatively, whether the user interface (UI) of the TMS can be used as the UI of the proposed application while using blockchain and smart contracts as its back-end.

(2) PBA contracts are similar to construction contracts in that they are unique and bespoke for each project, which creates complications in the business logic aspects of the proposed application because greater customisations would be required to accommodate these bespoke PBA functionalities.

(3) Despite the UK Government's stating in 2022 that it will be regulating stablecoins as a form of retail payment (HM Treasury, 2022, p. 2), they clarified in 2024 that, due to reduced retail demand for it, stablecoins have not yet been approved as legal tender but are still open for consideration when the financial market is ready for it (HM Treasury, 2024). Therefore, additional research and development are required to strategize how to bridge cryptocurrency stablecoins with traditional finance. The current approach for converting stablecoins to fiat is with online cryptocurrency exchanges; however, from a cybersecurity and practical perspective, this is not a viable solution for construction companies. For example, subcontractors cannot be expected to have to log in to online exchanges to convert their stablecoins for fiat currency. Therefore, additional application infrastructure is required to mitigate this.

(4) The proposed application overlooked know-your-customer (KYC) services entirely. When operating in the traditional finance landscape where users receive payments via their bank accounts, banks are the ones that conduct the KYC checks on account holders (Chai et al., 2020). In the blockchain space, there is no central authority that can verify the identity of blockchain wallet holders. However, the research uncovered that there are centralised and decentralised solutions already available on the market that provide KYC services for blockchain wallets, and thus, this area requires further investigation.

(5) Finally, the questionnaire respondents highlighted that the blockchain wallet provider used in the proposed application (i.e., Metamask) is inadequate for enterprise adoption and that an alternative wallet provider, one that provides satisfactory security for enterprises, is required. Therefore, additional research on blockchain wallets suitable for enterprises is essential for the application's progression.

Personal Reflection

Inevitably, as ambitious as researchers are in trying to achieve objectivity, we are all motivated by subjective, internal factors that underpin the reason why we do research. The author is an advocate for free information sharing, whether it be from the perspective of open-access research, open-source technology, or open standards. Blockchain, being entirely open-source and operating in a free information-sharing environment, is a unique approach to providing technology systems that are not under the authority of corporate influence. However, corporate technology is not the adversary. The author simply believes that a wider variety of technologies should be available that provide an economical alternative to the current technology landscape in which we operate. Many large corporate technology companies invest a small portion of their resources in open-source technologies. However, the blockchain ecosystem operates entirely on open-source and unrestricted information exchange. This openness to free information sharing provides economic opportunities for common pool resources. In particular, whether construction could benefit from a foundation infrastructure of technology services that is free and accessible to all.

Many individuals in the blockchain ecosystem have an aversion to centralised power. Even when this power is held with themself, they design systems that reduce their influence over the network. This is a stark comparison to typical centralised entities that seek to increase power in themselves (e.g., wealth, status, reputation) and in the organization they operate. During this research, the author read a book by Vitalik Buterin (the founder of the Ethereum blockchain), titled Proof of Stake: The Making of Ethereum and the Philosophy of Blockchains. In that book, he discussed an algorithm he created called quadratic voting. Quadratic voting delimits the voting rights of people in the blockchain network so users with voluminous cryptocurrency holdings cannot use wealth to influence the network. For example, someone with one million cryptocurrency coins versus someone with 10 cryptocurrency coins would have relatively similar voting power on the blockchain. One of the largest coin holders in Ethereum, Vitalik Buterin, designed the quadratic voting algorithm to reduce the power that large coin holders, such as himself, have on the blockchain. This also reduces capitalist influence over the network because mass wealth does not translate to mass voting power. Vitalik believed that democratisation and decentralisation were more important for technology than the centralised concentration of power. The early blockchain community (i.e., around 2009, when Bitcoin was launched) and the core developers of Ethereum, were influenced by an activist movement in the 1980s called the cypherpunks. The cypherpunks believe in individual freedom, open-source software, and free information sharing. They were a rebellious movement against large corporate technology companies and thus many in the public blockchain space have an aversion to working with corporate tech. When the private blockchain Hyperledger was invented by the Linux Foundation in 2015, many in the public blockchain space saw this as an encroachment of corporate tech to the values of the cypherpunk movement. The values of the cypherpunks, such as free information sharing and technology freedom, resonate with the values of digital public goods (DPGs). A good example of a DPG is DHIS2 (District Health Information Software, version 2) by Oslo University in Norway. According to the DHIS2 website, "DHIS2 is an open-source software platform developed and implemented by the HISP network, a global collaboration between by the HISP Centre at the University of Oslo and local HISP groups in Africa, Asia, the Middle East, and the Americas. HISP's work with local stakeholders over 30+ years has supported the adoption of DHIS2 as a locally-owned information system in more than 80 countries" (DHIS2, 2025). Currently, eight blockchain applications are registered with the Digital Public Goods Alliance (2024). Blockchain platforms share overlapping characteristics with DPGs because of their open-source and open-licence properties. The author hypothesises that the construction industry would benefit from DPGs because of the low profit margins that construction companies have for investing in innovation. When cost is the major factor that prevents construction companies from leveraging the benefits of technology, construction DPGs should step in to provide that support. The properties of blockchain naturally align with the values of DPGs, and thus the author saw this as an opportunity to investigate its practical feasibility from the blockchain application perspective.

Glossary

Table 18.
Glossary of terms used

Term	Description
Anti-money laundering (AML)	AML is a regulation that prevents financial systems, people, and organisations from laundering money.
Application programming Interface (API)	API is a software tool that allows various software, applications, and systems to communicate.
Application readiness level (ARL)	ARL is the method the author used to measure the maturity of the proposed application.
Blockchain - public	A public Blockchain is a decentralised platform and ledger system. Anyone can transact on it, and it is also a public computer that anyone can use to deploy decentralised applications.
Blockchain - private	A private blockchain is a decentralised platform and ledger system. It allows enterprises to set up a private blockchain between themselves that is invite-only. Privacy is its main selling point.
Building information modelling (BIM)	BIM is a collaborative process for creating and managing information about a built asset throughout its lifecycle from planning, design, construction, operations, and decommissioning.
BuildingSmart	BuildingSmart is an organisation whose aim is to improve information exchange in BIM and the construction industry.
Contract Event Management And Reporting (CEMAR) software.	CEMAR is a software designed for contract management, particularly for NEC (New Engineering Contract) and FIDIC (International Federation of Consulting Engineers) contracts.
Centralised finance (CeFi)	CeFi is the category for cryptocurrency-related financial services companies that offer buying, selling, lending, borrowing, and withdrawal services.
Copyleft	Copyleft is a licencing method that grants people the freedom to use, modify, and redistribute a piece of work with no legal consequences.
Cryptocurrency	A form of currency that is native to the blockchain.
Decentralised application (DApp)	Dapps are Web applications that use decentralised technologies, such as blockchain, as their infrastructure.
Decentralised autonomous organisation (DAO)	A DAO is a type of organization structure built on the blockchain, where decisions are made collectively by members through voting and smart contracts, without the need for a central authority.
Decentralised Finance (DeFi)	DeFi is the financial service of the blockchain. It aims to replicate the services of traditional banks but in a decentralised environment.
Decentralised identifier (DID)	DID is a service that allows people to prove their identity and verify the identity of other people on the blockchain to allow them to conduct business with each other.

Defects liability period (DLP)	DLP is a standard procedure in construction contracts that allows the client to withhold payments to insure against the defects at the project closeout stage (Davey et al., 2006).
Design science research (DSR)	DSR is a research method strategy that follows a six-stage process for developing solutions: (1) identify, (2) define, (3) design, (4) demonstrate, (5) evaluate, and (6) communicate (Peffers et al., 2007).
Digital public goods (DPG)	DPGs are open-source software, open standards, open data, and open content collections that are not owned by companies and are instead designed for the public and for anyone to utilise.
Enterprise resource planning(ERP)	ERP refers to a type of software that integrates and centralizes an organization's resources, data, and operations across various departments.
Ethereum	Ethereum is the second-largest public blockchain platform (based on market capitalisation).
Ethereum Goerli	Ethereum has several test networks, such as Goerli, for deploying test applications.
Ethereum layer two (L2)	Ethereum L2 is a scaling solution that increases the throughput of transactions on Ethereum, allowing for substantially cheaper transaction fees.
Ethereum L2: Polygon	Polygon is one of several L2s for Ethereum. Polygon can reduce blockchain transaction fees to negligible sums. For example, an Ethereum transaction fee of £20 can be reduced to £0.002 on Polygon (Besancon et al., 2022).
Industry Foundation Class (IFC)	IFC is an open-standard file format that allows users to transfer BIM data between various software.
Integrated project delivery (IPD)	IDP is a collaboration approach where a construction project uses a shared risk and reward contract to improve collaboration (Elghaish et al., 2020).
International Standards Organisation (ISO)	ISO is an independent, non-governmental international organization that develops and publishes standards for various industries.
Interplanetary File System (IPFS)	IPFS is a decentralised cloud storage system for decentralised applications.
Know-your-customer (KYC)	KYC is an identity verification process that institutions and companies use to validate the identity of users on their systems.
Multi-party computation (MPC)	MPC is used for blockchain wallet security, where multiple users share a blockchain wallet and multiple signatures from those users are required to send a transaction from the shared wallet.
Multi-signature	Multi-signature is when signatures from multiple blockchain wallets are required to send a transaction in a smart contract.
Non-fungible token (NFT)	NFT is a type of cryptocurrency that is cryptographically unique in the context that only one version of each NFT can exist and it cannot be duplicated.

Object-relational mapper (ORM)	ORMs allow the data in object-oriented programming languages, such as Javascript, to function like relational databases.
Blockchain oracle	A blockchain oracle is an API for blockchain platforms. For example, a software application can be designed to automatically send data to the blockchain through an oracle.
Project bank account (PBA)	A PBA is a form of escrow account used to store a construction project's funds. The PBA is controlled by signatories of the PBA trust deed.
PBA trust deed	A PBA trust deed includes a list of payment approvers and recipients. Only people listed in the PBA trust deed can send or receive funds from the PBA.
Proof of concept (PoC)	A PoC is one of several milestone steps for testing and proving the feasibility of a solution.
Proof of stake (PoS)	PoS is a consensus algorithm public blockchain platforms use to verify transactions.
Proof of work (PoW)	PoS is a consensus algorithm public blockchain platforms use to verify transactions. However, it is computationally intensive and uses substantial quantities of electricity in the process.
Scientometric	Scientometrics is the study of the quantitative aspects of scientific communication in research, such as citation analysis (i.e. the frequency one journal author cites the work of another author).
Small and medium enterprise (SME)	An SME is a company that has less than 250 employees.
Smart contract	A smart contract is a miniature piece of software deployed on the blockchain. It allows users to program If & Then statements that carry basic contract functions.
Stealth Address	A stealth address is when a sub-wallet is created from a blockchain wallet and is used for the purpose of conducting private transactions on a public blockchain.
Terminal management system (TMS)	A TMS is a type of software that allows users to monitor the data or transactions of a system. In the case of PBAs, a TMS is used to monitor cash flow in and out of the PBA.
Blockchain wallet	A blockchain wallet is a wallet used for sending and receiving cryptocurrencies on the blockchain.
Web 2	Web 2 is when a Web application uses a Web server to process its data.
Web 3	Web 3 is when a Web application uses blockchain smart contracts to process its data.
Zero-knowledge proof (ZKP)	ZKP is a cryptographic protocol that allows people to verify that data is correct even if the data remains encrypted. It is used in public blockchains to achieve private transactions.

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Appendices

Appendix 1: UCL Declaration Form for Published Work

Publication 1 of 5

1. For a research manuscript that has already been published
   a) What is the title of the manuscript?
   Project bank account (PBA) decentralised application for the construction industry.
   b) Please include a link to or doi for the work:
   https://doi.org/10.1108/CI-04-2023-0067
   c) Where was the work published?
   Construction Innovation journal
   d) Who published the work?
   This PhD dissertation's author and his principal and secondary supervisors
   e) When was the work published?
   January, 2024.
   f) List the manuscript's authors in the order they appear on the publication:
   Senior author Denis Scott, Professor Ling Ma (UCL), Professor Tim Broyd (UCL)
   g) Was the work peer reviewed?
   Yes, by the scientific journal.
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2. For multi-authored work, please give a statement of contribution covering all authors:
   The author developed the conceptual framework and wrote the paper, and the co-authors reviewed the work and provided several rounds of feedback to make the paper more academically acceptable for scientific publication.

3. In which chapter(s) of your thesis can this material be found?
   Chapter two: Literature Review. Chapter four: Conceptual Framework. Chapter six: Discussion. Chapter seven: Conclusion.

4. e-Signatures confirming that the information above is accurate (this form should be co-signed by the supervisor/ senior author unless this is not appropriate, e.g. if the paper was a single-author work):

e-Signatures confirming that the information above is accurate (this form should be co-signed by the supervisor/ senior author unless this is not appropriate, e.g. if the paper was a single-author work):

PhD candidate and senior author:

Denis Scott

Date

22nd of July 2024

Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/0924

Supervisor and publication co-author

Ling Ma

Date

7/31/2024

UCL Research Paper Declaration Form: referencing the doctoral candidate's own published work(s)

Publication 2 of 5

5. For a research manuscript that has already been published
   a) What is the title of the manuscript?
   Conceptual model utilizing blockchain to automate project bank account (PBA) payments in the construction industry.
   b) Please include a link to or doi for the work:
   https://doi.org/10.1007/978-981-19-3759-0_8
   c) Where was the work published?
   Springer Nature book
   d) Who published the work?
   This PhD dissertation's author and his principal and secondary supervisors
   e) When was the work published?
   Year 2022.
   f) List the manuscript's authors in the order they appear on the publication:
   PhD candidate Denis Scott, Professor Tim Broyd (UCL), Professor Ling Ma (UCL).
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6. For multi-authored work, please give a statement of contribution covering all authors:
   The author developed the conceptual framework and wrote the paper, and the co-authors reviewed the work and provided several rounds of feedback to make the paper more academically acceptable for scientific research.

7. In which chapter(s) of your thesis can this material be found?
   Chapter one: Introduction. Chapter two: Literature Review. Chapter six: Discussion.

8. e-Signatures confirming that the information above is accurate (this form should be co-signed by the supervisor/ senior author unless this is not appropriate, e.g. if the paper was a single-author work):

e-Signatures confirming that the information above is accurate (this form should be co-signed by the supervisor/ senior author unless this is not appropriate, e.g. if the paper was a single-author work):

PhD candidate and senior author:

Denis Scott

Date

22nd of July 2024

Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/09/2024

Supervisor and publication co-author

Ling Ma

Date

7/31/2024

UCL Research Paper Declaration Form: referencing the doctoral candidate's own published work(s)

Publication 3 of 5

1. For a research manuscript that has already been published
   a) What is the title of the manuscript?
   Conceptual framework of a Project Bank Account (PBA) blockchain payment application for the construction industry.
   b) Please include a link to or doi for the work:
   10.35490/EC3.2022.188
   c) Where was the work published?
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Denis Scott

Date

22nd of July 2024

Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/09/2024

Supervisor and publication co-author

Ling Ma

Date

7/31/2024

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   b) Please include a link to or doi for the work:
   https://doi.org/10.1016/j.autcon.2021.103914
   c) Where was the work published?
   Automation in Construction journal.
   d) Who published the work?
   This PhD dissertation's author and his principal and secondary supervisors
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   Year 2021.
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PhD candidate and senior author:

Denis Scott

Date

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Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/09/2024

Supervisor and publication co-author

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   b) Please include a link to or doi for the work:
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   c) Where was the work published?
   ITC Digital Library.
   d) Who published the work?
   This PhD dissertation's author and his principal and secondary supervisors
   e) When was the work published?
   Year 2020.
   f) List the manuscript's authors in the order they appear on the publication:
   PhD candidate Denis Scott, Professor Ling Ma, Professor Tim Broyd
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PhD candidate and senior author:

Denis Scott

Date

22nd of July 2024

Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/09/2024

Supervisor and publication co-author

Ling Ma

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Publication 1 of 2

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c) Where is the work intended to be published?
Journal of Information Technology in Construction.

d) List the manuscript's authors in the intended authorship order:
Senior author Denis Scott. Author Professor Tim Broyd (UCL).

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Denis Scott

Date

22nd of July 2024

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Professor Tim Broyd

Date

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Publication 2 of 2

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Knowledge transfer from computer science to construction: Exploring the technical concerns of using blockchain for payments in the construction industry.

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c) Where is the work intended to be published?
Journal of Information Technology in Construction.

d) List the manuscript's authors in the intended authorship order:
Senior author Denis Scott. Author Professor Tim Broyd (UCL).

e-Signatures confirming that the information above is accurate (this form should be co-signed by the supervisor/ senior author unless this is not appropriate, e.g. if the paper was a single-author work):

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Denis Scott

Date

22nd of July 2024

Principal supervisor and publication co-author

Professor Tim Broyd

Date

05/09/2024

Appendix 3: Codebase of all smart contracts deployed

Table 19 and Table 20 display the open-source codebase of all the smart contract tables and smart contract triggers deployed in the proposed PBA blockchain application.

Table 19.

List of all deployed smart contract (SC) tables.

SC Label	SC table name	Description	Link to the smart contract's codebase	Link to the SC's deployment address
A	Client	This SC table holds the wallet address of the client.	https://github.com/D-UCL/PBA-dApp/blob/main/A)%20scTable.Client.sol	https://goerli.etherscan.io/address/0x6Ad768315a7fabca8F8D8Ea475B745532043963B
B	Project Manager	This SC table holds the wallet address of the project manager.	https://github.com/D-UCL/PBA-dApp/blob/main/B)%20scTable.ProjectManager.sol	https://goerli.etherscan.io/address/0x8407E90a59583e1241D7158ee0488733a302a9CC
C	Main Contractor	This SC table holds the wallet address of the main contractor.	https://github.com/D-UCL/PBA-dApp/blob/main/C)%20scTable.MainContractor.sol	https://goerli.etherscan.io/address/0xdC032b81464e64b3592335DF8185799283dC23c7
D	Guarantor	This SC table holds the wallet address of the guarantor.	https://github.com/D-UCL/PBA-dApp/blob/main/D)%20scTable.Guarantor.sol	https://goerli.etherscan.io/address/0x9813904e03Fe98c57Eb4184bF3dF0C738751b09a
E	PBA Manager	This SC table holds the wallet address of the PBA manager.	https://github.com/D-UCL/PBA-dApp/blob/main/E)%20scTable.pbaManager.sol	https://goerli.etherscan.io/address/0xB3832720d2dDd6603585f65771F5BA7a2a799E10
F	Sub contractor	This SC table holds the wallet addresses of the subcontractors.	https://github.com/D-UCL/PBA-dApp/blob/main/F)%20scTable.Subcontractor.sol	https://goerli.etherscan.io/address/0x513E81F9CC57B65113D5216e5fC3ef1e7784EFFC
G	Cash-in	This SC table holds the entire cash-in schedule of the project.	https://github.com/D-UCL/PBA-dApp/blob/main/G)%20scTable.Cash-in.sol	https://goerli.etherscan.io/address/0x8A17A1fF265734D6ddF240f070a5090B8720F130
H	Cash-out	This SC table holds the entire cash-out schedule of the project.	https://github.com/D-UCL/PBA-dApp/blob/main/H)%20scTable.Cash-out.sol	https://goerli.etherscan.io/address/0xbb93F9eA1BaB92F71EF8A796f75ce586aC85AAb6
J	SubWorks	This SC table allows subcontractors to filter and pull their scheduled works (in read-only format) from SC table H.	https://github.com/D-UCL/PBA-dApp/blob/main/J)%20scTable.SubWorks.sol	https://goerli.etherscan.io/address/0x17e183D7457713483001156994A9ECe3458d03B8
L	Cash-in retention	This SC table enables project participants to	https://github.com/D-UCL/PBA-dApp/blob/main/L)%20CashInRetention.sol	https://goerli.etherscan.io/address/0x4c04b4d49428Ba359D2c2b61E9296D4a87747B3f

		manage cash-in retentions.		
M	Cash-out retention	This SC table enables project participants to manage cash-out retentions.	https://github.com/D-UCL/PBA-dApp/blob/main/M)%20CashOutRetention.sol	https://goerli.etherscan.io/address/0xB1a91ef76714904D13c8e00E569771394E209bCe

Table 20.
List of all deployed smart contract (SC) triggers.

SC Label	SC trigger name	SC trigger conditions*	Description	Link to the smart SC's codebase	Ethereum Goerli Etherscan address
A1	Client.Sign		Allows the user to sign the trust deed.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/A1)%20Client.Insert.sol	https://goerli.etherscan.io/address/0x964BB2e0730CB81cB3B636695cf90db839A3b29a
A2	Client. Delete	User's address is in SC table A: Client.	The client can unappoint themselves by removing their address from SC table A: Client.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/A2)%20Client.Delete.sol	https://goerli.etherscan.io/address/0x2fB5E99Fe3D1ac5d1AAd7A11cdBF401f7c84B209
B1	Project Manager. Sign		Allows the user to sign the trust deed.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/B1)%20ProjectManager.Insert.sol	https://goerli.etherscan.io/address/0xA40BBA332fB81Edd161fa6E3E87fA4550b622db3
B2	Project Manager. Delete	User's address is in SC table A: Client.	Allows the client to unappoint the PM by removing the PM's address from SC table B: Project manager.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/B2)%20ProjectManager.Delete.sol	https://goerli.etherscan.io/address/0xd9d396f1C4E7Ed80da572A27bC5a2EdA73211807
C1	Main Contractor. Sign		Allows the user to sign the trust deed.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/C1)%20MainContractor.Insert.sol	https://goerli.etherscan.io/address/0x0E6BE714fac33bc9E1a831e952907Ee6FC9b03cc
C2	Main Contractor. Delete	User's address is in SC table B: Project manager.	Allows the PM to unappoint the MC by deleting the MC's address	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/C2)%20Ma	https://goerli.etherscan.io/address/0x4C7f29Cf2D6d01f88f7b52ABE12b148D8b2a82a0

			from SC table C: Main contractor.	inContractor.Delete.sol	
E1	PBA Manage. Sign		Allows the user to sign the trust deed.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/E1)%20pbaManager.Insert.sol	https://goerli.etherscan.io/address/0x5E8993Aa12d0bCA6c20edaD83756D8955824980A
E2	PBA Manage. Delete	User's address is in SC table B: Project manager.	Allows the PM to unappoint the PBA manager from SC table E: PBA manager.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/E2)%20pbaManager.Delete.sol	https://goerli.etherscan.io/address/0xb7E8B4d818dB5D7C0c659A289DD5027dC40F2eC9
F1	Sub contractor. Sign		Allows the user to sign the trust deed.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/F1)%20Subcontractor.insert.sol	https://goerli.etherscan.io/address/0x840184aBE72723f2b83F20f58b48fb7f2e0676d1
F2	Sub contractor. Delete	User's address is in SC table C: Main contractor.	Allows the MC to unappoint the subs' from SC table F: Subcontractors.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/F2)%20Subcontractor.Delete.sol	https://goerli.etherscan.io/address/0x538c044F72F1aAfa15639D36393FEc1b54BF8130
G1	Cash-in. Insert	User's address is in SC table C: Main contractor.	Allows the MC to insert the cash-in schedule into SC table G: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G1)%20Cash-in.Insert.sol	https://goerli.etherscan.io/address/0xB3224f9f2FFEdc68140f12867c70260A70C72284
G2	Cash-in. Update	User's address is in SC table C: Main contractor.	Allows the MC to update data in the SC table G: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G2.2)%20Cash-in.Update.PercentComplete.sol	https://goerli.etherscan.io/address/0xbbb8D3136745A8F7D0d07717C9dd065DE9C7A67C
G2.1	Cash-in. Update. ActualPrice	User's address is in SC table C: Main contractor.	Allows the MC to update the price in SC table G: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G2.1)%20Cash-in.Update.ActualPrice.sol	https://goerli.etherscan.io/address/0xad47394e202070519f61fb8be978ccb2ffb7bfa9
G2.2	Cash-in. Update. Percent Complete	User's address is in SC table C: Main contractor.	Allows the MC to update the % of works completed in SC table G: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G2.2)%20Cash-	https://goerli.etherscan.io/address/0xE904E39758dfE9AE8CEec735c0423692D380467A

				in.Update.PercentComplete.sol	
G3	Cash-in. Update. Approve	User's address is in SC table A: Client.	The client can approve the cash-in schedule by updating SC table G: Cash-in.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G3)%20Cash-in.Update.Approve.sol	https://goerli.etherscan.io/address/0xe56c2bc5ffD846321bb6cdfE2f2625C05B501871
G4	Cash-in. Update. Pay	User's address is in SC table A: Client.	Allows the client to execute a cash-in payment by updating SC table G: Cash-in.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G4)%20Cash-in.Update.Pay.sol	https://goerli.etherscan.io/address/0x8E2F31968cd6c626adD119Eb883262533a6B2Da3
G5	Cash-in. Delete	User's address is in SC table C: Main contractor. PBA's address is not in SC table L: Cash-in retention.	Allows the MC to remove a cash-in record from SC table G: cash-in and ensures that the PBA cannot be removed while they have records stored in SC tables J & L because it causes the SC to malfunction.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/G5)%20Cash-in.Delete.sol	https://goerli.etherscan.io/address/0x6b4eaCa91cF7519Fe2170517Cc7ad45Eee678d4C
H1	Cash-out. Main contractor. Insert	User's address is in SC table C: Main contractor.	Enables the MC to insert the cash-out schedule into SC table H: Cash-out.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H1)%20Cash-out.MainContractor.Insert.sol	https://goerli.etherscan.io/address/0x09c12Dd70d08b3E0236c4a23c1748022327E3C9C
H2	Cash-out. Sub contractor. Update	User's address is in SC table F: Subcontractor.	Enables the subs' to update SC table H: Cash-out to alert tier-one parties that they have completed works on-site.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H2)%20Cash-out.Subcontractor.Update.sol	https://goerli.etherscan.io/address/0x2953cD74aD335D5a0F87c907beA5439D49B47404
H3	Cash-out. Main contractor. Update	User's address is in SC table C: Main contractor.	Enables the MC to update the cash-in schedule by updating SC table H: Cash-out.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H3)%20Cash-out.MC.Update.planned.sol	https://goerli.etherscan.io/address/0x49E046B79730A59612754703307b2b399Db7D0b1
H3.1	Cash-out. MC.Update. Percent Complete	User's address is in SC table C: Main contractor.	Allows the MC to update the % of works completed in SC table H: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H3.1)%20Cash-	https://goerli.etherscan.io/address/0xd48000276765449133041021f0632bcf01374853

				out.MC.Update.PercentageOfWork.sol	
H3.2	Cash-in. Update. ActualPrice	User's address is in SC table C: Main contractor.	Allows the MC to update the actual cost of performed works in SC table H: Cash-in schedule.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H3.2)%20Cash-out.MC.Update.ActualPrice.sol	https://goerli.etherscan.io/address/0x1c236A97A9D54AEE3BD644e8eddBdA4403EC3226
H4	Cash-out. MC. Approve	User's address is in SC table C: Main contractor.	Enables the MC to approve the completion of works by updating SC table H: Cash-out.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H4)%20Cash-out.MC.Update.Approve.sol	https://goerli.etherscan.io/address/0x2DFD828d70c74895E63D2Db300B6006213ac4eD2
H5	Cash-out. PM. Approve	User's address is in SC table B: Project manager.	Enables the PM to approve the quality of works completed by updating SC table H: Cash-out.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H5)%20Cash-out.PM.Update.Approve.sol	https://goerli.etherscan.io/address/0xffb547E105C28bD6407Ef058fe24eA50Fd72D365
H6	Cash-out. PBA. Update. Pay	User's address is in SC table E: PBA manager.	Enables the PBA manager to execute a cash-out payment from SC table E: PBA.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H6)%20Cash-out.PBA.Update.Pay.sol	https://goerli.etherscan.io/address/0x5f08C8889514173138797cF9F43f353C4CB498e2
H7	Cash-out. Main contractor. Delete	User's address is in SC table C: Main contractor. Payee's address is not in SC table J: SubWorks The payee's address is not in SC table M: Cash-out retention.	Enables the MC to remove a cash-out record from SC table H: Cash-out, and ensures that the subcontractor cannot be removed while they have works planned in SC tables J & M (because it causes the smart contract to malfunction).	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/H7)%20Cash-out.MainContractor.Delete.sol	https://goerli.etherscan.io/address/0x28839c9A0c991477c86f608DdeBE874200d31051
J1	Subworks. Insert	User's address is in SC table H: Cash-out.	Allows the subcontractor to pull their scheduled works from SC table H: Cash-out and place it into SC table J: SubWorks.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/J1)%20SubWorks.Insert.sol	https://goerli.etherscan.io/address/0x1Fe982F9B85C2449aC422638143aAa637D03105a

J2	View. Delete	User's address is in SC table H: Cash-out.	Allows the subcontractor to remove a record from SC table J: View.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/J2)%20SubWorks.Delete.sol	https://goerli.etherscan.io/address/0xf2Bd7ED060b9C7449BADF87611397486C7bC807E
L1	Cash-in Retention. Insert	User's address is in SC table E: pbaManager.	Allows the PBA manager to register the cash-in retention by interacting with SC table L1.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/L1)%20CashInRetention.Insert.sol	https://goerli.etherscan.io/address/0x17610f39fD29741b719d5845323594EBFEE7C28F
L2	Cash-in Retention. Update	User's address is in SC table C: Main contractor.	The MC can update the cash-in retention data by updating SC table L2.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/L2)%20CashInRetention.Update.sol	https://goerli.etherscan.io/address/0x14c4B4978901e06526b491024bD2b5D924a2D156
L3	Cash-in Retention. Approve	User's address is in SC table A: Client.	The client can approve the cash-in retention data by updating SC table L3.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/L3)%20CashInRetention.Approve.sol	https://goerli.etherscan.io/address/0x32253EBb203a34bED5D50F483cD0d833Ebf52ABd
L4	Cash-in Retention. Paid	User's address is in SC table A: Client.	Allows the client to execute the cash-in retention payment by updating SC table L4.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/L4)%20CashInRetention.Pay.sol	https://goerli.etherscan.io/address/0xccC6Ba989be52A6fbfBF0fF04e786eD17c59F223
L5	Cash-in Retention. Delete	User's address is in SC table C: Main contractor.	Allows the main contractor to remove the cash-in retention record from SC table L5	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/L5)%20CashInRetention.Delete.sol	https://goerli.etherscan.io/address/0x910d1A859F859de5CBCB3318f2fc07f2c8938035
M1	Cash-out Retention. Insert	User's address is in SC table F: Subcontractor.	Allows the subcontractors to register the cash-out retention by interacting with SC table M1.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/M1)%20CashInRetention.Insert.sol	https://goerli.etherscan.io/address/0xe4CEFC9D7a6d33ce9590b634F4667df22C956078
M2	Cash-out Retention. Update	User's address is in SC table C: Main contractor.	The MC can update the cash-in retention data by updating SC table M2.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%20triggers/M2)%20CashOutRetention.Update.sol	https://goerli.etherscan.io/address/0xBECb020105b6A12ED4Fce2a4594CE66DD9cE7D68
M3	Cash-out Retention. Approve	User's address is in SC table	The MC can approve the cash-in retention data by updating SC table M3.	https://github.com/D-UCL/PBA-dApp/blob/main/Smart%20contract%2	https://goerli.etherscan.io/address/0x178EFBbb1145dD601

		C: Main contractor.		0triggers/M3)%20CashOutRetention.Approve.sol	31656566923a057113cc1D5
M4	Cash-out Retention. Paid	User's address is in SC table C: Main contractor.	Allows the MC to execute the cash-in retention payment by updating SC table M4.	https://github.com/D-UCL/PBA-dApp/commit/02afc5fd1a33baee7cb741fe5050915322a811f7	https://goerli.etherscan.io/address/0x630Eb04B3C5cFFd41B5e55a8F0Eda8B182008609
M5	Cash-out Retention. Delete	User's address is in SC table C: Main contractor.	Allows the MC to remove the cash-in retention record from SC table M5.	https://github.com/D-UCL/PBA-dApp/commit/4521d4fdbb898604bb6d6d49794c2b0980301716	https://goerli.etherscan.io/address/0x4470Ba46901ea47493879e2C70B9e4137F4099D9

Notes.

SC = smart contract.

*Conditions = the *if & then* statements hard-coded in the SC triggers. Whenever the term *user's address* is mentioned in the conditions column, it represents the user interacting with the SC trigger.